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A Parametric Investigation of a Novel, Modular, Gasketless, Microfluidic Interconnect Using Parallel Superhydrophobic Surfaces

Christopher Ramsey Brown
Louisiana State University and Agricultural and Mechanical College

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A PARAMETRIC INVESTIGATION OF A NOVEL, MODULAR, GASKETLESS, MICROFLUIDIC INTERCONNECT USING PARALLEL SUPERHYDROPHOBIC SURFACES

A Thesis

Submitted to the Graduate Faculty of the Louisiana State University and Agricultural and Mechanical College in partial fulfillment of the requirements for the degree of Master of Science

in

The Department of Mechanical Engineering

by

Christopher R. Brown
B.S., Louisiana State University, 2009
May 2014
Acknowledgments

I would like to thank my friends, my family, and my fiancé for their love, patience, and support throughout my masters program.

I am deeply thankful for Dr. Murphy’s vision, patience, and guidance through my academic journey. The depth and breadth of his knowledge, gained through an ardent focus and discipline, has been an inspiration to me. He has fostered a habit of inquiry within the μSET lab that I hope will stay with me for the rest of my life. I am thankful for his time that he spent helping me through this academic journey. He has patiently fulfilled the roles professor, ethicist, and at some times councilor. I apologize for any time I misspent exploring and reporting on my curiosities, expounding upon my theories, and asking unrelated questions.

I would like to thank the μSET lab team for their inspiration, support, and infectious curiosity and the LSU Department of Mechanical Engineering for their facilities and allowing me to borrow and return equipment for my experiments.

I would also like to thank Mrs. Boudreaux for sharing her stories about life, Louisiana, and LSU over countless “cups of encouragement”. I admire her faithfulness, hospitality, work ethic, and moral fortitude. I hope I will succeed in emulating her goodness throughout my life.

I would like to acknowledge and thank providential grace for bringing me into existence and imbuing me with talents and mentality necessary to complete this journey.

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Abstract

The gasketless microfluidic interconnect has the potential to offer a standardized approach to interconnects between modular microfluidic components. This strategy uses parallel superhydrophobic surfaces (contact angle $\geq 150^\circ$) to passively seal adjacent, concentric, microfluidic ports separated by an air gap using a liquid bridge created between the chips. The parallel superhydrophobic surfaces do not require the addition of a gasket or other additional components so that the assembly process scales favorably with an increasing number of fluidic interconnects.

Two static analytical models were derived from the Young-Laplace equation to estimate the maximum steady-state pressure of the liquid at the liquid bridge and three sets of experiments were performed to evaluate performance of the gasketless interconnects. The first two experiments demonstrated proof that the concept could work. The third set of experiments used injection molded chips with injection molded through-holes to ensure repeatable dimensions for the chips and locations of the through-holes. Chip-level alignment and gaps were defined by ball-in-v-groove kinematic alignment structures, with precision ground silicon nitride ball bearings used for the balls. A closed-loop pressure regulator was used to control the driving pressure of the fluid supplied by a pressurized liquid reservoir, and a pressure sensor to determine the pressure at the interconnect. The data validated the first generation model by showing that the model estimates of maximum interconnect pressures within $\pm50\%$ of the measured maximum pressures for $76\%$ of the samples. The measured maximum pressures did not match the second generation model. In fact, $67\%$ of the pressure measurements were in the range of $+150\%$ to $+7600\%$ of the second generation model’s value. Further investigation should
be performed to determine if the discrepancy was due to the assumption that a semicircular arc approximates the shape of the meniscus or the pressure sensor’s resolution.

The gasketless seal withstands maximum pressures seen in microfluidic systems without adding additional kinematic constraints and is realizable within manufacturing variation. The first generation model can be used to estimate the required maximum pressure.
1 Introduction

1.1 Motivation

Advances in microfluidics and lab-on-a-chip technology are revolutionizing the field of clinical diagnostics [1]. From amplifying DNA [2-4], to bacteria capture [5], to capturing [6] and profiling circulating tumor cells [7], lab-on-a-chip technology has been applied to scale laboratory processes down onto small polymer, glass, or silicon microfluidic chips. The scaling improves the laboratory processes through reduction of sample volume, consumption of reagents, cycle times, and material costs. These benefits have the potential for point-of-care use leading to more rapid diagnosis, more personalized care [1], and new diagnostic applications.

One application for rapid diagnostics is the ability to use biomarkers to differentiate between the two types of stroke: ischemic or hemorrhagic. In ischemic stroke a blood clot cuts off circulation to the brain. It is treated with tissue plasminogen activator (tPA) which dissolves the clot [8]. Hemorrhagic stroke is caused by an aneurysm rupturing in the brain causing internal bleeding. Demchuk et al [8] and Wang et al [9] in their studies on the effectiveness of treating stroke patients with tPA found that the mean treatment time with tPA from the onset of symptoms was 143±58 minutes [8] and 148±52 minutes [9]. Additionally, Wang et al [9] found that the mean time from door to CT was 33±20 minutes and from door to laboratory was 28±21 minutes. Young et al notes [10] ‘time is brain’ and a current major clinical problem is the correct determination of a stroke. This project is part of a larger effort to develop a rapid disposable point-of-care platform for detecting the different types of stroke from the whole blood drawn from a patient. This test would be administered in the ambulance on the way to the hospital with definitive results available before arrival.
When designing a lab-on-a-chip platform, it is necessary to select the system architecture. There are two general types of system architectures: integrated and modular. In an integrated lab-on-a-chip system, all of the components are on one chip, the interfaces between the components are coupled [11], and there is a complex mapping between functional and physical components on the chip [11]. In a modular lab-on-a-chip system, the component chips are used as building blocks to create more complex microfluidic systems [11], there is a one-to-one mapping between the functional elements and the physical components [11], and standardized physical connections between component chips [11].

A modular architecture was selected for this platform because it allowed for component module specific material selection and it allowed for components to be recombined and reused into different future systems. In keeping with the spirit of a modular architecture, a standardized microfluidic interconnect was needed for chip-to-chip connections between component chip modules. Several groups have previously investigated different designs of microfluidic interconnects which will be further discussed in the Background section. However, most of the designs in the literature create unnecessary dead volumes, require additional components, post-processing, or trained technicians. Consequently, a new type of standardized microfluidic interconnect was proposed and investigated: the gasketless superhydrophobic interconnect. The gasketless interconnect uses parallel superhydrophobic surfaces to passively seal a liquid bridge suspended between concentric microfluidic through-holes. It decouples alignment between chips from the interconnect design, may be useful for multiple connections on the same chip at the same time, requires no additional components, has negligible pressure drop, has negligible dead volume, and may be mass produced.
1.2 Organization

The chapters are sequentially organized. The second chapter provides context to this research by surveying the interconnect designs presented in the literature, and the third chapter introduces concepts from surface chemistry and thermodynamics that elucidates the physics of the gasketless interconnect. The fourth chapter delves into the analytical models developed to predict the maximum pressure of the gasketless interconnect before rupture. The fifth, sixth, and seventh chapters explore the gasketless interconnect experiments developed to test the validity of the models. They reveal the iterative nature of the experimental process and show how conclusions gleamed from early experiments can be used to refine experiments. The eighth chapter summarizes the conclusions developed in this thesis and the ninth chapter will discuss the future work. An appendix is added to give additional explanations about topics discussed in the chapters and explore ancillary topics that it will give additional context to the research presented.
2 Review of Literature on Fluidic Interconnects

2.1 Introduction

In modular systems, the interfaces between components define the physical connections that provide paths to transmit power, light, load, mass, and information [12]. These take the form of thermal, electrical, optical, structural, and fluidic interconnects. Examples are ubiquitous in modern electrical, fluidic, mechanical systems, including thermal conducting grease between a heat sink and a desktop processor, the solder used to electrically connect a pin from an integrated circuit (IC) chip to a pad on a IC board, a fiber optic cable used to connect the audio from a DVD player to the receiver is an optical interconnect, kinematic alignment structures constraining two adjacent components exemplify structural interconnects, and National Pipe Thread (NPT) connections used to connect a hose to an outdoor faucet is a fluidic interconnect. These macroscale examples show the abundance and necessity of interconnects at all length scales. This literature review will focus on fluidic interconnections on the microscale applied to microfluidic chips and microfluidic systems. Specifically, it will discuss the classification systems repeated in the literature, propose a new classification system based on the sealing strategy of the fluidic interconnect, and classify the fluidic interconnects from the literature based on their sealing strategy.

In microfluidic systems, fluidic interconnects provide the passage for transmitting fluid, containing mass and information, between component chips and to and from the microfluidic system [12]. Many current platforms use integrated architectures, meaning all chemical processing, fluidic processing, thermal management, and optical readouts are performed on a single chip. These integrated platforms are beginning to reach levels of complexity, performing multiple tasks, each with multiple constraints, where trade-offs have to be made between chip materials, manufacturing processes, geometry, optical properties, heat transfer characteristics,
and thermal stability of the chip because of their integrated nature. The field’s quest for solving more complex problems without sacrificing performance, the length scales utilized in microfluidic and nanofluidic systems, and the influence of mass production techniques may lead to the adoption of modular architectures for microfluidic and nanofluidic systems. Modular design principles will allow for chip-level specification of polymer, structures, and processing based on the performance needs of the component chips and the microfluidic system. These future modular microfluidic/nanofluidics systems will consist of modular component chips coupled by standardized fluidic interconnects. These fluidic interconnects should be reversible, minimize dead volume, minimize fluid loss, not add kinematic constraint to the chip or system, take advantage of the dominant forces at the microscale, not add additional components, such as gaskets, minimize the connection footprint, and be capable of being mass produced.

A broad spectrum of microfluidic interconnects have been reported. They have been classified by: the components being connected, “world-to-chip” [13] or “chip-to-chip” [13]; the length scale of the connection, “macro-to-micro” [13] or “micro-to-micro”; the thermodynamics of the connection, “reversible” [14] or irreversible (“permanent”[14]); and the orientation of the interconnect with respect to the plane of the device, “planar” [14] or “out-of-plane”. A world-to-chip classification describes a fluidic link between the physical world and the microfluidic chip whereas a chip-to-chip classification describes a fluidic connection between individual microfluidic component chips in a microfluidics system. A macro-to-micro interconnect describes the linking of a macroscale assembly, such as a syringe with a capillary tube, to a microscale channel whereas a micro-to-micro fluidic connection describes the linking of two microchannels. An irreversible or permanent connection increases the entropy of the system if disconnected; breaking an adhesive bond between a capillary tube and a device hole may be
required whereas a reversible interconnect can be connected and disconnected with negligible change in the entropy of the system like the elastic compression of a gasket. A planar connection refers to an interconnect whose axis is in the plane of the microfluidic device whereas an out-of-plane interconnect describes an interconnect whose axis is not in the plane of the microfluidic device. Table 1 compares a subset of interconnects reported in the literature based on the classifications methods used in the literature.

However, the current interconnect classification systems reported in the literature imply differences in the fluidic interconnect designs even though these interconnects use the same sealing methods as interconnects presented earlier. For example, the world-to-chip, out-of-plane, press-fit fluid interconnect reported by Christensen et al [15] (Figure 4) is essentially the same as the world-to-chip, planar, press-fit fluid interconnect reported by Lo et al [16] (Figure 11). A more general framework for classifying designs is to classify interconnects based on their sealing strategy. A classification system based on sealing strategy best differentiates between fluidic interconnects in the literature by grounding the categories in the design used to achieve the fundamental goal of the fluidic interconnect, directed transportation of fluid. Sealing strategies can be subdivided into two categories: contact-based and proximity-based sealing strategies. Contact sealing strategies involve physical contact between fluidic interconnect components. Proximity sealing strategies do not involve direct physical contact of the fluidic interconnect components. Contact-based sealing strategies use either strain-induced in elastic component materials, or grouting of the gap between the fluidic interconnect components. Strain-induced in elastic component sealing mechanism classification can be further divided into interference fits or compression of a compliant component such as a gasket or o-ring. The grouting classification can be subdivided into those that use phase transition of the grouting materials or amorphous to
cross-linked transition grouting materials. The proximity-based sealing strategies category currently has only one design which uses capillary forces to draw fluid into a device without leakage. Future differentiation of the proximity-based sealing strategies category into additional sub-categories will be necessary if other proximity interconnects are designed that do not rely on capillary forces to provide a seal. Figure 1 displays the hierarchy of the sealing strategy based classification system.

A modified version of this proposed framework was adopted to classify interconnect designs in the literature. The modifications include adding combination categories for interconnects that use multiple methods to prevent leakage. Hopefully, this modified framework will better highlight the important similarities and differences between alternative designs. In some categories, similar interconnect designs were published by different groups at different times. Consequently, the date for each method was included to try to give recognition to the first use.

2.2 Contact Based Sealing Strategies

2.2.1 Strain-induced in Elastic Component

One strategy of sealing is to close the gap between the components by applying assembly forces that cause the adjacent fluidic interconnect interfaces to elastically or plastically deform. Both interference fits and compression of a gasket induce strain in elastic components.

2.2.1.1 Interference Fit Sealing Strategy

According to Shigley [17], an interference fit is “the assembly of two cylindrical parts by press-fitting or shrinking one member onto another” creating “contact pressure between [the] two members.” Several examples of fluidic interconnects that rely on interference fits have been demonstrated.
Figure 1: Hierarchy of Fluidic Interconnect Sealing Strategies

In 1998, González et al created two interconnections that relied on interference fits. One was a world-to-chip, macro-to-micro, reversible, planar interconnect that used an interference fit between a compliant plastic tube over an etched silicon tube that extends out from the device (Figure 2) [18]. The other was a chip-to-chip, micro-to-micro, reversible, in-plane connection that used an interference fit between a wet etched silicon fluidic mortise and tenon joints (Figure 3). These were manufactured in a cleanroom using an integrated process with silicon fabrication techniques. All of the connectors added constraint to the microfluidic system and were tested up to pressures of 138 kPa without leakage.
Table 1: Comparison of interconnect designs presented in the literature.

<table>
<thead>
<tr>
<th>Interconnect Description</th>
<th>Interconnection Blocks</th>
<th>World-to-chip</th>
<th>Macro-to-micro/ Micro-to-micro</th>
<th>Reversible/ Irreversible</th>
<th>In-plane/ Out-of-plane</th>
<th>Sealing Method</th>
<th>Maximum Pressure</th>
<th>System Constraint Independent of # of interconnects</th>
<th>Reference (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interconnection Blocks</td>
<td>World-to-chip</td>
<td>Macro-to-micro</td>
<td>Reversible</td>
<td>In-plane</td>
<td>compression of integrated O-ring</td>
<td>550 kPa</td>
<td>No</td>
<td>[14]</td>
<td></td>
</tr>
<tr>
<td>Gaskets/O-rings/wax</td>
<td>World-to-chip</td>
<td>Macro-to-micro</td>
<td>Reversible</td>
<td>In-plane/ Out-of-plane</td>
<td>Compression of gasket/o-ring/wax</td>
<td>200 kPa, 414 kPa, 608 kPa, N/A, 138 kPa, 345 kPa, 100 kPa, ?, 1.9 MPa, 420 kPa, 200 kPa, ?</td>
<td>No</td>
<td>[19], [20], [21], [18], [22], [23], [24], [25], [26], [27], [28]</td>
<td></td>
</tr>
<tr>
<td>Grouting with epoxy with Mylar membrane to prevent channel contamination</td>
<td>World-to-chip</td>
<td>Macro-to-micro</td>
<td>Irreversible</td>
<td>Out-of-plane</td>
<td>Grouting of epoxy</td>
<td>190 kPa</td>
<td>No</td>
<td>[29]</td>
<td></td>
</tr>
<tr>
<td>Melting polyethylene tube grouted with epoxy</td>
<td>World-to-chip</td>
<td>Macro-to-micro</td>
<td>Irreversible</td>
<td>Out-of-plane</td>
<td>Grouting with melted polyethylene and epoxy</td>
<td>Tested up to pressures of 5 kPa</td>
<td>No</td>
<td>[30]</td>
<td></td>
</tr>
<tr>
<td>Interlocking alignment structures with PDMS grouting</td>
<td>Chip-to-chip</td>
<td>Micro-to-micro</td>
<td>Irreversible</td>
<td>In-plane</td>
<td>Grouting with PDMS</td>
<td>103 kPa</td>
<td>No</td>
<td>[31]</td>
<td></td>
</tr>
<tr>
<td>Flange connection</td>
<td>World-to-chip</td>
<td>Macro-to-micro</td>
<td>Irreversible</td>
<td>Out-of-plane</td>
<td>Interference fit between capillary and flange in substrate</td>
<td>2.6 MPa, 6.6 MPa</td>
<td>No</td>
<td>[32]</td>
<td></td>
</tr>
<tr>
<td>Interconnect Description</td>
<td>World-to-chip/Chip-to-chip</td>
<td>Macro-to-micro/ Micro-to-micro</td>
<td>Reversible/ Irreversible</td>
<td>In-plane/ Out-of-plane</td>
<td>Sealing Method</td>
<td>Maximum Pressure</td>
<td>System Constraint Independent of # of interconnects</td>
<td>Reference (s)</td>
<td></td>
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<tr>
<td>Press-fit plastically deformed melted end of capillary and epoxy grouting</td>
<td>World-to-chip</td>
<td>Macro-to-micro</td>
<td>Irreversible</td>
<td>Out-of-plane</td>
<td>Interference fit with epoxy grouting</td>
<td>2.17 MPa</td>
<td>No</td>
<td>[33]</td>
<td></td>
</tr>
<tr>
<td>Press-fit capillary with silicone gasket</td>
<td>World-to-chip</td>
<td>Macro-to-micro</td>
<td>Reversible</td>
<td>Out-of-plane</td>
<td>Interference fit and compression of gasket</td>
<td>413 kPa</td>
<td>No</td>
<td>[19]</td>
<td></td>
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<tr>
<td>Press-fit connection</td>
<td>World-to-chip/chip-to-chip</td>
<td>Micro-to-micro</td>
<td>Reversible</td>
<td>Out-of-plane</td>
<td>Interference fit</td>
<td></td>
<td>No</td>
<td>[34], [25], [18], [35]</td>
<td></td>
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<tr>
<td>Compliant tube over Si tube</td>
<td>World-to-chip</td>
<td>Macro-to-micro</td>
<td>Reversible</td>
<td>In-plane</td>
<td>Interference fit</td>
<td>138 kPa</td>
<td>No</td>
<td>[18]</td>
<td></td>
</tr>
<tr>
<td>Ferrules</td>
<td>World-to-chip</td>
<td>Macro-to-micro</td>
<td>Reversible</td>
<td>Out-of-plane</td>
<td>Interference fit</td>
<td>750 kPa</td>
<td>No</td>
<td>[36]</td>
<td></td>
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<tr>
<td>Capillaries fixed in place with epoxy</td>
<td>World-to-chip</td>
<td>Macro-to-micro</td>
<td>Irreversible</td>
<td>Out-of-plane</td>
<td>Epoxy grouting</td>
<td>3.4 MPa</td>
<td>No</td>
<td>[19]</td>
<td></td>
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<tr>
<td>Interconnect Description</td>
<td>World-to-chip/ Chip-to-chip</td>
<td>Macro-to- micro/ Micro-to-micro</td>
<td>Reversible/ Irreversible</td>
<td>In-plane/ Out-of-plane</td>
<td>Sealing Method</td>
<td>Maximum Pressure</td>
<td>System Constraint Independent of # of interconnects</td>
<td>Reference (s)</td>
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<td>Needle press-fit into compliant tube press-fit in chip</td>
<td>World-to-chip</td>
<td>Macro-to-micro</td>
<td>Reversible</td>
<td>In-plane</td>
<td>Interference fit</td>
<td>640 kPa</td>
<td>No</td>
<td>[37]</td>
<td></td>
</tr>
<tr>
<td>Compliant tube UV-assisted bonded into PMMA chip</td>
<td>World-to-chip</td>
<td>Macro-to-micro</td>
<td>Irreversible</td>
<td>In-plane</td>
<td>Grouting through bonding</td>
<td>600 kPa</td>
<td>No</td>
<td>[37]</td>
<td></td>
</tr>
<tr>
<td>Needle press-fit into PDMS septum in chip</td>
<td>World-to-chip</td>
<td>Macro-to-micro</td>
<td>Reversible</td>
<td>In-plane</td>
<td>Interference fit</td>
<td>51 kPa</td>
<td>No</td>
<td>[38]</td>
<td></td>
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<tr>
<td>Needle press-fit into PDMS device</td>
<td>World-to-chip</td>
<td>Macro-to-micro</td>
<td>Reversible</td>
<td>Out-of-plane</td>
<td>Interference fit</td>
<td>100 kPa to 700 kPa</td>
<td>No</td>
<td>[15]</td>
<td></td>
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<tr>
<td>Notched cylinder in hole interference fit with beeswax gasket</td>
<td>Chip-to-chip</td>
<td>Micro-to-micro</td>
<td>Irreversible</td>
<td>Out-of-plane</td>
<td>Combination of interference fit and compression of beeswax</td>
<td>64.9 kPa</td>
<td>Yes</td>
<td>[23]</td>
<td></td>
</tr>
<tr>
<td>Compression of double-sided tape</td>
<td>Chip-to-Chip</td>
<td>Micro-to-micro</td>
<td>Irreversible</td>
<td>Out-of-plane</td>
<td>Compression of tape and grouting</td>
<td>190 kPa</td>
<td>No</td>
<td>[41]</td>
<td></td>
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<tr>
<td>Hydrophilic wicking</td>
<td>World-to-chip</td>
<td>Macro-to-micro</td>
<td>Reversible</td>
<td>Out-of-plane</td>
<td>Capillary forces</td>
<td>?</td>
<td>Yes</td>
<td>[42]</td>
<td></td>
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</table>
Figure 2: González et al created a world-to-chip, macro-to-micro, reversible, in-plane interconnect that used an interference fit between a compliant plastic tube over a silicon etched tube that extends from the device [18].

Figure 3: González et al created a chip-to-chip, micro-to-micro, reversible, in-plane connection that used an interference fit between silicon etched fluidic mortise and tenon joints [18].

In 2005, Christensen et al created a world-to-chip, macro-to-micro, reversible, out-of-plane interconnection that used an interference fit between a needle and a PDMS substrate (Figure 4)[15]. Post-processing including manual coring and insertion of a needle into the device were needed. Every additional interconnect adds additional constraint to the system. A maximum pressure of between 100 kPa and 700 kPa was reported. This interconnect had a diameter of approximately 1 mm.
Figure 4: Christensen et al created a world-to-chip, macro-to-micro, reversible, out-of-plane interconnection that used an interference fit between a needle and the PDMS substrate. The image to the left shows the process of coring PDMS with a modified 20 gauge needle. The image to the right shows the interconnects on a microfluidic chip. [15]

In 2008, Gray’s group at Simon Fraser University in British Columbia, in Gray et al [34], Jaffer et al [43], and Westwood et al [16] described a chip-to-chip, micro-to-micro, reversible, out-of-plane interconnection that used a ‘peg-in-hole’ interference fit between a PDMS, SU-8, or silicon cylinder and a PDMS, SU-8, or silicon hole (Figure 5-Figure 7).

Figure 5: Westwood et al design of ‘peg-in hole’ interconnect using SU-8 and PDMS [16].
This approach used integrated processing including silicon processing techniques such as photolithography, soft lithography, and deep reactive ion etching, in a cleanroom. The added constraint due to the interference fit between the cylinder and the hole produces an indeterminate assembly. The maximum pressure the PDMS post/PDMS hole interconnection could withstand was 6.9 kPa with water [43] and 21 kPa with air [34, 43]. The maximum pressure silicon
post/silicon hole interconnection could withstand was 69 kPa at a flow rate of 1.95 mL/min using wax to assist sealing [34]. The maximum pressure the SU-8 post in the silicon hole could withstand was 200 kPa [43]. The maximum pressure SU-8 posts/PDMS hole could withstand was 148 kPa [16]. The footprint of the interconnection was 200-400 μm.

In 2008, Yuen created a chip-to-chip, micro-to-micro, reversible, out-of-plane interconnection which used an interference fits between miniaturized standardized male/female Luer fittings between components (Figure 8 and Figure 9)[35, 44]. These interconnects had microchannels with diameters of 635 μm and were created using stereolithography and manually assembled. They were tested to a maximum pressure of 350 kPa in a pressure test.

Figure 8: Yuen created standardized fluidic interconnects that used standardized Luer fittings created by stereolithography [44].
In 2008, Perozziello et al created a world-to-chip, macro-to-micro, reversible, out-of-plane interconnection which used an interference fit between an external metal ferrule and an embedded Sylastic® RVM elastomer ring (Figure 10)[36]. This interconnection used integrated manufacturing for the PMMA housing and modular manufacturing for the embedded elastomer rings. The components were then manually assembled and a cover was thermally bonded over them. The metal tubes were manually inserted into the elastic rings. They added additional constraint to the system and the maximum pressure without leaking was 750 kPa. These interconnects were robust since this maximum pressure was maintained even after removing the ferrule from the ring 300 times. This interconnect was 4 mm in diameter and 3.5 mm deep.
Figure 10: Perozziello et al created a world-to-chip, macro-to-micro, reversible, out-of-plane interconnection which uses a press fit connection between an external metal ferrule and an imbedded Sylastic® RVM elastomer ring. The top two images show a cross section of a capillary tube connected to a microfluidics device using a ferrule interconnect and the bottom two images show real chips with the featured interconnections [36].

In 2008, Lo et al created a world-to-chip, macro-to-micro, reversible, planar interconnect that used an interference fit between a needle and a PDMS septum (Figure 11 and Figure 12) [38]. This interconnect relied on integrated processing using “conventional micromachining techniques” [38]. The needle had to be manually aligned with the PDMS septum. It added additional constraint to the system with each additional interconnect. A maximum pressure of 51 kPa was supported and the device had a footprint of approximately 1cm by 1 cm.
Figure 11: Lo et al created a world-to-chip, macro-to-micro, reversible, planar interconnection that utilizes an interference fit between a needle and a PDMS septum. The image shows a needle on the left side of the image piercing the PDMS septum and delivering red fluid to the microchannel [38].

Figure 12: These images show the different shapes of PDMS septums that Lo et al tested [38].

In 2010, Sabourin et al created a world-to-chip, macro-to-micro, reversible, planar fluidic interconnect that used an interference fit between a blunted needle and a compliant tube [37] (Figure 13). The compliant tubing was manufactured separately from the microfluidic device and then assembled with it. A maximum pressure of 640 kPa was supported before failure. Each additional interconnect imposed constraints between the microfluidic device and the blunted needle connected to it.
Figure 13: Sabourin et al created a world-to-chip, macro-to-micro, reversible, planar fluidic interconnect that utilizes an interference fit between a blunted needle and a compliant tube [37].

2.2.1.2 Compression of Elastic Component(s)

Another strain-induced sealing strategy uses “an elastic material or combination of materials clamped between two separable members of a mechanical joint” [17] to span the gap between the members and form a fluidic seal.

In 1993, Schoot et al designed a chip-to-chip, micro-to-micro, reversible, and out-of-plane interconnect which used compression of an elongated polysiloxane o-ring to seal between microchannels (Figure 14 and Figure 15)[21]. It was manufactured during the processing of the modular component chip using photolithography to define the polysiloxane elongated o-ring. This added constraint to the component chip through the compression of the elongated o-ring.

Figure 14: Schoot et al designed a chip-to-chip, micro-to-micro, reversible, and out-of-plane interconnect which employs compression of a polysiloxane elongated o-ring to seal between microchannels [21].
In 1998, González et al showed a chip-to-chip, micro-to-micro, reversible, out-of-plane connection that used elastic averaging of interlocking structures to align through-holes on adjacent chips and photo-patternable silicone O-rings for sealing (Figure 16) [18]. This interconnect was manufactured in a cleanroom using an integrated process with silicon processing techniques. The interconnect design added constraint between the adjacent microfluidic chips in the microfluidic system and it was tested up to pressures of 138 kPa without leakage.
In 2001, Hasegawa et al developed a chip-to-chip, micro-to-micro, reversible, out-of-plane interconnect using compression of silicone rubber (PDMS) gaskets sandwiched between microfluidic chips to seal the microfluidic stack (Figure 17)[26]. The microfluidic stack was preloaded with a spring to compress the silicone gaskets. The silicone gaskets were formed in a polymer mold made from microstereolithography and the maximum pressure for 200 μm thick gaskets was 420 kPa.

Figure 17: Hasegawa et al developed a chip to chip interconnect that used the compression of a silicone gasket to seal between component chips [26]. The image on the left shows the 14mm by 14mm component chips used in the microfluidic stack and the image on the right shows a silicone rubber gasket prototype.

In 2001, Nittis et al designed a world-to-chip, macro-to-micro, reversible, out-of-plane interconnect which used silicone elastomer membrane as a gasket between the capillary tubes and the microfluidic chip (Figure 18)[20]. The interconnection was manufactured separately from the microfluidic chip. Constraint was added through the compression of the silicone elastomer sealing membrane. The maximum pressure was 608 kPa and it was tested up to a flow rate of 1.5 mL/min. The footprint of the interconnect was difficult to determine because the interconnection was created using an outer housing to completely enclose the chip and align the
through holes with the interconnections. The outer housing dimensions were 38 mm x 35 mm x 30 mm.

Figure 18: Nittis et al designed a world-to-chip, macro-to-micro, reversible, out-of-plane interconnect which uses silicon elastomer membrane as a gasket between the capillary tubes and the microfluidics chip. The top image shows the assembly assembled and the bottom image shows the assembly parts including part 7 which is the sealing membrane which fits over the capillary tubes.

In 2003, Yang et al created a world-to-chip, macro-to-micro, reversible, out-of-plane interconnect that utilize a compression of flexible silicone tube to seal around a through-hole in a
microfluidic chip (Figure 19) [27]. A modular socket was designed to align the silicon tubes with the through-holes on the microfluidic chip. The silicone tubes had an inner diameter of 0.5 mm, an outer diameter of 1 mm, and rise 0.6 mm from the socket module toward the microfluidic chip. Additional constraint was added to the microfluidic chip through the compression of the flexible tube with the top of the microfluidic device. The maximum pressure supported was 200 kPa.

![Diagram of microfluidic chip and socket](image)

Figure 19: Yang et al designed a world-to-chip interconnect that used a compression of a flexible silicone tube against the top of a microfluidic chip to prevent leakage [27].

In 2003, Tiggelaar et al created a chip-to-chip, micro-to-micro, irreversible, out-of-plane interconnect that utilized a preloaded o-ring sandwiched between a component module soldered in place and the fluidic circuit board (Figure 20) [24]. The o-ring module was created separately from the processing of the component module chip and the fluidic circuit board. This interconnect relies on manual assembly of the component module, o-ring, and fluidic circuit
board and manual soldering to lock the components into place. Additional constraint is added to the system with each additional interconnect. The maximum pressure and the footprint of this interconnect were not discussed.

Figure 20: Tiggelaar et al created a chip-to-chip, micro-to-micro, irreversible, out-of-plane interconnect that utilized a preloaded o-ring sandwiched between a soldered in place component module and the fluidic circuit board. The image above shows the assembly process. [24]

In 2004, Gray et al described a chip-to-chip, micro-to-micro, irreversible, out-of-plane interconnect that relies on the interlocking “fin” structures to align through-holes and beeswax to form a gasket between the mating interfaces (Figure 21) [23]. It was manufactured in silicon using photolithography and deep reactive ion etching. The interlocking fingers induce
overconstraint in the microfluidic chips and does not scale well with an increasing number of interconnects. It was tested up to a pressure of 100 kPa.

Figure 21: Cross-section of an interconnect designed by Gray et al that used mechanically interlocking fins to align chip-to-chip through-holes and beeswax to serve as a gasket[23].

In 2005, Hashimoto et al created a chip-to-chip, micro-to-micro, reversible, out-of-plane interconnect that used compression of a poly (dimethylsiloxane) (PDMS) o-ring microgasket to seal between through-holes on adjacent chips (Figure 22) [28]. The PDMS gasket had a 400 μm thickness with a 100 μm laser-drilled through-hole. The dead volume of the interconnection was <200 nL. A maximum interconnect pressure was not reported. Constraint was added with each interconnect through the compression of the o-ring.

Figure 22: Hashimoto et al created a chip-to-chip interconnect using a PDMS microgasket with a 100 mm drilled through-hole. 1) Polycarbonate ligase detection reaction chip, 2) PMMA zip code array microfluidic chip, 3) PDMS gasket, 4) laser-drilled interconnecting microchannel, 5) Fused-silica capillaries, 6) Clamps, and 7) Kapton film heaters.
In 2008, Misrendino et al demonstrated a chip-to-chip, micro-to-micro, reversible, out-of-plane interconnect that used compression of silicone microgaskets to seal between through-holes (Figure 23 and Figure 24) [22]. It relied on modular processing because the interconnect chip with the microgaskets was manufactured separately from the microfluidic chip. These chip stacks were visually aligned, manually assembled, and microgaskets preloaded with screws. The chips were fabricated by spinning on a photodefinable silicone, patterning the silicone, dry etching the residue, and releasing the pattern in alcohol. Each additional microgasket added additional constraint to the system. Misrendino et al acknowledged one problem with the design was that “the maximum compression is near or possibly smaller than the variation in the surface flatness” [22]. This problem associated with surface flatness will increase with an increasing the number of interconnects. The maximum pressure that the microgaskets could withstand was 345 kPa at 5μL/min. The footprint was 900 μm in diameter.

Figure 23: (a) shows an SEM image of a microgasket with dimensions, and (b) shows an array of microgaskets from the interconnect chip [22].

Figure 24: Misrendino et al created a chip-to-chip, micro-to-micro, reversible, out-of-plane interconnection that used compression of silicone microgaskets to seal between through-holes. The above image shows the interconnect chip, containing the silicone microgaskets, sandwiched between the cover and the device chip.
In 2009, Sabourin et al designed a chip-to-chip, micro-to-micro, reversible, planar, fluidic interconnect that relied on compression of gaskets integrated into fluidic interconnection block to seal multiple planar microchannels (Figure 25-Figure 27) [14]. The interconnection blocks with integrated gaskets were cast ‘in situ’ in one piece of PDMS inside a poly(methyl methacrylate) (PMMA) mould. The interconnection block required only that the microchannels be aligned with the microchannels on the microfluidics chip and then be clamped to compress the gaskets. This adds additional constraint to the adjacent microfluidic chips. The interconnection blocks supported a maximum pressure of 550 kPa before leaking.

Figure 25: Sabourin et al created a chip-to-chip, micro-to-micro, reversible, planar, fluidic interconnect that relied on compression of gaskets integrated into fluidic interconnection block to seal between multiple planar microchannels. The PDMS box of interconnection block have a length (l) of 30 mm, a height (h) of 4 mm, a width (w) of 10 mm, and both sides of o-ring structure have an inner diameter (ID) of 1.0 mm, an outer diameter (OD) of 1.8 mm, and are raised above the PDMS box by 0.4 mm. [14]
Figure 26: A top view of the interconnection mentioned previously. This interconnection block (IB) is sandwiched between two needle assemblies on an aluminum base plate. The assembly is aligned using 2 mm alignment pins. [3]

Figure 27: Representative alignment between interconnection block (on the right) and needle assembly on the left [14].

### 2.2.1.3 Combination of Strain-induced Sealing Strategies

Some interconnects use a combination of interference fits and compression of an elastic component to seal the fluidic connections.

In 1999, Benett et al created three world-to-chip, macro-to-micro, reversible, out-of-plane fluidic interconnections [25]. All three interconnects utilized compression of an o-ring to provide sealing with three different configurations. The first configuration, the “screw connector”, used a hollow screw and a ferrule to compress the o-ring and align the polyether ether ketone (PEEK)
tubing with the through hole. The second configuration, the “double o-ring snap connector”, featured a snap fitting where a cartridge fitted with an upper and lower o-ring was placed in a counter sunk hole above the fluidic through hole and the insertion of the PEEK tubing caused the top o-ring to lock the tubing in place and the bottom o-ring to compress and create the seal. The third configuration, the molded ring snap connector, used an injection molded ring set inside a hollow set screw to provide a snap fitting when the PEEK tubing was inserted (Figure 28-Figure 30)[25]. The components were fabricated separately from the microfluidics chip and manually assembled. They added additional constraint to the microfluidic system. The maximum pressure the “screw connector” could withstand was 6.8 MPa and its footprint was defined by its ferrule diameter of 1.5mm. The maximum pressure the “double o-ring snap connector” could withstand was 1.8 MPa and its footprint was determined by its diameter 3.6mm. The maximum pressure the “molded ring snap connector” could withstand was 3.4 MPa and its footprint was defined by the countersunk hole diameter of 2.6 mm.

Figure 28: Benett et al created this interconnect that used a hollow screw and a ferrule to compress the o-ring and align the PEEK tubing with the through hole. [25]
Figure 29: Benett et al created this interconnect that uses a snap fitting where a cartridge is fitted with an upper and lower o-ring is placed in a counter sunk hole above the fluidic through hole and the insertion of the PEEK tubing causes the top o-ring to lock the tubing in place and the bottom o-ring to compress and create the seal.

Figure 30: Benett et al created this interconnect that uses an injection molded ring set inside a hollow set screw to provide a snap fitting when the PEEK tubing is inserted. [25]

In 2002, Thompson demonstrated two a chip-to-chip, micro-to-micro, reversible, out-of-plane interconnect. One used an interference fit between two sets of interlocking concentric rings with a trapezoidal cross section and a gold gasket layer to form a seal (Figure 31-Figure 33)[45, 46]. The second featured a “quasi-kinematic coupling” with an applied pre-load between a
pyramid with four through holes on its faces and a pyramidal pit with four through holes on its faces and a deposited gold gasket. The concentric ring trapezoidal geometry was created in silicon using the silicon processing techniques of directional reactive ion etching, deep reactive ion etching, growing silicon dioxide, spin coating, photolithography, and removal of the oxide pattern. The pyramid/pyramidal pit geometry was created in silicon using the silicon processing techniques of wet etching with potassium hydroxide and deep reactive ion etching. The diameter of the inner most ring was 400 μm and the inner rings were nominally 40 μm above the surface. Thompson was not able to test either interconnect design due to fabrication issues. In 2005, Jonnalagadda [47] concluded that the Thompson’s micro-scale interconnects were not commercially viable due to the fabrication cost, and the difficulty of manual assembly. The focus was shifted to meso-scale versions of Thompson’s microfluidic interconnects. Jonnalagadda machined the concentric ring design in 1” diameter aluminum stock using a high speed CNC mill. He found that the meso-scale concentric ring design sealed up to pressures of 862 kPa (Figure 34).

Figure 31: Side view of concentric ring fluidic interconnect created by Thompson et al [46].
Figure 32: Side view of assembly of a chip with two concentric ring fluidic interconnects created by Thompson et al [45].

Figure 33: Side view of Thompson et al pyramid/pyramidal pit fluidic interconnect design[45].

Figure 34: Jonnalagadda meso-scale version of Thompson's interlocking concentric ring fluidic interconnect machined using high speed CNC mill in 1” diameter aluminum stock [47].
2.2.2 Grouting the Gap Between Interconnect Components

An alternative contact-based sealing strategy is to prevent leakage by filling the gap between interconnecting component with another material. The process of filling a gap is called grouting, and it is usually done with either a material that cross-links or a material that undergoes a phase transition.

2.2.2.1 Cross-linking Materials

In 2008 and 2011, Burns’ group reported work by Rhee et al [48] and Langelier et al [31].

Rhee et al created a chip-to-chip, micro-to-micro, irreversible, in-plane interconnect that used either liquid adhesive or UV- curable PDMS to grout the gap between component chip modules (Figure 35) [48]. The devices were manually assembled using tweezers, a high magnification stereoscope, and a PDMS coated glass substrate. The adhesive solution was applied around the device and excessive solution that leaked into the channel was removed by aspiration. Depending on the grouting material used, the device was then either cured at 150⁰ C for 15 minutes or placed in a “UV-crosslinker” for 10 minutes. The maximum pressure the adhesives could withstand was 207 kPa.

Figure 35: Rhee et al created a chip-to-chip interconnect that used an adhesive solution to grout the gap between component chips [48].

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Langelier et al created a chip-to-chip, micro-to-micro, irreversible, in-plane interconnect that utilized ‘puzzle piece style’ alignment structures to align through holes and the cross-linking of PDMS to grout and seal the connection (Figure 36) [31]. The PDMS ‘puzzle piece style’ featured modular microfluidic components were manually assembled with fine tweezers into systems. The fluidic interconnects were then connected with tweezers and either stamped and cured or bonded using an O₂ plasma treatment. Leaks were corrected by manually grouting with PDMS and curing on a hotplate at 140° C for an unspecified time. This integrated approach manufactured the interconnects with the microfluidic device. A SU-8 master mold was replicated using a low viscosity liquid silicone to create a flexible mold. This mold was then cast with PDMS to create the microfluidic modules. These interconnections add additional constraint to the system. The maximum pressure these interconnections could withstand was 103 kPa. The footprint was not stated but the channel width was 80 μm.

Figure 36: Langelier et al created a chip-to-chip, micro-to-micro, irreversible, in-plane interconnect that utilized ‘puzzle piece style’ interconnecting alignment structures to align through holes and PDMS grout and seal the connection. (a) shows different shapes of modular component pieces, (b) show how you can make a device by connecting the components and grouting them with PDMS, and (c) shows an actual device [31].
2.2.2.2 Phase Transition

In 2000, Enikov et al designed a chip-to-chip, micro-to-micro, irreversible, out-of-plane interconnect that used an electroplated gold seal that bonded with the silicon of the “multi-chip-module” to create a hermetic gold-silicon eutectic bond (Figure 37) [40]. The module chips were created using silicon processing techniques: spin coating, photolithography, wet etching, and electroplating. The electroplated gold for the fluidic seal was 8 μm thick and was heated to 372⁰ C to create the eutectic gold-silicon bond. The maximum pressure is not discussed. This interconnect adds constraint between the chips.

![Figure 37: Enikov et al created a chip-to-chip interconnect by grouting the gap using a gold-silicon eutectic bond [40].](image)

2.2.2.3 Combination of Grouting Techniques

In 2000, Wijngaart et al designed a world-to-chip, macro-to-micro, irreversible, out-of-plane fluidic interconnect that employs a melted polyethylene tube grouted with epoxy to seal the connection (Figure 38)[30]. It was manufactured by a combination of deep reactive ion etching (DRIE) of silicon, and heating with a hot plate. It was manually assembled after the microfluidics chip is manufactured. This interconnect added constraint to the microfluidics device which will lead to alignment problems between the microfluidics chip and the input devices with an increasing number of fluidic interconnects. This interconnect was tested up to pressures of 5 kPa with no leakage. The footprint of this interconnect was not mentioned.
Figure 38: Wijngaart et al designed a world-to-chip, macro-to-micro, irreversible, out-of-plane fluidic interconnect that employs a melted polyethylene tube grouted with epoxy to seal the connection [30].

2.2.3 Combinations of Contact Based Sealing Strategies

In 1994, Verpoorte et al created a chip-to-chip, micro-to-micro, irreversible, out-of-plane interconnect that used a plastic liner and epoxy adhesive to seal through-holes in silicon wafers in a microfluidic stack (Figure 39 and Figure 40) [39]. The clamping of the silicon through-holes together brings the flat silicon mating surfaces into intimate enough contact to butt. The interconnects were manufactured with the devices using integrated silicon processing techniques. This interconnect adds additional constraint to the system with additional interconnects.

Figure 39: Verpoorte et al created a chip-to-chip, micro-to-micro, reversible, out-of-plane interconnect that used a stack of clamped together through-holes in silicon wafers to transport liquid from one chip to another [39].
In 1999, Gray et al designed two different fluidic interconnects that used a combination of contact based sealing strategies: a press-fit capillary tube using a silicone gasket and an epoxy grouted capillary tube (Figure 41-Figure 43) [19]. The press-fit connection is a world-to-chip, macro-to-micro, reversible, out-of-plane interconnect that combined an interference fit between the capillary tube and the device and compression of the gasket to provide a seal. The epoxy grouted connection is a world-to-chip, macro-to-micro, irreversible, out-of-plane interconnect which used epoxy to seal it. The press-fit connection was manufactured using DRIE, metal deposition, and wafer bonding techniques. The epoxy interconnect consists of a capillary tube, epoxy, and the microfluidic device. Manual assembly by a trained researcher is required. The press-fit connection was also manually assembled. Both connections add constraint to the microfluidics device which will produce indeterminate constraints between the microfluidics device and the macro-scale world. The maximum pressure sustained by the press fit interconnect was 414 kPa and by the epoxy interconnect was 3.4 MPa. The footprint of the press-fit connection was not reported and the footprint of the epoxy interconnection was 360 μm.
Figure 41: Gray et al created an epoxy grouted capillary tube interconnect. The images above show the manufacturing of the chip with the interconnect. [19]

Figure 42: Gray et al created a press-fit capillary tube using a silicone gasket. This image is a cross-section view of the press-fit interconnect. [19]
Figure 43: Silicon/plastic press-fit coupler with injection molded press fittings described by Gray et al [19].

In 2001, Galambos et al designed a chip-to-chip, micro-to-micro, irreversible, out-of-plane interconnect that used compression of 0.002” thick double-sided pressure sensitive adhesive tape (VHB™ double coated adhesive transfer tape, 3M, Minneapolis, MN) to seal between capillaries and through-holes (Figure 44)[41]. The interconnection has eight connections over an area of 5 mm² and the chips are manually assembled using the Finetech PicoPlacer. The interconnection withstood a maximum pressure of 2 MPa without leaking.

Figure 44: Galambos et al created a chip-to-chip interconnect that used compression of pressure sensitive adhesive tape to seal between component chips [41].

In 2001, Tsai et al designed a world-to-chip, macro-to-micro, irreversible, out-of-plane fluidic interconnect that employed an irreversible grouting technique. It uses a Mylar membrane surrounding a press fit capillary connection to prevent glue from contaminating channels in a silicon/Pyrax substrate (Figure 45 and Figure 46) [29]. This interconnect is manually assembled
after the microfluidic chip is manufactured. This interconnect adds constraint to the microfluidics device which will lead to alignment problems between the microfluidic chip and the input devices with an increasing number of fluidic interconnects. The maximum pressure this interconnect could withstand before leaking was 190 kPa. The footprint of the glue was 3 mm.

Figure 45: Tsai et al designed a world-to-chip, macro-to-micro, irreversible, out-of-plane fluidic interconnect that employed an irreversible grouting technique that uses a Mylar membrane surrounding the press fit capillary connection to prevent glue from contaminating channels in a silicon/Pyrex substrate [29].

Figure 46: SEM image of grouted interconnect designed by Tsai et al [29].
In 2002, Puntambekar et al designed a world-to-chip, macro-to-micro, irreversible, out-of-plane fluidic interconnect that employs an interference fit between a capillary tube and a flange in a substrate to seal the connection (Figure 47-Figure 49) [32]. The flanges were created by heating a PEEK or Teflon tubing to slightly lower than the glass transition temperature and forcing the polymer to flow into the cavity surrounding the microchannel with a metal insert to prevent polymer from flowing into the microchannel. Both a serial process and parallel process to manufacture these flanged interconnects was developed. These interconnects combined mechanical drilling, photolithography, heating on a hotplate, and applying a load. This interconnect was manually assembled with the microfluidic device. It adds kinematic constraint to the microfluidic device, which will lead to alignment problems between the microfluidics chip and the input devices as the number of fluidic interconnects increases. The maximum pressure these interconnects could withstand was in excess of 206 kPa.

![Figure 47](image1.png)

Figure 47: Puntambekar et al designed a world-to-chip, macro-to-micro, irreversible, out-of-plane fluidic interconnect that employs an interference fit between capillary tube and flange in substrate to seal the connection. (a) Shows the flanging operation using PEEK or Teflon® tubing to form the flange and a metal insert to prevent polymer flow into the microchannel. (b) shows the final interconnect with PEEK tubing inserted into PEEK flange created in (a) [32].

![Figure 48](image2.png)

Figure 48: (a) shows a chip with several flanged interconnects and (b) shows a zoomed in picture of two interconnects [32].
Figure 49: This image shows flanged interconnection on both sides of a chip [32].

In 2003, Gray et al published a paper on a press-fit connection that featured interlocking notched cylinder/hole pairs utilized, and beeswax to serve as a gasket between the interfaces (Figure 50 and Figure 51) [23]. This is a chip-to-chip, micro-to-micro, irreversible, out-of-plane chip. This interconnect was manufactured using deep reactive ion etching by specialized technicians inside a cleanroom. This interconnect adds additional constraints between the adjacent microfluidic chips. The maximum pressure was 69 kPa at a flow rate of 1.95 ml/min.

Figure 50: Gray et al SEM photograph of notched cylinder and hole mating interfaces. The cylinders and holes have a diameter of 250 μm and the notch is 10 μm wide [23].
In 2003, Pattekar et al designed a world-to-chip, macro-to-micro, irreversible, out-of-plane fluidic interconnect that employs a combination of a press-fit, plastically deformed melted end of a capillary tube and epoxy to grout the fluidic connection (Figure 52) [33]. This interconnect is manufactured using a hot plate and epoxy. Additionally, a trained researcher manually assembles them serially. This interconnect adds kinematic constraint to the microfluidic device which will lead to indeterminate constraint between the system and the macroscale world as the number of interconnects increases. The maximum pressure this interconnect could withstand was 2.16 MPa. The footprint of this interconnect was 4 mm.
In 2010, Sabourin et al created a macro-to-micro, world-to-chip, irreversible, planar interconnect that used UV-assisted physical bonding between “oversized, deformable tubing” and two adjacent poly(methyl methacrylate) (PMMA) substrates with undersized semi-circular ports milled into them [37] (Figure 53 and Figure 54). This interconnect had a footprint of 1.9 mm and could withstand a maximum pressure of 600 kPa.

Figure 53: Cross-section of the Sabourin et al UV-assisted bonding process for permanent world-to-chip interconnect [37].

Figure 54: Permanent fluidic interconnects designed by Sabourin et al which feature flexible tubes bonded in PMMA [37].

2.3 Proximity-Based Sealing Strategies

An interconnect could alternatively use a proximity-based sealing strategy. These strategies do not rely on physical contact between interconnect components to work. Currently, all proximity-based sealing strategies use capillary forces to prevent leakage.

Andersson’s group at the Department of Mechanics at the Royal Institute of Technology in Stockholm, Sweden produced conference papers in 2000 [42] and 2003 [49], and a patent in 2005 [50] describing a world-to-chip, interconnect that used capillary forces induced by a hydrophilic channels to draw fluid in their “lab-on-a-cd” platform. Ekstrand et al described it in a Micro Total Analysis Systems conference paper in 2000 [42] and Jesson et al described it in a
2003 at the 7th International Conference on Miniaturized Chemical and Biochemical Analysis Systems (Figure 55) [49]. This interconnect is a world-to-chip, macro-to-micro, reversible, out-of-plane interconnect. This interconnect can draw 10-100 nl drops into the chip. This design does not add constraint the microfluidic device.

Figure 55: Ekstrand et al developed a world-to-chip interconnect that used capillary forces from hydrophilic inlet channel to draw sample into the microfluidic chip [42].

2.4 Conclusions

A microfluidic interconnect provides a passage to transport fluid, containing mass and information, between component chips and to and from the microfluidic system. Over the years, a spectrum of designs of microfluidic interconnects have been documented in the literature [13, 14, 16, 18, 50]. As the topic area has grown, classifications have emerged to aid in discriminating one interconnect design from another. Terms like world-to-chip, chip-to-chip, macro-to-micro, micro-to-micro, permanent, reversible, out-of-plane, and planar attempt to distinguish between the interconnect designs by distinguishing between the types of components connected, length-scale the components connected, the thermodynamics of the connection, and the orientation of the connection. However, this classification system does not adequately address the fundamental similarities and differences between interconnects. This literature review adopted a classification framework based on the sealing mechanism of the interconnect. This system allowed direct comparison between designs that used similar sealing strategies and
reduces the number unique design categories. The interconnects discussed from the literature have a range of reported maximum pressures from 51 kPa [38] to 6.8 MPa [25]. Additionally, there seems to be a preference toward designs that mimic macroscale fluidic interconnections strategies such as gaskets, press-fit connections, and National Pipe Thread fittings.
3 The Physics of the Gasketless Interconnect

Insight into the physics of the gasketless interconnect can be gained by the study of the physical chemistry of surfaces [51], intermolecular and surface forces [52], capillary forces [53], differential geometry [54], and thermodynamics [55]. This section will use the equilibrium thermodynamics framework to explore the concepts of surface energy of interfaces, the wettability of surface, capillary forces, dimensional analysis, and meniscus stability.

3.1 Surface Energy of Interfaces

Thermodynamics is the science of energy and entropy [56]. Its foundation is the three laws of thermodynamics: conservation of energy [55], the change in entropy is not conserved for natural processes [55], and the entropy of a perfect crystal of a substance is zero at the temperature of absolute zero [56]. Equilibrium thermodynamics refers to the subset of thermodynamics that studies the movement of systems toward a set of fixed state properties. Some physical properties of systems such as internal energy, kinetic energy, potential energy, entropy, enthalpy, Gibbs free energy, and Helmholtz free energy, are state functions due to their path independence. State functions allow the thermodynamic description of the change of the system by the change in the system state variables. A response function is a partial derivative of a state function with respect to a state variable holding one or more state variables constant. Response functions are used in the description of thermodynamic processes. A thermodynamic process is the transition of a system from one state to another.

Reversible processes can be reversed without changing the system or surroundings [56]. Several thermodynamic potentials for reversible processes can be defined. Two potentials that are important to the gasketless seal are the Helmholtz free energy, and the Gibbs free energy. The Helmholtz \((F)\) and Gibbs \((G)\) free energies are defined by equations (1 and 2):
\[
F \equiv U - TS \tag{1}
\]
\[
G \equiv H - TS \tag{2}
\]
where \(U\) is the internal energy, \(T\) is the temperature, and \(S\) is the entropy. Gibbs and Helmholz free energy can be represented in terms of temperature, pressure, and chemical compositions using equations (3-5):
\[
dG = \left(\frac{\partial G}{\partial T}\right)_{P,n} dT + \left(\frac{\partial G}{\partial P}\right)_{T,n} dP + \sum_i \left(\frac{\partial G}{\partial n_i}\right)_{T,P,n_j \neq n_i} dn_i \tag{3}
\]
\[
dG = -S dT + V dP + \sum_i \left(\frac{\partial G}{\partial n_i}\right)_{T,P,n_j \neq n_i} dn_i \tag{4}
\]
\[
dF = -S dT - P dV + \sum_i \left(\frac{\partial F}{\partial n_i}\right)_{T,V,n_j \neq n_i} dn_i \tag{5}
\]
where \(V\) is the volume, \(P\) is the pressure, and \(n_i\) is the composition. It can be shown that both the partial derivative of the Gibbs free energy with respect to the composition, holding temperature and pressure constant, and the partial derivative of the Helmholtz free energy with respect to the composition, holding temperature and volume constant, are equal \([55]\). Each describes the chemical potential, \(\mu_i\) in equation (6):
\[
\mu_i = \left(\frac{\partial F}{\partial n_i}\right)_{T,V,n_j \neq n_i} = \left(\frac{\partial G}{\partial n_i}\right)_{T,P,n_j \neq n_i} \tag{6}
\]
For a thermodynamic process at constant temperature, the Helmholtz free energy gives the maximum available work. Given a closed system at constant temperature and volume, the equilibrium is attained when \(F\) is a minimum. If the change in \(F\) is negative at a constant temperature and volume, the thermodynamic process has a positive driving force and can occur spontaneously. Additionally, for a process in a closed system at constant temperature and
pressure, the equilibrium is attained when G is at a minimum. If the change in G is negative at a constant temperature and pressure, the process has a positive driving force and does not need external work. These thermodynamic concepts can be applied to interfaces.

An interface is the two dimensional boundary between two disparate phases and/or materials. These boundaries are manifested in the form of liquid-liquid, solid-solid, solid-liquid, liquid-vapor, solid-vapor, or solid-liquid interfaces. There is a Gibbs free energy associated with their configuration called the surface free energy. The change in the Gibbs free energy is given by equation (7):

$$dG = -S \, dT + \gamma \, dA + \mu_1 \, dn_1 + \mu_2 \, dn_2 + \cdots$$  \hspace{1cm} (7)

At constant temperature, pressure, and composition, $\gamma$ can be written as equation (8):

$$\gamma = \left( \frac{\partial G}{\partial A} \right)_{T,P,n_i}$$  \hspace{1cm} (8)

which is the reversible work needed to increase the existing surface area. For fluid-fluid systems the reversible work is equal to the surface free energy, but that is not the case for solid-solid, or solid-fluid systems. For solid-solid or solid-fluid system, the surface stress is related to the surface free energy and the change in surface energy with the change in surface strain in equation (9):

$$f_{ij} = \gamma \delta_{ij} + \frac{\partial \gamma}{\partial \varepsilon_{ij}}$$  \hspace{1cm} (9)

where $f_{ij}$ is the surface stress tensor, $\gamma$ is the surface free energy, $\delta_{ij}$ is the Kronecker delta function, and $\varepsilon_{ij}$ is the strain tensor. For fluid-fluid systems, the change in surface energy with the change in surface strain is zero so the surface stress equals the scalar surface free energy. The concept of interface surface energies can be applied to problems involving the equilibrium shape.
of a two dimensional droplet on a substrate (Figure 56). The equilibrium of the droplet shape can be assumed to be determined by the minimum of the Gibbs free energy of the configuration between the liquid-vapor, liquid-solid, and solid-vapor interfaces. This leads to the derivation of Young’s equation [51] or also known as the Young-Dupré equation [53].

![Diagram of a two dimensional droplet on a substrate](image)

**Figure 56**: The equilibrium shape of a 2D liquid droplet on a hydrophobic solid surface.

### 3.2 Young’s Equation [51]

Young’s equation [51] also known as the Young-Dupré equation [53] describes the ability of a liquid drop to wet a geometrically smooth solid surface. Generally, a liquid droplet brought into contact with a solid surface will form a measurable contact angle with the surface at the line defined where the liquid-solid, liquid-vapor, and solid-vapor surfaces meet. Young’s equation can be derived by considering a change in surface free energy, $\Delta G^s$, with a small displacement of the liquid at the contact line and an associated change in area of solid surface covered by the liquid, $\Delta A$ [51] using equation (10):

$$\Delta G^s = \Delta A \left( \gamma_{SL} - \gamma_{SV} \right) + \Delta A \gamma_{LV} \cos (\theta - \Delta \theta)$$  \hspace{1cm} (10)

Under equilibrium conditions, equation (11) can be combined with equation (10),
resulting in equation (12):

\[ \gamma_{SL} - \gamma_{SV} + \gamma_{LV} \cos \theta = 0 \]  

or equation (13):

\[ \gamma_{SV} - \gamma_{SL} = \gamma_{LV} \cos \theta \]

where \( \gamma_{SV} \) is the surface energy of the solid-vapor interface at equilibrium with the saturated vapor phase, \( \gamma_{SL} \) is the surface energy of the solid-liquid interface, \( \gamma_{LV} \) is the surface energy of the liquid-vapor interface (also described as the surface tension of the liquid), and \( \theta \) is the angle that the liquid-vapor interface makes with the solid-liquid interface (also described as the contact angle) [51]. The contact angle is used to quantify the ability of a fluid to wet a solid surface. Using aqueous solutions, surfaces with contact angles greater than 90\(^\circ\) are said to be hydrophobic and surfaces with contact angles less than 90\(^\circ\) are said to be hydrophilic. The sessile drop is a common method of measuring contact angles [51]. It involves observing the contact angle from the side of a liquid drop on a horizontal surface using a microscope objective and then measuring the contact angle. This method was used to gage the wettability of the selected superhydrophobic surfaces, and as an input to the maximum pressure models to gage the point of rupture of the gasketless interconnect.

Overall, Young’s equation models the fundamental mechanisms behind the wetting process. However, this equation assumes a homogenous smooth solid surface with a constant surface energy; most surfaces in reality are not geometrically smooth. This led to Wenzel’s work on wetting behavior [57].
3.3 Wenzel’s Equation

Wenzel explored the relationship between wetted rough surfaces, their observed contact angle with liquids, and the balance of interface energies. Wenzel derived an equation that sought to describe the reality that “within a measured unit of area on a rough surface, there is actually more surface” compared to a smooth surface [57]. The Wenzel equation approximates this reality using a roughness factor when describing the relationship between the contact angle and the interface energies [57] in equation (14).

\[ r(y_{SV} - y_{SL}) = y_{LV} \cos \theta \]  
(14)

where \( r \) is the roughness factor whose constitutes are represented by equation (15):

\[ r = \text{roughness factor} = \frac{\text{actual surface}}{\text{geometric surface}} \]

(15)

Wenzel’s equation effectively accounted for the proportional increase in surface area and consequently proportional increase in surface energy of a fully wetted rough surface and its effect on the apparent contact angle. Others have studied Wenzel’s equation with some interesting insight.

Good [58] observed the equation derived by Wenzel does not explain the phenomena of contact angle hysteresis. According to Adamson [51], contact angle hysteresis is the general observation that “the contact angle measured for a liquid advancing across a surface exceeds that of one receding from the surface”. This means that as a droplet moves across the surface the contact angle measured at the front of the droplet will differ from the contact angle measured at the back of the droplet. In his paper, Good [58] derived a Wenzel’s Equation using the free surface energy and proposed a theory to explain the hysteresis of contact angles on surfaces. To
begin the derivation of both Wenzel’s Equation and Good’s Theory of Hysteresis, Good [58] draws on the definition on free surface energy in equation (16):

\[ \gamma_n = \frac{\partial G_n}{\partial a_n} \]  

(16)

where \( G_n \) is the Gibbs free energy of an nth interface, and \( a_n \) is the actual interface area of the nth interface. Good [58] then derived the Gibbs free energy relations of the system containing three interfaces at equilibrium (solid-liquid, solid-vapor, and liquid-vapor) using equation (17-19):

\[ dG = 0 = \left( \frac{\partial G_{SL}}{\partial a_{SL}} \right) dA_{SL} + \left( \frac{\partial G_{SV}}{\partial a_{SV}} \right) dA_{SV} + \left( \frac{\partial G_{LV}}{\partial a_{LV}} \right) dA_{LV} \]  

(17)

\[ \frac{\partial G}{\partial A_{SL}} = 0 = \left( \frac{\partial G_{SL}}{\partial a_{SL}} \right) \left( \frac{\partial a_{SL}}{\partial A_{SL}} \right) \left( \frac{\partial A_{SL}}{\partial A_{SL}} \right) + \left( \frac{\partial G_{SV}}{\partial a_{SV}} \right) \left( \frac{\partial a_{SV}}{\partial A_{SV}} \right) \left( \frac{\partial A_{SV}}{\partial A_{SL}} \right) \]  

+ \left( \frac{\partial G_{LV}}{\partial a_{LV}} \right) \left( \frac{\partial a_{LV}}{\partial A_{LV}} \right) \left( \frac{\partial A_{LV}}{\partial A_{SL}} \right) \]  

(18)

\[ \frac{\partial G}{\partial A_{SL}} = 0 = \gamma_{SL} A_{SL} + \gamma_{SV} A_{SV} + \gamma_{LV} \left( \frac{\partial A_{LV}}{\partial A_{SL}} \right) \]  

(19)

\( G = \) the Gibbs free energy of the system

\( G_{SL} = \) the Gibbs free energy of the solid-liquid interface

\( G_{SV} = \) the Gibbs free energy of the solid-vapor interface

\( G_{LV} = \) the Gibbs free energy of the liquid-vapor interface

\( \gamma_{SL} = \) the surface energy of the solid-liquid interface

\( \gamma_{SV} = \) the solid-vapor surface energy
\[ \gamma_{LV} = \text{the surface energy of the liquid-vapor interface} \]

\[ A_{SV} = \text{the “apparent” solid-vapor area in the “geometrical” interface} \]

\[ A_{SL} = \text{the “apparent” solid-liquid area in the “geometrical” interface} \]

\[ A_{LV} = \text{the “apparent” liquid-vapor area in the “geometrical” interface} \]

\[ a_{SL} = \text{the actual area of the solid-liquid interface} \]

\[ a_{LV} = \text{the actual area of the liquid-vapor interface} \]

\[ r = \text{the roughness factor which a ratio of the actual area over the “apparent” area} \]

Good [58] pointed out that \( \frac{\partial A_{LV}}{\partial A_{SL}} \) evaluated by consideration of a small section of the triple interface is \( \cos \theta \) where \( \theta \) is the observed contact angle of the surface. This equation then becomes the Wenzel equation. Good [58] extrapolated this equation to include the non-equilibrium case in equation (20):

\[
\frac{\partial G}{\partial A_{SL}} = \pm r (\gamma_{SL} - \gamma_{SV}) + \gamma_{LV} \cos \theta_{obsd} \tag{20}
\]

Substituting in Wenzel’s equation and rearranging the terms yields equation (21):

\[
\frac{\partial G}{\partial A_{SL}} = \pm \gamma_{LV} \left( \cos \theta_{obsd} - \cos \theta_{eq} \right) = \gamma_{LV} \Delta \cos \theta \tag{21}
\]

where \( \theta_{obsd} \) is the observed contact angle, and \( \theta_{eq} \) is the equilibrium contact angle. Good [58] said that “the driving force toward the attainment of the equilibrium contact angle is proportional to the surface tension of the liquid and to the deviation of the cosine of the contact angle form the equilibrium value”.

Further, if an energetic obstacle exists in the path of a liquid drop that results in the stretching of the liquid-vapor interface and this energy per unit area is greater than the driving
force then the droplet will stop changing its shape and its contact angle will not correspond to the equilibrium value. This extra “contortional energy” requirement explained the difference in advancing and receding contact angles.

Despite the advance in understanding over Young’s equation, Wenzel’s equation did not capture the effects of rough surfaces that were not fully wetted like those experienced with porous surfaces. This led to Cassie and Baxter’s work [59].

3.4 Cassie’s Equation [51]

Cassie and Baxter examined the wettability of porous surfaces [59] extending Wenzel’s equation to cover the partial wetting of structured surfaces. Partial wetting refers to the liquid bridging between wetted solid structures on a rough surface creating a surface patterned with solid-liquid and liquid-air interfaces. This proportion of wetted solid and liquid-vapor bridging of the partial wetted surface is captured in the equation by the inclusion of fractions, $f_1$, and $f_2$ (where $f_2=1-f_1$) and results in a larger observed contact angle (apparent contact angle). This equation follows equation (22):

$$\cos(\theta_D) = f_1 \cos(\theta_A) - f_2$$  \hspace{1cm} (22)

where $\theta_D$ is the apparent contact angle of the partially wetted surface, $\theta_A$ is the advancing contact angle of the solid substrate, $f_1$ is the fraction of the surface that is a solid-liquid interface, and $f_2$ is the fraction of the partially wetted surface that is a liquid-vapor interface [59]. This equation was proven to be a special case of the more general Cassie equation [51] which describes wetting behavior on heterogeneous surfaces through an apparent contact angle, $\theta_D$ in equation (23 and 24):

$$f_1 (\gamma_{SV1} - \gamma_{SL1}) + f_2 (\gamma_{SV2} - \gamma_{SL2}) = \gamma_{LV} \cos(\theta_D)$$  \hspace{1cm} (23)

or

$$f_1 (\gamma_{SV1} - \gamma_{SL1}) + f_2 (\gamma_{SV2} - \gamma_{SL2}) = \gamma_{LV} \cos(\theta_D)$$  \hspace{1cm} (24)
\[ \cos(\theta_D) = f_1 \cos(\theta_1) + f_2 \cos(\theta_2) \]  

(24)

where \( \theta_1 \) is the contact angle of material 1, and \( \theta_2 \) is the contact area of material 2. The Cassie equation [51] elucidates the interaction between the solid-liquid, solid-vapor, and liquid-vapor interfaces at the contact line. The problem of the three-dimensional equilibrium shape across a single fluid-fluid interface such as the liquid-vapor interface can be found through the Young-Laplace equation.

### 3.5 Young-Laplace Equation [51]

The Young-Laplace equation models the difference in pressure across a curved surface interface under tension. A simple example of this phenomenon is the floating soap bubble. When it is pierced, it explodes due to the greater pressure inside the curved liquid-vapor interface than outside the surface. The Young-Laplace equation [51] [53] is defined in equation (25):

\[ \Delta P = \gamma \left( \frac{1}{R_1} + \frac{1}{R_2} \right) = 2\gamma H \]  

(25)

Where \( \Delta P \) is the difference in pressure across the interface (\( P_{in} - P_{out} \)), \( \gamma \) is the surface tension (or surface energy) of the liquid, \( R_1 \) is the radius of curvature of the first radius of curvature, \( R_2 \) is the radius of curvature that is oriented at a right angle to the plane of \( R_1 \), and \( H \) is the mean surface curvature.

Additionally, the Young-Laplace equation can be derived [51, 53] for an axisymmetric liquid bridge using differential geometry [53] resulting in equation (26):

\[ -\frac{r''}{(1 + r'^2)^{3/2}} + \frac{1}{r(1 + r'^2)^{1/2}} = \frac{P_{in} - P_{out}}{\gamma} \]  

(26)

where \( r \) is the distance to the meniscus from the line of revolution, \( r' \) is the partial derivative of \( r \) with respect to the gap distance, \( z \), between the surfaces, \( r'' \) is the partial derivative of the \( r' \)
with respect to the gap distance, \( z \), \( \gamma \) is the surface tension of the liquid, \( P_{in} \) is the pressure inside the liquid bridge, and \( P_{out} \) is the pressure outside the liquid bridge. The Young-Laplace equation explains the phenomena of differential pressures across elastic curved surfaces under tension. This background allows for the introduction to capillary forces.

### 3.6 Capillary Forces

Capillary forces are a combination two different forces: forces derived from the minimization of the solid-liquid, solid-vapor, and liquid-vapor interface energies at the contact line, referred to as surface tension forces, and forces derived from the differential pressure across curved elastic interface under tension, referred to as Laplace forces [53]. These contributions to capillary forces [53] are demonstrated in equation (27):

\[
F_c = F_t + F_L
\]

(27)

where \( F_c \) is the capillary force, \( F_t \) is the surface tension force contribution, and \( F_L \) is the Laplace force contribution. Further investigation into capillary forces can be achieved by examining the problem of a cylindrical liquid bridge spanning two solid substrates (See Figure 57).

![Cross section of a liquid bridge spanning two solid substrates](image)

**Figure 57**: This image shows the cross section of a liquid bridge spanning two solid substrates.

For a liquid bridge, the surface tension force is the liquid-vapor surface tension, \( \gamma \), of the liquid acting on the line of contact acting on the circumferences of the two parallel circular ends with radii of \( R_1 \) at an angle \( \theta \) with the solid substrate described in equation (28).
The Laplace force then is related by the liquid-vapor surface tension, $\gamma$, the radius of curvature of the liquid column, $R_1$, the radius of curvature of the meniscus, $R_2$, and the cylindrical projected area of the meniscus in equation (29).

$$F_L = \gamma \left(\frac{1}{R_1} + \frac{1}{R_2}\right)2\pi R_1 z$$

(29)

where $R_1$ is the radius of each through-hole, $\gamma$ is the surface tension of the liquid, $z$ is the distance between solid substrates, and $\theta$ is the angle between the solid and liquid interface. The combination of the surface tension forces and Laplace forces is represented in equation (30):

$$F_c = 2(2\pi R_1 \gamma \sin \theta) + \gamma \left(\frac{1}{R_1} + \frac{1}{R_2}\right)2\pi R_1 z$$

(30)

Recognizing that $\gamma$ and $\theta$ are constant, reveals that the capillary force equation scales with the first power of the characteristic length $[53]$. This scaling law shows that capillary forces scale well with the decreasing length scales associated with microfluidic systems and nanofluidic systems. Additional, qualitative comparisons of the relative strength of different forces can be found through dimensional analysis.

### 3.7 Dimensional Analysis

Dimensional analysis relies on the concept of dimensional homogeneity to gain qualitative insight into a problem. Several significant dimensionless groups are relevant for the gasketless interconnect. These include the Reynolds number, the capillary number, the bond number and capillary length.

The Reynolds number is used to determine the flow regime a fluid. It is the ratio of the viscous forces to the inertial forces. The Reynolds number enables qualitative comparison of the
relative strengths of viscous forces and inertial forces for a fluid flow. Equation (31) is the equation for the Reynolds number [60].

\[ Re = \frac{\rho V D}{\mu} \]  

(31)

The Reynolds number is composed of the following parameters: density of the fluid, \( \rho \), the mean velocity of the fluid, \( V \), the diameter of the through-hole, \( D \), and the viscosity of the fluid, \( \mu \).

The capillary number is the ratio of viscous forces to the surface tension forces for a fluid flow and it allows for the qualitative comparison between the relative strength of the viscous and surface tension forces. Equation (32) is the equation for the capillary number [60].

\[ Ca = \frac{\mu V}{\sigma} \]  

(32)

The capillary number is composed of the following parameters: the viscosity of the fluid, \( \mu \), the mean velocity of the fluid, \( V \), and the surface tension of the fluid, \( \sigma \).

Similarly, the bond number is the ratio of the gravitational body force to the surface tension force and it enables the qualitative comparison between the relative strength of the gravitational body force and the surface tension force. Equation (33) describes the bond number [60].

\[ Bo = \frac{\rho g l^2}{\sigma} \]  

(33)

The Bond number is composed of the following parameters: the density, \( \rho \), the acceleration due to gravity, \( g \), the characteristic length, \( l \), and the surface tension of the fluid, \( \sigma \).

Using equation (33), the characteristic length can be solved for to derive equation (34).

\[ l = \sqrt{\frac{\sigma Bo}{\rho g}} \]  

(34)
From equation (34), the characteristic length where gravitational effects are negligible can be derived by assuming a bond number of 1 is the cut-off to neglect gravitational forces [53], the surface tension of water is 0.072 N/m, the density of water is 1000 kg/m$^3$, and the acceleration due to gravity is 9.8 m/s$^2$. This cut-off length for gravitational effects compared to capillary effects is approximately 2.7 mm.
4 Models of the Gasketless Interconnect

4.1 Introduction

Logical arguments and assumptions, grounded in the physics of a problem, are used to extend rational understanding of a problem. In engineering, these arguments coupled with assumptions culminate in a mathematical model that is used to parametrically study a system. This section explores the insight gained into the performance of the gasketless interconnect (Figure 58) using dimensional analysis and analytical models derived from the Young-Laplace equation. The performance criterion of the gasketless interconnect is the maximum gage pressure it can withstand before rupture. This maximum pressure corresponds both to the maximum pressure range of the interconnect and the maximum driving pressure for downstream component modules.

![Diagram of gasketless interconnect with liquid bridge spanning the gap distance between two concentric through-holes in two adjacent superhydrophobic solid surfaces. R₂ is the radius of curvature of the meniscus in the plane of the paper and R₁ is the radius of curvature of the through-holes perpendicular to the plane of the paper.](image)

Figure 58: Side cross-sectional view of the gasketless interconnect featuring a liquid bridge spanning the gap distance between two concentric through-holes in two adjacent superhydrophobic solid surfaces. R₂ is the radius of curvature of the meniscus in the plane of the paper and R₁ is the radius of curvature of the through-holes perpendicular to the plane of the paper.

4.2 Dimensional Analysis

The gasketless interconnect uses capillary forces to prevent leakage at the fluidic interconnect. In order for this to occur, capillary forces must dominate over inertial and viscous forces of the fluid. The additional constraint that gravitational effects be negligible compared to
the capillary forces arises from the need that the maximum pressure across the interconnect be independent of the orientation of the fluid passage with respect to gravity. This constraint stems from the need for devices to be oriented at any angle with respect to gravity to achieve a performance specification such as fitting a specific device footprint or alignment with an existing piece of equipment. The interconnect and corresponding microfluidic chips that it connects are assumed to share an inertial reference frame which implies that at the microfluidic chip scale forces induced from rotation are negligible.

Dimensional analysis was used to qualitatively determine the maximum mean velocity and maximum diameter of the through-holes to meet the constraints. The maximum diameter was selected over the gap distance because the gap distance was assumed to be much smaller than the diameter. The Reynold’s number (Re) compared the inertial forces to viscous forces, the capillary number (Ca) compared the viscous forces to the surface tension forces, and the bond number (Bo) compared the gravitational forces to the surface tension forces. When the Re <<1, Ca << 1, and the Bo <<1, surface tension forces dominate inertial, viscous, and gravitational forces. Much less than 1 was assumed to correspond to the dimensionless numbers being less than or equal to 0.001. Under these conditions, the dynamic interconnect problem can be treated as a static geometric model.

For the initial maximum pressure experiments, the Reynolds number, the Capillary number, and the Bond number were investigated by varying the velocity and diameter of the through-hole. Using the diameter of the through-holes (0.813 mm), the viscosity of water (0.001 Pa s) [15], the density of water (998 kg/m³) [15], the surface tension of water (0.072 N/m)[1], and varying the mean velocity from 1 mm/s to 20 mm/s, the Reynolds number (Figure 59), Capillary number (Figure 60), and Bond number (Figure 61) were plotted to show the range of
experimental parameters for which surface tension forces dominate over all other forces. Figure 59-Figure 61 revealed through the range of typical through-hole diameters and range of mean velocities the Reynolds number constrained the maximum mean velocity and the Bond number determined the maximum diameter of the through-hole to be 2.7 mm.

Figure 62 translates these constraints, $Ca<< 1$, $Re << 1$, and $Bo << 1$, into usable design parameters showing flow rates as a function of through-hole diameters. This shows the range of flow rate for different through-hole diameters where the surface tension forces dominate over other forces. A static model is equivalent to a dynamic model for all combinations of flow rates and diameters within the cross-hatched triangle in Figure 62.

Figure 59: Variation of the Reynolds number of water flowing through the device with the mean velocity and diameter of the through-hole.

Figure 60: Change of the Capillary number of water flowing through the device with varying velocity.
Figure 61: Variation of Bond number of water with varying the diameter of the through-hole.

Figure 62: The constraints of \( \text{Re} \ll 1 \), \( \text{Ca} \ll 1 \), and \( \text{Bo} \ll 1 \) are satisfied within the triangle. Within this triangle, a static model will work as a dynamic model.

4.3 Analytical Models

Two static analytical models were derived from the Young-Laplace equation [53] to estimate the maximum steady-state pressure difference across the liquid-air interface of the gasketless seal before rupture. Both of these models relate the contact angle of the parallel superhydrophobic substrates, the gap distance between the through-holes, and the surface tension of the liquid to the maximum pressure difference across the liquid-air interface. The second
geometric model added the influence of the parallel offset distance between the edges of the through-hole and through-hole diameter to the maximum pressure difference across the liquid-air interface.

Assumptions shared by both models include: (1) the edges of the liquid bridge are pinned at the corner of the through-hole, (2) the pressures on the inside and outside of the liquid bridge are constant and different, (3) the superhydrophobic surfaces are parallel, (4) the parallel superhydrophobic surfaces have equal and constant contact angles, (5) the superhydrophobic surfaces are a fixed constant distance apart, (6) the composition of the air in the gap is constant, (7) gravity effects are negligible, (8) the diameters of the top and bottom through-holes are equal, (9) the liquid is deionized water, (10) the shape of the meniscus can be approximated by a semicircular arc, (11) there is negligible pressure gradient across the liquid bridge, (12) viscous forces and inertial forces are negligible. The initial geometric model additionally assumed that the through-holes were perfectly concentric with zero lateral offset, and the through-hole diameter was large compared to the radius of the meniscus.

4.3.1 Initial Static Geometric Model

The initial static geometric model was used to estimate the maximum pressure difference across the liquid-air interface for a given gap distance and contact angle. Figure 63 highlights the geometry of the problem through a cross-sectional view of the gasketless interconnect with $R_1$, the radius of curvature of the through-hole, is in the plane perpendicular to the page, $R_2$, the radius of the circular arc that models the meniscus, in the plane of the plane of the page, $z$ is the gap distance, $P_{in}$ is the pressure of the liquid inside the liquid bridge, $P_{out}$ is atmospheric pressure, the solid lines designates the two substrates through which the through-holes span, and the dashed line is the line of axisymmetry.
Figure 63: Side view of a gasketless interconnect featuring liquid flowing from one chip to another via two through-holes, and parallel superhydrophobic surfaces.

Figure 64: Side view of the geometry of the liquid meniscus used to derive the relationship between the contact angle, the gap distance, and the radius of circular arc.

Figure 64 is a cross-section of the liquid meniscus that was used to relate the radius of circular arc to the contact angle ($\theta_c$), and gap distance ($z$). The derivation is shown in equations [1-6]:

$$\beta = \theta_c - 90$$  \hspace{1cm} (35)

$$R_2 \sin \beta = R_2 - h$$  \hspace{1cm} (36)

$$z = 2(R_2 - h)$$  \hspace{1cm} (37)

$$z = 2(R_2 \sin \beta)$$  \hspace{1cm} (38)
For the gasketless interconnect, the contact angle is \( \theta_c \geq 90 \) which leads to a positive radius for the circular arc that models the shape of the meniscus. The assumption is that the Young-Laplace equation approximates the maximum pressure across the liquid meniscus. Capillary forces are made up of two components: surface tension forces at the intersection of the solid-liquid-gas interfaces at the contact line (the Young-Dupre equation), and Laplace forces due to the curvature across the liquid meniscus (the Young-Laplace equation). The Young-Laplace equation provides a model of the pressure difference across the liquid-air interface at a certain distance away from the triple point; prior to that distance the balance of the surface energies of the intersection of the three interfaces contributes to the curvature in addition to the pressure difference across the liquid-air interface. The Young-Laplace equation is given in equation [7]:

\[
\Delta P = \gamma \left( \frac{1}{R_1} + \frac{1}{R_2} \right) \tag{41}
\]

Where \( \Delta P \) is the pressure difference across the liquid-air interface, \( \gamma \) is the surface tension of the liquid, \( R_1 \) is the radius of the through-hole, \( R_2 \) is the radius of the meniscus, and both radii reside in planes that are perpendicular to each other. Assuming the radius of the through-hole is much greater than the radius of the meniscus, the equation reduces to:

\[
\Delta P \approx \gamma \left( \frac{1}{R_2} \right) \tag{42}
\]
Substituting equation [6] into equation [8] yields:

\[
\Delta P = P_{in} - P_{out} \approx \gamma \frac{2 \sin(\theta_c - 90)}{z}
\]

\[
\sin \theta_c = \sin(-\theta_c)
\]

\[
\Delta P = P_{in} - P_{out} \approx -\gamma \frac{2 \sin(90 - \theta_c)}{z} = -\gamma \frac{2 \cos \theta_c}{z}
\]

where \( P_{in} \) is the pressure of the liquid, \( P_{out} \) is atmospheric pressure, \( \gamma \) is the surface tension of the fluid, \( z \) is the gap distance, and \( \theta_c \) is the sessile drop contact angle of the solid substrate. This equation gives the maximum gage pressure for the gasketless interconnect by assuming that the liquid bridge begins to radially expand when it approaches the sessile drop contact angle of the surface. This assumption is based on the derivation of the sessile drop contact angle equilibrium of the intersection between the solid-gas, liquid-gas, and solid-liquid interfaces. Equation [9] states that the maximum interconnect pressure depends directly on the surface tension of the fluid (\( \gamma \)) and the negative cosine of the contact angle (\( \theta_c \)), and inversely on the gap distance (\( z \)). Equation [9] was plotted for various gap distances and contact angles in Figure 65.

Figure 65: The maximum pressure difference across the liquid bridge as a function of the gap distance and contact angles based on the initial static geometric model.
Consequently, the maximum pressure difference of the gasketless interconnect constrains the downstream device by providing a ceiling for the maximum equilibrium driving pressure. The pressure drop across (or backpressure of) the downstream device has to be less than this maximum equilibrium driving pressure or the interconnect will rupture and leak. A comparison between the maximum driving pressure and the pressure drops across microfluidic devices provides a reality check to see if the driving pressures created by the liquid bridge are sufficient. An informative manner of presenting pressure drop data for microfluidic devices is as a load characteristic, pressure drop as a function of flow rate. The maximum equilibrium driving pressure graph was compared to the load characteristics for the devices created in the Louisiana State University (LSU) Microsystems Engineering Team (μSET) lab [2-4, 61-64] (see Appendix 10) which reveals that the pressure drops are on the same order of magnitude as the maximum driving pressure for gap distances less than 10 μm.

4.3.2 Second Geometric Model with Offset between Through-holes

The second geometric model sought to estimate the behavior of the initial pressure test experiments by determining the maximum pressure difference across the liquid-air interface for a given gap distance, contact angle, and lateral offset (Figure 66). A new method of derivation for the radius of the meniscus was needed to relate the offset, gap distance, and contact angle because the added offset created a problem that lacked the right triangles utilized in the previous derivation.

![Figure 66](image_url)

Figure 66: The geometry used for the derivation of the second static geometric model to relate the radius of the meniscus to the gap distance, the contact angle, and the offset.
To achieve this aim, the coordinate axes were aligned to coincide with the base point of the meniscus with the x-axis parallel to the solid substrate. The first goal in solving the problem was to find the center of the circular arc that modeled the meniscus using the equation for a circle (equation [12]), the implicitly differentiated equation for a circle (equation [13]), and the equation of the perpendicular bisector of the line connecting the edge points (0,0) and (-2ΔO,z) (equation [14]).

\[
(x - a)^2 + (y - b)^2 = R^2 \tag{46}
\]

\[
2(x - a) + 2(y - b)y' = 0 \tag{47}
\]

\[
y = \frac{2\Delta O}{z}x + \frac{z}{2} + \frac{2(\Delta O)^2}{z} \tag{48}
\]

Equation [12] and [13] are normal to the circle and intersect at point (a,b). The differential \(y'\) is equal to \(y' = \frac{dy}{dx} = -\tan \beta\) at point (0,0) where \(\beta\) is equal to \(180 - \theta_c\) and \(\theta_c\) is the contact angle.

This assumes that the maximum pressure occurs when the angle at the edge of the meniscus approaches the contact angle.

Substituting the point (0,0) and the value for \(y'\) into equation [13] yields:

\[-2a + 2 \tan \beta b = 0 \tag{49}\]

It is known that the perpendicular bisector of a chord passes through the center of a circle at point (a,b). Plugging point (a,b) into equation [14] yields:

\[-\frac{2\Delta O}{z}a + b = \frac{z}{2} + \frac{2(\Delta O)^2}{z} \tag{50}\]

Using Cramer’s rule to solve simultaneous equations [15] and [16] yields the coordinates of the center of the circular arc (a,b):
Since the coordinate axis origin was set as the base point on the meniscus, the radius of the circular arc created by the meniscus can be calculated using the Pythagorean theorem and the coordinates between the center of the circular arc \((a,b)\) and the bottom edge of the through-hole \((0,0)\):

\[
R^2 = a^2 + b^2 = \frac{\left(\frac{z}{2} + \frac{2(\Delta O)^2}{z}\right)^2}{\left(1 + \frac{2\Delta O}{z}\tan \beta \right)^2} \tag{53}
\]

\[
R = \frac{\left(\frac{z}{2} + \frac{2(\Delta O)^2}{z}\right)\sec \beta}{1 + \frac{2\Delta O}{z}\tan \beta} \tag{54}
\]

\[
\frac{1}{R} = \frac{\left(1 + \frac{2\Delta O}{z}\tan \beta \right)}{\left(\frac{z}{2} + \frac{2(\Delta O)^2}{z}\right)} \cos \beta = \frac{2 \left(1 + \frac{2\Delta O}{z}\tan \beta \right)\cos \beta}{z + \frac{4(\Delta O)^2}{z}} \tag{55}
\]

\[
\frac{1}{R} = \frac{2 \left(1 + \frac{2\Delta O}{z}\tan(180 - \theta_c)\right)\cos(180 - \theta_c)}{z + \frac{4(\Delta O)^2}{z}} \tag{56}
= -\frac{2 \left(1 - \frac{2\Delta O}{z}\tan(\theta_c)\right)\cos(\theta_c)}{z + \frac{4(\Delta O)^2}{z}}
\]

It was assumed that the Young-Laplace equation (equation [7]) can approximate the maximum pressure difference across the liquid-air interface of the meniscus.
\[ \Delta P = \gamma \left( \frac{1}{R_1} + \frac{1}{R_2} \right) \]

Where \( \Delta P \) is the pressure difference across the liquid-air interface, \( \gamma \) is the surface tension of the liquid, \( R_1 \) is the radius of the through-hole, \( R_2 \) is the radius of the meniscus, and both radiiuses reside in planes that are perpendicular to each other. Substituting in equation [22] for \( R_2 \) yields the following:

\[ \Delta P = \gamma \left( \frac{1}{R_1} - \frac{2 \left( 1 - \frac{2 \Delta O}{z} \tan(\theta_c) \right) \cos(\theta_c)}{z + \frac{4(\Delta O)^2}{z}} \right) \] (57)

Where \( 2\Delta O \) is the offset between the bottom edge of the meniscus and the top edge of the meniscus, \( z \) is the gap distance, \( \theta_c \) is the contact angle of the surface, \( \gamma \) is the surface tension of the fluid, \( \Delta P \) is the pressure difference across the liquid meniscus, and \( R_1 \) is the radius of the through-hole. This equation converges to the previous solution equation [12] in the limit as \( \Delta O \) goes to zero with \( R_1 \gg R_2 \):

\[ \lim_{\Delta O \to 0} \Delta P = -\gamma \left( \frac{2 \left( 1 - \frac{2 \Delta O}{z} \tan(\theta_c) \right) \cos(\theta_c)}{z + \frac{4(\Delta O)^2}{z}} \right) = -\gamma \left( \frac{2(1 - 0) \cos(\theta_c)}{z + 0} \right) = -\gamma \left( \frac{2 \cos(\theta_c)}{z} \right) \]

\[ = \frac{2\gamma \sin(\theta_c - 90)}{z} \]

This result equals equation [9] by inspection. Additionally, to test that equation [23] goes to zero in the limit as \( \Delta O \) goes to infinity with \( R_1 \gg R_2 \), we take the limit:

\[ \lim_{\Delta O \to \infty} \Delta P = -\gamma \left( \frac{2 \left( 1 - \frac{2 \Delta O}{z} \tan(\theta_c) \right) \cos(\theta_c)}{z + \frac{4(\Delta O)^2}{z}} \right) = -\gamma \left( \frac{2(1 - \infty) \cos(\theta_c)}{z + \infty^2 / z} \right) = -\gamma (0 - 0) = 0 \]
Equation [23] was plotted for different offset distances and contact angles and a through-hole radius of 500 μm. Figure 67-70 show the maximum pressure difference across the liquid-air interface for gap distances 1-25 μm for surfaces with contact angles of 150°, 155°, 160°, and 165°.

Figure 67: Maximum pressure difference across the liquid-air interface for surfaces with contact angle of 150° varying the gap distance and offset distance between the adjacent through-holes.

Figure 68: Maximum pressure difference across the liquid-air interface for surfaces with contact angle of 155° varying the gap distance and offset distance between the adjacent through-holes.
Figure 69: Maximum pressure difference across the liquid-air interface for surfaces with contact angle of $160^\circ$ varying the gap distance and offset distance between the adjacent through-holes.

Figure 70: Maximum pressure difference across the liquid-air interface for surfaces with contact angle of $165^\circ$ varying the gap distance and offset distance between the adjacent through-holes.

### 4.4 Summary of the Models of Gasketless Interconnect

Three models were developed to predict the behavior of the gasketless interconnect. Additionally, dimensional analysis was used to determine the range of flow rates and through-hole diameters where surface tension forces dominated over gravitational, viscous, and inertial forces. A preliminary static model was developed from the Young-Laplace equation that related the maximum pressure of the interconnect before rupture to the gap distance and contact angle of the superhydrophobic surface. The preliminary static model revealed that to reach microfluidic driving pressures, the gap distance needed to be less than $10 \, \mu m$. A second generation model
expanded the preliminary static model to include the effect of the offset between the through-holes on the maximum pressure before rupture. The second generation model revealed that the effect of a small offset (~10 μm) between through-hole caused a large effect on the maximum pressure for gap distances below 10 μm.
5 Proof of Concept Experiment

A proof of concept experiment provided a method of observing the physics of the gasketless seal by showing liquid flow from one through-hole across an air gap to another through-hole. It also allowed the validation of the assumption in the models based on the Young-Laplace equation that the liquid bridge would radially expand when the curvature of the meniscus reached the static contact angle of the superhydrophobic surface. Two PMMA substrates with nanoimprinted superhydrophobic surfaces, had through holes drilled through each superhydrophobic surface, an Upchurch Scientific (Oak Harbor, WA) polyether ether ketone (PEEK) 1/32 x 0.0035 inch capillary tube, deionized water with red food coloring, a 1 mL syringe (BD, Franklin Lakes, NJ). A Nikon Measurescope MM-11 (Melville, NY) with a Diagnostic Instruments, Inc. microscope camera (Sterling Heights, MI), and SPOT Advanced Imaging Software was used to visualize the liquid bridge.

The polymethylmethacrylate (PMMA) sample substrates were prepared using soft-UV nano-imprint lithography to create superhydrophobic surfaces (See Figure 71-Figure 72). Additional details are located in Appendix 19.

The measured contact angle of the samples using the Fta32 system (First Ten Angstroms, Inc, Portsmouth, VA) was $143^\circ \pm 22^\circ$ using the 95% confidence interval for the Student t distribution.

Figure 71: A PMMA substrate with PDMS nanoimprinted superhydrophobic elephant ear leaf pattern.
Holes approximately 800 μm in diameter were mechanically drilled through the chips with a MicroLux variable speed miniature drill press (Berkeley Heights, NJ) using a #67 jobber drill bit (See Figure 73).

The gap between the two parallel superhydrophobic surfaces was defined to be approximately 600 μm using two 0.025” ± 0.00125” shims from Precision Brand (Downers Grove, IL) and Staple’s brand 3/5” mini binder clips to apply pressure to the two chips (See Figure 74). The through-holes were concentrically aligned using a 1/32” OD capillary tube fixture. A 1/32 x 0.0035 inch capillary tube was attached to one side using Pacer Z-Poxy 5
minute resin and hardener (Rancho Cucamonga, CA) and fitted with a 1 mL syringe (BD, Franklin Lakes, NJ).

![Image](image_url)

Figure 74: The proof of concept interconnect assembly featuring parallel superhydrophobic surfaces separated by a gap distance set by two 0.025" thick shims from Precision Brand (Downers Grove, IL).

Using the syringe, deionized water mixed with red food coloring was injected into the capillary tube. From there, it flowed through the first chip through-hole, across the gasketless superhydrophobic interconnect without leakage, and through the second chip through-hole. The syringe flow rate was increased until gasketless interconnect ruptured. The flow across the superhydrophobic interconnect was viewed using a Nikon Measurescope MM-11 (Melville, NY) with a Diagnostic Instruments, Inc. microscope camera (Sterling Heights, MI), and SPOT advanced imaging software. Figure 75 (A-I) shows the formation of the liquid bridge due to the capillary forces and the presence of the liquid-vapor interface. Figure 75 (J) shows the contact angle measured with AutoCAD® Mechanical version F.51.0.0 (Autodesk, Inc, San Rafael, CA) of the liquid bridge (water and red food coloring) before rupture. The asymmetry in the meniscus on either side of the image is thought to be due to a slight misalignment of the holes in each substrate.
Figure 75: (A-I) A sequential side view of the formation of the liquid bridge across the gasketless interconnect featuring water dyed with red food coloring flowing from the top chip to bottom chip via two through holes, and parallel superhydrophobic surfaces on a PMMA substrate separated by a gap distance of approximately 602 µm. These images were captured using a Nikon Measurescope MM-11 (Melville, NY) with a Diagnostic Instruments, Inc microscope camera (Sterling Heights, MI), and SPOT Advanced imaging software. (J) Side view of Figure 5 (I) with contact angle measurement using AutoCAD® Mechanical Product Version: F.51.0.0 (Autodesk, Inc., San Rafael, CA).

The proof of concept experiment enabled the observation of the superhydrophobic interconnect using an optical microscope and the validation of the assumption that the liquid bridge would radially expand when the curvature of the meniscus reached the static contact angle of the superhydrophobic surface. The measured contact angle of the surface using the Fta32 system (First Ten Angstroms, Inc, Portsmouth, VA) was $143^\circ \pm 22^\circ$ using the 95% confidence interval for the student-t distribution and the contact angle of the liquid bridge measured with AutoCAD® Mechanical version F.51.0.0 (Autodesk, Inc, San Rafael, CA) before rupture was $142^\circ$. 

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6 Preliminary Pressure Test Experiment

6.1 Initial Validation

The preliminary pressure test sought to both determine the maximum pressure that the liquid bridge could withstand before rupturing as a function of gap distance and test the validity of the first generation model based on the Young-Laplace equation.

Experimental samples were prepared using soft imprint lithography in the steps described in Appendix 19. To gage the hydrophobicity of the imprinted surfaces, the samples’ water contact angles were measured using the sessile drop method [51] with a contact angle measuring machine from First Ten Angstroms FTA125 (Portsmouth, VA) and a Gilson Distrimon X10082H with a 1µL to 12 µL Gilson Distritip (Middleton, WI) to dispense 1 µL drops. Using Student’s-t distribution and a 95% confidence interval [66], hydrophobic samples in the preliminary experiment had contact angles of 147°±22° and 144°±14°.

The experimental samples were then processed to create experimental assemblies. The details of the experimental assembly fabrication are described in Appendix 16. Each experimental assembly consisted of two 2 cm x 2 cm superhydrophobic samples with a #67 drilled through-hole 1 mm from the edge, two precision color coded shims from Precision Brand (Downers Grove, IL) with a thickness of either 25µm or 102 µm, two Staples Brand (Framingham, MA ) 3/5” mini binder clips, and a world-to-chip connection of a 1/32 x 0.0032 in PEEK tube concentrically fixed to the inlet through-hole using Pacer Z-Poxy 5 minute resin and hardener (Rancho Cucamonga, CA). These devices were then used with the experimental apparatus (See Figure 76).
The experimental apparatus consisted of an Upchurch Scientific P-727 TEE junction attached to a 0 to 5 psi ASDX005A2 Honeywell pressure transducer (Golden Valley, MN) connected to LabVIEW (National Instruments Corp., Austin, TX), a T-740 AMETEK portable pneumatic tester (Berwyn, PA) capable of applying small amounts of pressure, and the superhydrophobic devices. The experimental procedure involved first driving deionized water through the 5 inch length of the 1/32 x 0.0035 inch tubing, across the liquid bridge, and through the through-hole on the other side of the device using a 1 mL syringe (BD, Franklin Lakes, NJ). The device was then attached to the tee junction with an Upchurch Scientific F-247x tubing sleeve. The through-hole was then plugged and an AMETEK portable pneumatic pressure tester
(Berwyn, PA) increased the pressure in increments of 0.1 psi every few seconds while the liquid bridge was visually monitored and pressure readings were recorded. The experiments were stopped when the liquid bridge expanded radially and the maximum pressure readings were noted from the gathered readings. When the devices were disassembled, it was observed that the radial expansion of the liquid bridge caused an irreversible reduction in the contact angle in an area up to 3 mm distance from the through-holes. These wetted areas were the only visibly damaged areas on the two 2 cm by 2 cm superhydrophobic surfaces. Since there were only eight superhydrophobic samples, it was decided that the damaged areas would be cut-off and superhydrophobic samples would be reused to maximize the number of experimental data points. An area up to 4 mm from the edge on both the inlet and the outlet superhydrophobic surface of the device were cut off using the MicroLux Tools Tablesaw (Berkeley Heights, NJ). The superhydrophobic samples then were reused for additional rupture pressure data points.

6.2 Experimental Results

The experiment gathered liquid bridge maximum pressure data for two gap distances: \(~25 \mu m\) and \(~102 \mu m\) (Figure 77). The averages of four maximum pressure values for each shim thickness were compared to the estimates of the model in Figure 77.

![Figure 77: The model of the maximum pressure difference across the liquid bridge compared to experimental measurements of the liquid bridge.](image)
These values are on the same order of magnitude as the model’s pressures. However, more experiments are needed to verify the model. Specifically, the average of the maximum pressure of the 102 µm gap distance samples was slightly higher than the average maximum pressure of the 25 µm gap distance samples. This relationship contradicted the model prediction. Several factors that might serve to explain this discrepancy are discussed in the next section.

Additionally, these experiments showed that the radial expansion of the liquid bridges caused a permanent change to the hydrophobicity around the through-holes. These damaged devices would not hold a seal following liquid bridge rupture even two days after the former superhydrophobic surface dried.

6.3 Experimental Methods: Error Sources in Initial Validation

A detailed investigation of the potential sources of errors in the initial static pressure test experimental design, identified several factors that needed to be refined in the design of future studies of the mechanics of gasketless fluidic interconnects.

With respect to general experimental design, the through-holes were placed as close as possible to the edge of the substrates so that the liquid bridge rupture could be visually confirmed, in addition to the drop in the pressure sensed by the 0-5 psi ASDX005A2 Honeywell pressure transducer (Golden Valley, MN). This location was heavily dependent on the skill of the operator using the MicroLux variable speed miniature drill press (Berkeley Heights, NJ). The operator induced error in the placement of the through-holes resulted in through-holes being located in the range from 0.5 mm to 1.9 mm away from the edge of the substrate. The further the through-holes were from the edge, the more difficult it was to visually confirm that the liquid bridge had ruptured. This failure to visually confirm rupture resulted in some experimental data points being discarded, which increased the statistical uncertainty due to low sample count.
The height of the nanostructures comprising the elephant ear leaf over the area of interest was estimated to be on the order of 25 μm. Subsequent measurements using an optical profilometer disproved this hypothesis; the maximum nanostructure height over the area of interest was approximately 300 μm. The scans were conducted using a Nanovea 3D Profilometer (ST-400, Irvine, CA) optical profilometer with step sizes of 100 μm in the x-direction and 10 μm in the y-direction and the 400 μm optical range optical pin which has a z-resolution of 12 nm, an accuracy of 60 nm, and a lateral resolution of 1.3 μm. The substrate was made reflective prior to the scan by sputtering it with 80 nm of platinum. Figure 78(a) shows a sample surface created with nanoimprinted elephant ear leaf pattern, Figure 78(b) shows the overall surface height measurement, Figure 78(c) shows a contour map for the entire surface, and Figure 78(d) shows a profile along the cross-section A-A featured in Figure 78(b). Cross-section A-A was selected as a representative profile because this was near the location of the drilled fluid ports. The larger structure in the center of the cross-section was due to veins on the elephant ear leaf used to generate the pattern. A more uniform pattern should decrease the height of the nanostructures used to produce the superhydrophobic surface and reduce the uncertainty in the gap distance.

Additional error was contributed by the variability of the sessile drop static contact angle across the superhydrophobic surface. From the previously reported contact angle measurements using the Student t distribution and a 95% confidence interval [12], the contact angle of the samples were found to be 147°±22° and 144°±14° [12]. When measuring the static contact angle, the droplets would occasionally roll across the surfaces making it difficult to measure the static contact angle in certain areas of the substrate. In this case it was assumed that the static contact angle was represented by the mean of the sample contact angles measured, with the error
bars given through the Student t distribution. This assumption could affect the standard deviation of the error and cause an increase in the error. Future experiments will consider alternative methods of creating superhydrophobic surfaces with a uniform static contact angle across the surface.

Figure 78: (a) shows a sample surface created with nanoimprinted elephant ear leaf pattern, (b) shows the overall surface height measurement, (c) shows a contour map for the entire surface, and (d) shows a profile along the cross-section A-A featured in Figure 78(b). Cross-section A-A was selected as a representative profile because this was near the location of the drilled fluid ports.

The through-holes served several purposes during the experiment. They were used to deliver the liquid to and from the gap, and served as alignment structures that concentrically aligned with each other and the Upchurch Scientific (Oak Harbor, WA) 1/32” polyether ether ketone (PEEK) capillary tube fixture. The through-holes were used to connect an Upchurch Scientific PEEK 1/32 x 0.0035 inch capillary tube to the input of the assembly with epoxy. The diameter of the drilled through-hole varied by 200 μm throughout the length of the through-hole.
The experiment was designed to neglect the dimensional uncertainty of the drilled through-holes by the assumption in the derived model that the radius of curvature of the through-hole was much greater than the radius of curvature of the meniscus. From an experimental standpoint, this decision was made to reduce the number of variables that needed to be controlled and observed. This strategy will be applied in future experiments to reduce the unnecessary complexity in the experimental design.

The compression of the Precision Brand (Downers Grove, IL) color coded shims was hypothesized to be negligible. According to the material data sheet provided by the company, the thickness of the shim decreased by 1.0% at a pressure of 5000 psi, which equated to a shrinkage of 1.02 μm for the 102 μm shim and 0.25 μm for the 25 μm shim. This change was negligible for the sake of the experimental apparatus. Assuming each binder clip can apply a force of about 10 lbf (measured using Pelouze Model 7842 hanging Viking Scale), on an area of the shim that was 0.5 inch by 0.5 inch, the pressure on the shim under the binder clips was ~40 psi, which was much less than 5000 psi.

During the pressure test experiment, after the liquid bridge was established, a gloved finger was used to manually apply a load on the exit of one through-hole to block the liquid flow so that pressure could be built up in the liquid bridge. During the design of the experiment the effect of the deflection of the substrate on the gap distance was not considered. Using a simple beam model, the maximum deflection of the bottom plate of the device can be analyzed. From Timoshenko [67] (See Figure 79), the maximum deflection $\delta_{\text{max}}$ of a simple beam by a point load $P$ can be described using the following equation 58:

$$\delta_{\text{max}} = \frac{Pb}{9\sqrt{3EI}} \left( \frac{t^2}{b^2} \right)^{\frac{3}{2}}$$  \hspace{1cm} (58)
where $P$ is the concentrated load, $a$ is the distance from the point load to the left constraint, $b$ is the distance from the point load to the right constraint, $l$ is the length of the beam, $I$ is the moment of inertia of the cross section with respect to the neutral axis, and $E$ is the modulus of elasticity. Assuming the force a finger can exert on the substrate to be a point load of 22 N, the modulus of elasticity of polymethyl methacrylate (PMMA) is about 3 GPa, the thickness of the beam is about 2 mm, and the point load is in the middle of the 1.5 cm length beam, the maximum deflection of the beam is about 40 μm. This effect will be addressed in future experiments to reduce the uncertainty in the gap distance.

Another difficulty experienced during the experiments included the time consuming nature of drilling holes close to the edge of the substrate, assembling chips using capillary to align through-holes, Precision Brand color coded shims (Downers Grove, IL) to set the gap distance, and binder clips to hold the chips together, grouting world-to-chip interconnects with epoxy, visually confirming the liquid bridge rupture, and manually increasing pressure with the T-740 AMEXTEK pneumatic pressure tester (Berwyn, PA). A different experimental apparatus will be created for future experiments to minimize the manufacturing and assembly time so more time can be spent gathering experimental data points.
6.4 Conclusions

The preliminary pressure test experiment using precision shims 25 μm and 100 μm thick to set the gap distance showed that the maximum pressures were on the same order of magnitude as the model (1-10 kPa). Additionally, rupture of the liquid bridge caused a permanent change to the superhydrophobic surface of the device.

However, after a detailed investigation of the potential sources of errors in the preliminary pressure test experimental design, several factors were identified that need to be refined in the design of future experiments. These factors include: the variability of through-hole placement, the flatness of the superhydrophobic surface, the uniformity of the contact angle of the superhydrophobic surface, the use through-hole geometry and a capillary tube to align the adjacent through-holes, the use of a gloved finger as a manual valve, and the difficulty of manufacturing, assembling, and testing samples.
7 Modified Pressure Test Experiment

7.1 Motivation

The modified pressure test evaluated the maximum pressure that the gasketless seal could withstand before rupture and compared the results to the models derived from the Young-Laplace equation. The preliminary pressure test experiments revealed several flaws in the experimental design and limited the conclusions that could be drawn from the experimental data. These flaws in the experimental design included:

- The gap distance was set by shims and the shims only had a limited number of thicknesses;
- The through-holes were concentrically aligned using a capillary tube and the alignment could shift when clamping the samples together with binder clips;
- The experimental pressure was increased by manually adjusting the pressure pneumatic pressure tester which led to different samples receiving different pressure ramp rates;
- The variation in the height across the superhydrophobic surface was assumed to be approximately 25 μm but it was actually greater than 300 μm. This led to the gap distance being defined by the surface features instead of the shims;
- A gloved finger was used to plug the back through-hole to build up pressure across the interconnect. This action caused the chips to deflect which arbitrarily reduced the gap distance;
• The distance of the through-hole from the edge varied from sample to sample which made it difficult to align the samples and visually confirm a rupture. The failure to visually confirm rupture resulted in some possible data points being discarded;

• A limited number of samples were tested due to the difficulty in manufacturing the samples;

The flaws in the preliminary experiment motivated a complete redesign of the experimental devices and experimental apparatus. The modified pressure test aimed to address the problems with the preliminary pressure test experiment and yield statistically significant results to validate the models derived from the Young-Laplace equation. The following sections will discuss the design and manufacturing of the samples, the design and assembly of the experimental apparatus, the experimental procedure, and the experimental results of the modified pressure test.

7.2 Design and Manufacturing of the Samples

The goals of the design of modified pressure test samples were to increase the total sample yield, to reduce the manufacturing and assembly time, to reduce the amount of tedious labor per sample, to increase the flatness of the samples, and increase the geometric repeatability. These led to the manufacturing decisions to injection mold and polish the samples, and to select a superhydrophobic coating that could be spin coated.

In the μSET Lab, the injection molding process requires two mold die inserts, each made from a block of 353 brass, to be micromilled, and assembled into the 3in injection mold die (See Appendix 14). The two mold inserts include an A-side mold insert which is closest to the barrel and features the sprue hole, and the B-side mold insert, the mold insert that is opposite the barrel.
Ideally, the mold insert cavity and mold features are simply the inverse of the design of the part being produced. For single-sided molding, the mold inserts and features are only located on the B-side mold insert. For double-sided molding, the mold cavity is located on the B-side mold insert but the features are located on both the a-side and b-side mold insert. Most single and double-sided mold insert designs are not ideal and require additional features beyond the features required for a part’s geometry for proper function. These features include venting channels for the mold cavity, alignment pins to align the mold inserts, ejector pin hole(s), on the B-side insert, to interface with the ejector system of the injection molding machine, and a sprue hole, on the A-side, the polymer from the sprue entering the cavity. The mold inserts must additionally be designed with adequate draft angles on the mold features enable the ejection of the part from the mold cavity. The interplay between the geometry of the final part and the mold requirements for production makes the mold design process iterative.

For the modified pressure test experiment, two sets of single-sided mold inserts were designed, manufactured, and tested to arrive on the final design of the mold insert. In the final round of inserts, four B-side mold inserts were designed with triangular prisms that would produce v-grooves that when assembled with three ball bearings would set gap distances of the assemblies to 5 μm, 25 μm, 50 μm, and 100 μm. However, tool offset error created in the micromilling of the triangular prisms produced four different measured prism dimensions, using a Nanovea 3D Profilometer (ST-400, Irvine, CA) optical profilometer, corresponding to four different gap distances: -250 μm, -35 μm, 30 μm, and 100 μm. The negative gap distance means that the surface features of the parts would set the gap distance instead of the kinematic alignment structures. The prism dimensions measurements resulted in a remanufacturing of the 50 μm design to obtain gap distances between 30 and 100 μm. The remanufactured 50 μm insert
had measured prism dimensions corresponding to a gap distance of 50 μm. In total, five B-side mold inserts were created with measured dimensions of triangular prisms that would produce parts with gap distances of -250 μm, -35 μm, 30 μm, 50 μm, and 100 μm. Additionally, one blank A-side mold insert was manufactured and used with all four B-side mold insert designs. It featured a sprue hole to mate with the cold sprue and four mold insert alignment pins that mated with the four alignment slots on the B-side mold inserts. Drawings of the mold inserts are in Appendix 14. It is best to view the features of the B-side mold insert through the lens of the final parts produced (see Figure 80). The final design of the chips included injection molded through-holes to facilitate repeatable placement of the through-holes both in distance from the chip edge and with respect to the kinematic alignment v-grooves (See Figure 81 and Figure 82).

Figure 80: The sample geometry of half of an interconnect assembly. It features injection molded through-holes, three ball bearings resting in three v-grooves, two alignment standards, and areas raised 20 μm above the surface of the part to ease the polishing procedure. The ring around the drilled hole in the center of the part is on the backside of the part and does not contribute to the experiment.
Figure 81: Shows the geometry of the injection molded through hole adjacent to the chip edge.

Figure 82: Shows the geometry of the chip assembly with an exploded view of the cross section of the adjacent through holes.

The chips were assembled using three pairs of v-grooves coupled with three silicon nitride ball bearings kinematically constrained all six degrees of freedom of the two chip assembly using six point contacts (See Figure 83). Additionally, these kinematic alignment structures passively aligned the through-holes, and set the gap distance between chips. Alignment standards were used to measure the misalignment between sample chips, and areas of the chip that were raised 20 μm above the rest of the chip to simplify the polishing process. The
injection molded through holes, v-grooves, and alignment standards are located on areas raised 20 μm above the samples surface to isolate them from the rest of the chips features during the polishing process. The injection molded through holes had a diameter of 750 μm and the center was located 1.122 mm from the edge. The design of the kinematic alignment structures can be located in Appendix 17. The alignment standards were the same as used by You et al [69].

The chips were printed in Cyclic Olefin Copolymer (COC) (Topas® 5013S-04, TOPAS Advanced Polymers, Florence, KY) using the injection molding machine (Battenfeld BA 500/200 CDK-SE, Kottingbrunn, Germany) located in the μSET lab. The injection molding processing conditions for each mold insert are given in Appendix 13.

![Image of an assembled device using three silicon nitride ball bearing and three pairs of v-grooves to kinematically constrain all six degrees of freedom of the assembly.](image)

Figure 83: Image of an assembled device using three silicon nitride ball bearing and three pairs of v-grooves to kinematically constrain all six degrees of freedom of the assembly.

After injection molding, the cold sprue was drilled out of the samples center using a drill press with a 3/8” jobber drill bit and the back side of each sample’s through-holes were drilled out to a depth of 1 mm with a #53 jobber drill bit using a MicroLux Tools variable speed miniature drill press (Berkeley Heights, NJ). The #53 jobber drill bit was selected because it was empirically found to provide the best press-fit connection with the 0.0625” OD (0.03” ID) FEP tubing (part number 1520) from Upchurch Scientific (Oak Harbor, WA).
The samples were then washed in a bath of deionized (DI) water and Dawn Manual Pot and Pan Detergent (Procter & Gamble Professional, Cincinnati, OH) liquid detergent, rinsed with DI water, and dried at a temperature of 100°C in a VWR 1602 (Radnor, PA) oven for 4 hours. The dried samples were then transported over to the DoAll surface stone (Des Plaines, IL) which had a flatness of 0.0001” for polishing. First, the back sides of the samples (A-side) were hand polished using 600 grit 12” diameter disks (Pace Technologies (Tucson, AZ)) attached to the surface stone with a pressure sensitive adhesive (PSA) backing, and then hand polished using a 9 μm grit 12” diameter Fibermet Disk from Buehler (Lake Bluff, IL) attached to the surface stone with a PSA backing. The polishing disks were changed every 20 samples. Next, the front of the samples were hand polished using a 600 grit 12” diameter disk with a PSA backing (Pace Technologies), 9 μm grit 12” diameter disk with a PSA backing from Buehler, and 3 μm 12” diameter disk with a PSA backing from Buehler. Then, the samples were washed again using Dawn Manual Pot and Pan Detergent (Procter & Gamble Professional) liquid detergent diluted in DI water and rinsed with DI water. Next, the samples were loaded into a VWR 1602 (Radnor, PA) constant temperature oven at 60º C for 4 hours to prepare the samples for the spin coating of the superhydrophobic coating.

Hydrobead-P (specified by vendor as Hydrobead-P “old formula”) (Hydrobead, San Diego, CA), was selected for the superhydrophobic coating because of its low thickness (~2-14 μm), high contact angle uniformity, and its high mean contact angle (~150°). Figure 84 and Figure 85 show SEM images (FEI Quanta3D FEG, Helios Nanolab, Hillsboro, OR) of Hydrobead-P on COC substrates coated with 80 nm of platinum. The experimental data for Hydrobead-P is in Appendix 18. The coating was mixed according to the instructions as 4 parts of part-b (100 mL) to 1 part of part-a (25 mL). After thoroughly mixed, the solution was spin
coated onto the samples using a BIDTEC model SP100 spin coating machine. The spin coating machine ramped the speed up at a rate of 25 RPM/s until reaching 1500 RPM which was held for 30 s, and then ramped down the speed to zero at a rate of 25 RPM/s. After spin coating, the samples were then cured in a VWR 1602 (Radnor, PA) oven at 100°C for one hour. The samples were then checked to see if they were superhydrophobic by applying droplets of DI water on them from a 10 mL BD syringe. The samples that were not superhydrophobic were spin coated again and cured. All of the samples were superhydrophobic by the third spin coating and curing cycle. It is unknown why some samples were superhydrophobic on the first coating while others it took three coatings.

Figure 84: Example of Hydrobead-P surface spin coated on COC.

Figure 85: Zoomed in top view of hydrobead-P spin coated on COC substrate.
After becoming superhydrophobic, assemblies of samples were created using two samples, three 1/32” Silicon Nitride grade 5 [70] ball bearings (Boca Bearing Company, Boynton Beach, FL), and low shrink Pacer Z-Poxy 5 minute resin and hardener (Rancho Cucamonga, CA) applied at three 1.87 mm x 2 mm locations around the edge to fixture the assembly together. The kinematic alignment structures (three ball bearings and six v-grooves) were used to both set the gap distance between the samples and passively align the adjacent 750 μm diameter through-holes. Two loading conditions were applied to the assemblies: unclamped and clamped. The unclamped assemblies sandwiched three ball bearings between three pairs of v-grooves on two different samples and used Staples Brand (Framingham, MA) medium binder clips placed over the kinematic alignment structures to hold the whole assembly together. The clamped assemblies sandwiched three ball bearings between three pairs of v-grooves on two different samples, used medium binder clips placed over the kinematic alignment structures to hold the whole assembly together, and then applied a clamping force over the through holes locations using a 5” deep throat u-clamp from Harbor Freight Tools USA, Inc (Calabasas, CA). Afterwards, for each of the loading conditions, low shrink epoxy was applied at four different locations around the edge of the assembly. After the epoxy cured, the u-clamps and binder clips were removed and the through-holes were prepared for a world to chip connection. A broken micromilling bit was rotated by hand to taper the backsides of the through holes and then ultra high purity nitrogen was blown through the through holes to remove loose particles. Next, the ends of two 3-3/8” length 1/16” OD x 0.03” ID fluorinated ethylene propylene (FEP) tubing (1520, Upchurch Scientific, Oak Harbor, WA) were press fit into the tapered through holes on both the inlet and outlet side of the assembly and then low shrink Pacer Z-Poxy 5 minute resin and hardener (Rancho Cucamonga, CA) was applied to the base of the connections to reinforce
them. After that, a Vacutight headless fitting (P-844, Upchurch Scientific, Oak Harbor, WA) and a Vacutight ferrule (P-840, Upchurch Scientific, Oak Harbor, WA) were assembled on the exposed end of the inlet side tubing and a super flangeless nut with ¼ -28 thread (LT-115, Upchurch Scientific, Oak Harbor, WA) and a super flangeless ferrule (P-250, Upchurch Scientific, Oak Harbor, WA) were assembled onto the outlet side tubing to interface with the experimental apparatus.

7.3 Design and Assembly of Experimental Apparatus

The modified pressure test experimental apparatus addressed the perceived flaws in the previous experiment. The solutions included a steady pressure source, automatic ramping of the system pressure using a closed-loop pressure regulator, automatic measurement of upstream pressure and pressure of interconnect, developing an integrated system that allowed automated measurements and parameter setting, automatic shut-off when the pressure sensor sensed a rupture, a controlled priming procedure, ball valves to both shut-off the flow downstream to build up the system pressure and upstream to isolate the experimental apparatus from the pressure of the pressurized liquid column, and standardized fittings to connect the system components together and to quickly change out experimental assemblies.

The previous experiments required the experimenter to manually increase the system pressure using a hand pump style pneumatic pressure tester until the liquid bridge ruptured. This method was not repeatable. Two pressure sources were investigated for these experiments: a syringe pump and a pressurized liquid column. Initial experiments revealed that the pressure from the syringe pump oscillated with time. Consequently, a pressurized liquid column was selected as a pressure source for the system. The liquid column was pressurized with ultra high purity nitrogen regulated by a 0-5 psig dual valve pressure controller (68027-60, Cole-Parmer, Vernon Hills, IL) which accepted an analog voltage set point and streamed a measured pressure
as an analog voltage. Consequently, the dual valve pressure controller had two resolutions of interest: a resolution for its accuracy in setting a pressure and a resolution for its accuracy in measuring the downstream pressure. The accuracy of the pressure controller was ±0.086 kPa and the accuracy of its pressure sensor was ±0.034 kPa.

The maximum pressure of the gasketless interconnect was measured using one of two ASDX series Honeywell S&C (Golden Valley, MN) pressure transducers: a 0-1 psi (0-6.89 kPa) pressure range, and a 0-5 psi (0-34.47 kPa) pressure range. The 0-1 psi pressure transducer had an accuracy of ±0.138 kPa and the 0-5 psi pressure transducer had an accuracy of ±0.689 kPa. Both transducers had a time constant of 1 ms. The 0-1 psi pressure transducer was used to measure the low range of rupture pressures and the 0-5 psi transducer was used to measure the range of pressures above 1 psi and below 5 psi. These pressure transducers were interchangeable in the experimental apparatus. For all of the interconnect assemblies, the low range was first tested and then the high range was tested. The pressure transducers were made interchangeable by the design of their connection to the system. The pressure sensor was connected to an Upchurch Scientific P-727 TEE junction (Oak Harbor, WA) using a ½” length of 1/16” OD neoprene tubing as a union between the pressure transducers inlet port and a 1” length of 1/16” OD x 0.03” ID fluorinated ethylene propylene (FEP) tubing (1520, Upchurch Scientific, Oak Harbor, WA). The other end of the FEP tubing was assembled with a VacuTight™ headless fitting (P-844, Upchurch Scientific, Oak Harbor, WA) and a VacuTight™ ferrule (P-840, Upchurch Scientific, Oak Harbor, WA) which connected to the Upchurch Scientific P-727 TEE junction. The other two junctions on the P-727 TEE were connected to the inlet tubing to the interconnect assembly via the VacuTight™ headless fitting and ferrule, and outlet tubing from the upstream microfluidic ball valve via the headless fitting and ferrule.
The system instrumentation was built around the NI USB-6212 DAQ (National Instruments, Austin, TX) board interfacing with the experiment’s custom designed LabVIEW 2012 (National Instruments, Austin, TX) program running on a laptop computer. The data acquisition board allowed for easy integration of the system outputs, pressure measurements from the interconnect pressure sensor and the Cole-Parmer pressure controller, and the pressure controller set point into an intuitive experimental interface. A sampling rate of 5000 Hz was set through the LabVIEW 2012 program. The ramp rate of the pressure controller was also set to increase the set point in steps of 0.002 psi (0.0138 kPa) every 120 ms. The pressure was cut-off automatically when the ASDX pressure sensor sensed a rupture. This was implemented through the LabVIEW 2012 program by dividing the data stream from the ASDX pressure sensor into 100 ms segments and calculating the average of each segment. Then each segment’s running average was compared to the previous running average to determine if the pressure had dropped more than the resolution of the pressure sensor. If it had, the system would shut down the experiment and turn on a light on the laptop’s screen indicating a rupture. The ruptured interconnect assembly would then be replaced with a new assembly. The new assembly required priming with liquid before an experiment could begin. The integrated system greatly improved the control over the priming process and enabled repeatable priming conditions.

Flow control of the deionized water to and from the microfluidic system was provided by two P-732 microfluidic ball valves from Upchurch Scientific (Oak Harbor, WA). The upstream microfluidic ball valve was connected to Upchurch Scientific (Oak Harbor, WA) U-501 1/4” male NPT to ¼-28 male adapter. The ¼” male NPT fitting was connected to a ¼” female NPT to 3/8” male NPT adapter which was connected to a 3/8” NPT bronze 3-way ball valve. One of the ports of the 3-way valve was connected a 3/8” NPT to ¼” tube compression fitting, then to a 6
inch length of ¼” OD 0.170” ID high density polyethylene tubing, then to a 3/8” NPT ball valve, then to a 4’ length of ¼” OD 0.170” ID high density polyethylene tubing, and then to a multi-stage cylinder pressure regulator attached to a size 35 cylinder of research grade carbon dioxide. The other port of the 3-way valve connected to a 3/8” NPT to ¼” tube compression fitting, then to a 2 ½ foot length of ¼” OD 0.170” ID high density polyethylene tubing, then to a 3/8” NPT to ¼” tube compression fitting that was attached to the outlet of the pressurized liquid column. The use of compression fitting connectors for the macroscale components and ferrule connectors in the microfluidic components greatly simplified the assembly of the experimental apparatus.

A simplified version of the apparatus is shown schematically in Figure 86. Ultra high purity nitrogen (1) is regulated down to 25 psi by its cylinder regulator (2) then it runs through a 5 μm line filter (3) before it is regulated to pressure between 0 and 5 psi by the Cole-Parmer dual valve pressure controller (4). The regulated nitrogen then passes a 3/8” NPT bronze tee junction (5) with a 25 psi ASME-Code Brass Pop-Safety Valve (6) to the top of the pressurized liquid column (7). Pressurized fluid exits the bottom of the pressurized liquid column and is transported through a 3/8” NPT bronze 3-way valve to the P-732 microfluidic ball valve (8). The fluid proceeds out of the microfluidic ball valve to the P-727 tee junction (9) which is connected to the ASDX pressure sensor (10) and the interconnect assembly (11). The fluid exits the interconnect assembly and flows through the downstream P-732 microfluidic ball valve (12) out of the system. A complete description of the experimental apparatus can be found in Appendix 21.

7.4 Experimental Procedures

The experiment consisted of four main parts: start-up, interconnect assembly priming, testing, and gap distance and misalignment measurement. Detailed descriptions of each are in Appendix 20.
Figure 86: Schematic of the experimental apparatus. The components include 1) ultra high purity nitrogen, 2) cylinder regulator, 3) 5 μm particle filter, 4) Cole-Parmer 0-5 psi dual valve pressure controller, 5) 3/8” NPT bronze tee, 6) 0-25 psi pressure relief valve, 7) PVC pressurized liquid column, 8) P-732 upstream microfluidic ball valve, 9) P-727 microfluidic tee, 10) ASDX pressure sensor, 11) interconnect assembly, 12) P-732 downstream microfluidic ball valve.

7.5 Experimental Results

The maximum rupture pressure, assembly gap distance, and assembly offset were measured for ninety-nine interconnect assemblies. These were composed of samples from four different mold inserts entitled the 5μm insert, the 25 μm insert, the 30 μm insert, and 50 μm insert. Originally, the 5μm insert, the 25 μm insert, and the 50 μm insert were named after their designed gap distance. However, after remanufacturing the 50 μm insert to the design specifications, the old 50 μm insert was renamed to the 30 μm to correspond with the gap distance set by the dimensions of its triangular prisms. Additionally, two different loading conditions were applied to the assemblies: clamped and unclamped. The resulting experimental
data are represented in Figure 87. The gap distance for each assembly was the average of ten gap distance measurements at ten locations along the edge of the assembly within a range of ±2 mm from the centerline of through hole. The horizontal error bars represent a 95% confidence interval for gap distance based on the Student t distribution. The results were compared to the first generation model with a contact angle of 150°. The model’s 95% confidence interval is based on the Student t distribution of the contact angle measurements of Hydrobead-P (See Appendix 18). The experimental results reveal that 80% of the assemblies were within ±50% of the first generation model’s value using a contact angle of 150° and the high gap distance value from the 95% confidence interval of the gap distance measurements.

Figure 87: All data representing the relationship between interconnect assemblies maximum pressure and gap distance compared to the first generation maximum pressure model and the pressure drop across different microfluidic devices at their optimal flow rate.

To verify the second generation model, vertical and horizontal offset measurements were gathered for a subset of the assemblies. The mean horizontal offset was calculated by adding together the mean of the offset measurements from the left alignment standard and the mean of the offset measurements from the right alignment standard. The mean vertical offset was
calculated from the offset measurements of the tool marks centered on the through hole. The magnitude of the horizontal and vertical mean offset was calculated by taking the square root sum of the squares of the mean vertical offset and the mean horizontal offset.

Figure 88 compares a subset of the rupture pressure, mean gap distance, and total mean offset to the first generation maximum pressure model using a contact angle of 150⁰ and Figure 89 compares the subset of the data to the second generation maximum pressure model using a contact angle of 150⁰. The graphs qualitatively show that the subset of the data do not match the second generation model.

Figure 88: A subset of the rupture pressure, mean gap distance, and total mean offset data in magenta squares compared to the first generation maximum pressure model represented by blue lines.

Figure 89: A subset of the rupture pressure, mean gap distance, and total mean offset data represented by magenta squares compared to the second generation maximum pressure model represented by blue lines.
Additionally, group experimental statistics were calculated for this unbalanced, single factor experiment with eight treatments: four gap distances at two loading conditions. A single factor analysis of variance was performed on the treatment rupture pressure means and the null hypothesis was rejected with any P>5.3e-14. Figure 90 displays the mean rupture pressure and mean gap distance for the eight treatments and applied simultaneous 95% confidence intervals to mean maximum pressure and mean gap distance data using a student’s t-distribution with a Bonferroni correction [71]. The group data shows fair agreement with the first generation model.

Figure 90: Group experimental data of eight treatments arranged from the lowest mean rupture pressure to the highest mean rupture pressure. A 95% confidence interval with a Bonferroni correction was applied to both the mean rupture pressure and mean gap distance for each treatment.

7.6 Conclusions

The modified pressure test experiments were designed to improve upon the preliminary pressure test experiments. These experiments designed, manufactured, and assembled injection molded interconnect assemblies, commercially available Hydrobead-P was selected as the superhydrophobic surface, and a new experimental apparatus to test the maximum rupture
pressure of the assemblies. Rupture pressure, gap distance, and offset data was measured for ninety-nine samples. The rupture pressure and gap distance data validated the first generation model with 80% of the samples within ±50% of the first generation model’s value using a contact angle of 150° for the high gap from the 95% confidence interval. A subset of rupture pressure, gap distance, and offset measurements were compared to the offset model with very poor agreement. This may have been due to the sensitivity of the pressure transducers preventing the observation of the initial rupture. Additional group statistics were calculated and had good agreement with the first generation model. Overall, the gasketless seal withstands maximum pressures seen in microfluidic systems without adding additional kinematic constraints and it is realizable within manufacturing tolerances.
8 Conclusions

Microfluidic interconnects provide a passage to transport fluid between component chips and to and from the microfluidic system. A broad spectrum of interconnect designs have been documented in the literature. However, most of these create unnecessary dead volumes, require additional components, post-processing or trained technicians, and add additional kinematic constraints leading to over- or under-constrained systems. These problems motivated the investigation into a new interconnect technology.

A new type of standardized microfluidic interconnect, the gasketless interconnect, was proposed and evaluated. The gasketless interconnect uses capillary forces to seal the connection between two concentrically aligned through-holes in superhydrophobic surfaces separated by a gap distance.

Capillary forces are a combination surface tension forces and Young-Laplace forces. Two static models based on the Young-Laplace equation were developed to estimate the maximum pressure of the interconnect before rupture. The first model related the maximum rupture pressure to the surface tension, the gap distance and the contact angle of the surface. It found that a gap distance of less than 10 μm was needed to drive a typical microfluidic device described in Appendix 10. The second model was developed to capture the effect of lateral offset distance between through-holes on the maximum rupture in addition to the parameters from the first model. This offset model showed that though-hole offset should have a significant effect on the maximum pressure of the interconnect. Dimensional analysis was used to show the combination of velocities and through-hole diameters under which the static models worked as dynamic models.
To validate the models, three sets of experiments were designed and performed on sample gasketless interconnects. The first experiment demonstrated proof of the concept and confirmed the assumption in the first and second generation models that the liquid bridge ruptured when it approached the static contact angle of the surface. The second experiment sought to test the maximum pressure for two different gap distances: 25\(\mu\)m and 102\(\mu\)m. Due to a low sample size and experimental error, the measurements only showed agreement on the same order of magnitude as the first generation model. The third set of experiments addressed several flaws in the second experiment and tested ninety-nine assemblies with gap distances spanning 4-240 \(\mu\)m. The experiments revealed that 80\% of the measured maximum pressures were \(\pm 50\%\) of the first generation model at the high gap distance from the 95\% confidence interval of the gap distance measurements. Most of the difference between the model and the experimental results was attributed to manufacturing variability from the manual polishing process, spin coating process used to apply the superhydrophobic surface, mold insert fabrication, and injection molding parameters. Additionally, for a subset of samples, the nominal assembly offset was measured and compared with the maximum pressure data to determine the agreement with the second generation model. The subset of data matched the first generation model but did not match the offset model. The subset pressure values revealed that 67\% of the samples were in the range of +150\% to +7600\% of the offset model’s value using the high gap distance from the 95\% confidence interval of the gap distance measurements. This may have been due to assumption in the offset model that a semicircular arc approximated the shape of the meniscus or it could have been that the pressure sensor lacked the resolution to resolve the initial liquid bridge rupture. The results of the experiments validated the first generation model based on the Young-Laplace equation. Overall, the gasketless seal withstands maximum pressures up to 21 kPa seen in
microfluidic systems without adding additional kinematic constraints and is realizable within manufacturing variation of microfabrication processes.
9 Future Work

The gasketless seal is ripe for future investigation both from a scientific and an engineering standpoint. The following are a list of future work and open questions:

- Using the existing experimental setup, sample assemblies, and an aqueous solution of fluorescin, run the experiment in the confocal microscope while observing the liquid bridge. This should give an image of the shape of the meniscus up to rupture. Compare the shape with the semicircular arc used in the first generation model. Using the curvature from the image, find the maximum pressure. Compare the maximum pressure from the image to the maximum pressure measured by the pressure sensor.
- Test the maximum pressure of the interconnect at different flow rates and at lower gap distances. Is the burst energy (pressure times volume flow rate) constant? What gap distances does the first generation model break down?
- Develop differential model of interconnect shape using differential geometry and compare it experimental results from modified pressure test experiments and the confocal experiments.
- Investigate the gasketless interconnect’s connection to the literature investigating meniscus stability. Does the gasketless interconnect experiments contribute something new to the field?
- Investigate the effect of evaporation. If there are multiple interconnects, does liquid bridge coarsening play a role?
- Investigate the effect of using biological aqueous fluids. Do the constituents of the fluid segregate toward the liquid-vapor interface?
- Isolate and quantify the sources of manufacturing errors.
- Develop new injection mold inserts that minimize burr formation in the part around injection molded through holes and around the part edge.
- Increase the flatness of the injection molded parts by incorporating more raised areas in the mold insert.
- Develop a torque specification for mold insert bolts that minimize the warpage of the insert due to thermal expansion from heating the mold dies.
- Find a superhydrophobic surface that has a flatness < 3μm. Preferably one that can be mass produced.
- Find optimal vacuum pressure for part flatness for the vacuum chuck on the fly cutting machine.
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Appendix

10 Load Characteristics of Lab-on-a-chip Devices

10.1 Introduction

Over the years, the Microsystems Engineering Team (μSET) lab has designed and manufactured several integrated lab-on-a-chip microfluidic devices that perform specific functions: Polymerase chain reaction (PCR), mutation detection, mixing, multi-phase flow, capture of tumor cells, and reverse transcription. These devices provide the foundation for the μSET labs current and future work. With the increasing complexity of microfluidic systems, more emphasis has been placed on the use modular architectures in the design of components for microfluidic systems. The μSET lab-on-a-chip devices were designed with this foresight so that in the future they could be incorporated as modular component chips into more complex microfluidic systems. The future has arrived and one of the necessities to incorporate the modules into a system is to define the basic load characteristic of the device. The load characteristic defines the pressure drop across a microfluidic chip for different flow rates. The majority of devices designed and manufactured in the lab employed single-phase flow through a rectangular cross-section.

Dryden et al [72] characterized the analytical solution for velocity profile and the flow rate to the single phase flow through a rectangular cross-section problem where the width of the channel is defined by \(-a \leq x \leq a\) and the depth of the channel is defined by \(-b \leq y \leq b\). Also, the z-axis is aligned with the positive direction of the channel. The velocity profile is given by:

\[
\frac{w(x,y)}{K} = \frac{1}{2} \left( b^2 - y^2 + \frac{4}{b} \sum_{n=0}^\infty (-1)^{n+1} N^{-3} \text{sech } Na \cosh Nx \cos Ny \right)
\]

where,
\[ 2bN = (2n + 1)\pi \]
which leads to,
\[ N = \frac{(2n + 1)\pi}{2b} \]
where,
\[ K = -\frac{1}{\mu} \frac{dp}{dz} \]
Where \( w(x,y) \) is the velocity profile, \( dp/dz \) is the pressure drop, \( \mu \) is the viscosity, \( a \) is half the width of the channel, \( b \) is half the depth of the channel, \( x \) is the coordinate along the \( x \)-axis, and \( y \) is the coordinate along the \( y \)-axis.

The flow rate is given by:
\[ Q = K \left[ \frac{4}{3} ab^3 - \frac{8}{b} \sum_{n=0}^{\infty} N^{-5} \tanh(Na) \right] = 4abU \]
Where \( Q \) is the flow rate, and \( U \) is the mean velocity. The flow rate equation can be rearranged to give the pressure drop per unit length (\( dp/dz \)) in terms of \( a \), \( b \), \( \mu \), and \( U \).
\[ \frac{dP}{dz} = -\frac{3U\mu}{b^2} \left[ 1 - \frac{192b}{a^5} \sum_{i=1,3,5,...}^{\infty} \frac{1}{i^5} \tanh \left( \frac{a\pi i}{2b} \right) \right]^{-1} \]
The pressure drop per unit length multiplied by the length of the channel will give the pressure drop for a given mean velocity. The pressure drop and flow rate at each mean velocity are combined to find the load characteristic. Each \( \mu \)SET lab-on-a-chip devices load characteristic will be discussed in chronological order and use the name of the author that originally designed the chip.
10.2 Continuous Flow Polymerase Chain Reaction (CFPCR) Device [2, 61, 62]

Mitchell et al designed and manufactured the CFPCR device with a total channel length of 1.78 m [62], width of 50 μm, and depth of 150 μm. The length of the channel was 1.78 m [62]. The device was tested using mean velocities from 1 mm/s to 5 mm/s which correspond to flow rates from 0.45 μL/min to 2.25 μL/min. The optimal flow rate was found to be 0.45 μL/min. The load characteristic data is shown in Table 2 and the load characteristic curve is shown in Figure 91.

Table 2: The load characteristic information for the continuous flow polymerase chain reaction developed by Mitchell et al. The underlined numbers were the empirical parameters that represented the highest efficiency.

<table>
<thead>
<tr>
<th>Mean Velocity (mm/s)</th>
<th>Flow Rate (μL/min)</th>
<th>Pressure Drop (kPa)</th>
<th>Pressure Drop (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.45</td>
<td>10.837</td>
<td>1.57</td>
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<tr>
<td>2</td>
<td>0.9</td>
<td>21.675</td>
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<td>3</td>
<td>1.35</td>
<td>32.512</td>
<td>4.72</td>
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<tr>
<td>4</td>
<td>1.8</td>
<td>43.350</td>
<td>6.29</td>
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<tr>
<td>5</td>
<td>2.25</td>
<td>54.187</td>
<td>7.86</td>
</tr>
</tbody>
</table>

Figure 91: Load Characteristic for Mitchell et al CFPCR Device.
10.3 Separation of Breast Cancer Cells from Peripheral Whole Blood [63]

Feng et al created three generations of cancer cell capturing devices. All the devices featured channels with rectangular cross sections. The first generation device had a width of 50 μm, a depth of 100 μm, and a length of 5 cm. The second generation device had a width of 20 μm, a depth of 70 μm, and a length of 10 cm. The third generation device featured 17 parallel microchannels with widths of 50 μm, depths of 120 μm, and a length of 5 cm. The load characteristic data is shown in Table 3 and the load characteristic curve is shown in Figure 92.

Table 3: Load characteristic data from Feng et al’s three generations of devices to separate breast cancer cells from peripheral whole blood.

<table>
<thead>
<tr>
<th></th>
<th>First Generation Device</th>
<th>Second Generation Device</th>
<th>Third Generation Device</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean Velocity (mm/s)</td>
<td>Flow Rate (μL/min)</td>
<td>Pressure Drop (kPa)</td>
<td>Pressure Drop (psi)</td>
</tr>
<tr>
<td>1</td>
<td>0.3</td>
<td>0.351</td>
<td>0.051</td>
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<td>0.102</td>
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<tr>
<td>3</td>
<td>0.9</td>
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<td>0.153</td>
</tr>
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<td>4</td>
<td>1.2</td>
<td>1.402</td>
<td>0.203</td>
</tr>
<tr>
<td>5</td>
<td>1.5</td>
<td>1.753</td>
<td>0.254</td>
</tr>
</tbody>
</table>

Figure 92: Load characteristic for 1st generation of the separation of cancer cells from blood.
10.4 High Throughput, 96 Well PCR Device [3, 4]

Chen et al developed a high throughput PCR platform that could perform n-cycles of CFPCR on 96 independent samples. The CFPCR reactors varied the residence time of the samples in the different temperature zones (Denaturation, Annealing, Extension) by changing the width of the channel from 20 μm to 40 μm. The channels had a rectangular cross-section and maintained a constant depth of 40 μm but the lengths varied for each temperature zone in the cycle. One cycle is one pass through the Denaturation, Annealing, and Extension temperature zones. The Denatureation zone had a length of 4843 μm and a width of 40 μm. The Annealing
The Denaturation zone had a length of 4843 μm and a width of 40 μm. The Extension zone had a 9686 μm and a width of 20 μm. The total pressure drop of the system is the addition of the pressure drops through the Denaturation, Annealing, and Extension zones times the number of cycles of the reaction. The two formats tested in [4] featured 20 cycles and 25 cycles. The flow rates tested in [4] included 0.048 μL/min, 0.096 μL/min, 0.144 μL/min, and 0.192 μL/min which corresponded to mean velocities of 1 mm/s, 2 mm/s, 3 mm/s, and 4 mm/s. The maximum efficiency of the device occurred at a flow rate of 0.048 μL/min. The load characteristic data is shown in Table 4 and Table 5 and the load characteristic curve is shown in Figure 95 and Figure 96.

Figure 95: The load characteristic for the 20 cycle high throughput, 96-well CFPCR device.
Table 4: The load characteristic data for the high throughput, 96 well PCR device with 20 cycles. The underlined numbers were the empirical parameters that represented the highest device efficiency.

<table>
<thead>
<tr>
<th>Mean Velocity (mm/s)</th>
<th>Flow Rate (μL/min)</th>
<th>Pressure Drop in Denaturation (kPa)</th>
<th>Pressure Drop in Annealing (kPa)</th>
<th>Pressure Drop in Extension (kPa)</th>
<th>Pressure Drop for 20 cycles (kPa)</th>
<th>Pressure Drop for 20 cycles (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.048</td>
<td>0.043</td>
<td>0.043</td>
<td>0.212</td>
<td>5.970</td>
<td>0.866</td>
</tr>
<tr>
<td>2</td>
<td>0.096</td>
<td>0.0863</td>
<td>0.0863</td>
<td>0.424</td>
<td>11.940</td>
<td>1.732</td>
</tr>
<tr>
<td>3</td>
<td>0.144</td>
<td>0.129</td>
<td>0.129</td>
<td>0.637</td>
<td>17.910</td>
<td>2.598</td>
</tr>
<tr>
<td>4</td>
<td>0.192</td>
<td>0.173</td>
<td>0.173</td>
<td>0.849</td>
<td>23.880</td>
<td>3.463</td>
</tr>
</tbody>
</table>

Table 5: The load characteristic data for the high throughput, 96 well PCR device with 25 cycles. The underlined numbers were the empirical parameters that represented the highest device efficiency.

<table>
<thead>
<tr>
<th>Mean Velocity (mm/s)</th>
<th>Flow Rate (μL/min)</th>
<th>Pressure Drop in Denaturation (kPa)</th>
<th>Pressure Drop in Annealing (kPa)</th>
<th>Pressure Drop in Extension (kPa)</th>
<th>Pressure Drop for 25 cycles (kPa)</th>
<th>Pressure Drop for 25 cycles (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.048</td>
<td>0.043</td>
<td>0.043</td>
<td>0.212</td>
<td>7.463</td>
<td>1.082</td>
</tr>
<tr>
<td>2</td>
<td>0.096</td>
<td>0.0863</td>
<td>0.0863</td>
<td>0.424</td>
<td>14.925</td>
<td>2.16</td>
</tr>
<tr>
<td>3</td>
<td>0.144</td>
<td>0.129</td>
<td>0.129</td>
<td>0.637</td>
<td>22.388</td>
<td>3.247</td>
</tr>
<tr>
<td>4</td>
<td>0.192</td>
<td>0.173</td>
<td>0.173</td>
<td>0.849</td>
<td>29.850</td>
<td>4.329</td>
</tr>
</tbody>
</table>
Figure 96: The load characteristic for the 25 cycle high throughput, 96-well CFPCR device.

10.5 Injection Molded CFPCR device

Chen et al design a continuous flow polymerase chain reaction microfluidic chip to be injection molded using the 3” multiple unit die. The width of the channel was 50 μm, the depth of the channel was 150 μm, and the length of the channel was 2.377 m. The load characteristic data is shown in Table 6 and the load characteristic curve is shown in Figure 97.

Table 6: The load characteristic data for the injection molded CFPCR device.

<table>
<thead>
<tr>
<th>Mean Velocity (mm/s)</th>
<th>Flow Rate (μL/min)</th>
<th>Pressure Drop (kPa)</th>
<th>Pressure Drop (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.45</td>
<td>14.472</td>
<td>2.10</td>
</tr>
<tr>
<td>2</td>
<td>0.9</td>
<td>28.945</td>
<td>4.20</td>
</tr>
<tr>
<td>3</td>
<td>1.35</td>
<td>43.417</td>
<td>6.30</td>
</tr>
<tr>
<td>4</td>
<td>1.8</td>
<td>57.889</td>
<td>8.40</td>
</tr>
<tr>
<td>5</td>
<td>2.25</td>
<td>72.362</td>
<td>10.5</td>
</tr>
</tbody>
</table>
Figure 97: The load characteristic of the injection molded CFPCR Device.
11 Assembling and Disassembling the 3in Mold Die

The numbers one through six are punched in the tops of each of the mold die plate and zero is stamped at the bottom of the mold die plates. Orient the 3 in mold die so that numbers 1-6 are visible.

Figure 98: The top of the 3in injection mold die.
11.1.1 Disassembling the A-side (plates 1 and 2)

1) Put on gloves to prevent getting hand oils on mold die. (will prevent rust)

2) Unscrew the Brass Extension plugs and roll a paper towel and stick it in each
    Thermolator hole on the A and B side to sop up some of the remaining water trapped in
    mold die from thermolator lines. (There is quite a bit of water that is deep inside the mold
    die and unable to be sopped up. Don’t worry about it.)

![Figure 99: Top of injection mold die.](image)

3) Unscrew bolts on holding ring with a 3/16” allen wrench and remove it.

![Figure 100: Front of the injection mold die.](image)

4) Unscrew (with a 3/16” allen wrench) 3 bolts behind the locating ring which hold the
    thermoblock assembly to plate 1 and remove the screws.
5) Unscrew the 4 bolts (with a 3/8” allen wrench) holding plate 1 together with plate 2.

6) Line up brass plug with the cold sprue and tap it to get the cold sprue out of the mold insert. Twist and pull on the back of the cold sprue. Leave the cold sprue partially lodged in plate 1.
Figure 103: Images showing the removal process of the cold sprue.

7) Set plate 1 aside and this is the front of plate 2.

Figure 104: A-side of the mold die.

8) Hold hand in front of insert and hit back of spacer plate with hammer until 3in insert an thermoblock come out. Leave spacer plate partially lodged in plate 2.
9) Unscrew 4 bolts on the back of thermoblock with 7/64” allen wrench to release the mold insert.

11.1.2 Assembling the A-side

1) Take plate 2 with numbers facing up and take out the partially lodged spacer plate.

Figure 105: Images showing the process to remove the a-side thermal assembly.

Figure 106: Images showing the assembly process of the a-side.
2) Line up the up side of the mold insert and thermoblock together. The thermoblock should have bolt pattern with upside down triangle. (Check and make sure you can push the cold sprue through the mold insert hole with only your hands. It should have a snug fit.)

3) Loosely bolt the mold insert to the thermoblock using the four 7/64” bolts. Needs to have a little bit of movement to make your life easier.

Figure 107: Back side of the a-side thermal block.

4) Insert the partially bolted assembly into the back of plate 2.

Figure 108: Assembling the a-side.

5) Hold hand on the other side of mold to catch just in case assembly decides to slide freely.
6) Evenly push with hand and or tap with rubber hammer until thermoblock is even with the back of plate 2 or just a bit past.

Figure 109: Assembling the a-side.

7) Tighten 4 bolts on the thermoblock with 7/64 allen wrench until snug but do not over tighten or you will strip the threads in the brass insert and have to re-tap it. If you can’t get it snug, the threads are stripped and you must re-tap the hole.

Figure 110: Assembling the a-side.
8) Orient spacer plate with bolt holes in triangle down orientation and insert spacer plate into back of plate 2 and push with hand until flush.

Figure 111: Assembling the a-side.

9) Wipe faces of plate 1 and plate 2 with Kimtech Kimwipes and orient the back of plate 1 to face the front of plate 2. Make sure the cold sprue is partially lodged in plate 1.

Figure 112: Assembling the a-side.

10) Take plate 1 and align with plate 2 and then push them together.
11) Insert the three 3/16 bolts through the back of plate 1 and then tighten them a few turns so that they are still loose. Be sure to tighten them evenly.

12) Then insert the four 3/8 bolts and tighten them completely. Be sure to tighten the bolts evenly. ½ a turn on each in a rotating fashion.
13) Now finish tightening the 3/16 bolts and push on the front of the insert to make sure it is flush with the back of plate 2.

14) Orient the holding ring around the cold sprue and on the front of plate 1. Line up the tapered holes with the horizontal tapped holes.
15) Insert tapered 3/16 allen screws into the holding ring tapered holes and tighten.

![Assembling the a-side.](image)

Figure 118: Assembling the a-side.

16) Use orange plastic hammer to lightly tap the front of the cold sprue until its back is flush with the back of plate 2. Put your hand on the front to prevent sliding of the insert/press fit assembly.

17) If you can’t get the cold sprue past the mold insert, do not worry. The nozzle of the machine will push it in.

11.1.3 Disassembling the B-side

1) Unscrew the four 3/8 allen bolts on the back side of plate 6 by placing the allen wrench in the bolt and then tapping on it with the orange plastic hammer to loosen the bolts and then loosen them completely. (These bolts hold together plates 6, 5, 4, and 3) Remove the 3/8 allen bolts and place them to the side.
Figure 119: Disassembling the b-side.

2) Insert flat head screw driver into cutouts on the top in between plate 5 and plate 4 and use a hammer to pry the plates apart.

Figure 120: Disassembling the b-side.

3) Remove plates 5 and 6 and remove the Ejector plate assembly from plate 4.

Figure 121: Disassembling the b-side.
4) Unscrew three 3/16 bolts on the back of plate 4.

Figure 122: Disassembling the b-side.

5) Pull plates 3 and 4 apart.

Figure 123: Disassembling the b-side.

6) Use orange hammer to tap on back side of spacer plate until the mold insert is completely hanging out of the front side.

Figure 124: Disassembling the b-side.
7) Unscrew the two 9/64 bolts on the back of the spacer plate.

![Figure 125: Disassembling the b-side.](image)

8) Take out the Thermoblock and mold insert assembly

![Figure 126: Disassembling the b-side.](image)

9) Unscrew the two 3/32 bolts on the back side of the thermoblock assembly
10) Remove the mold insert

11.1.4 Assembling the B-side

1) If spacer plate, Insulation plate and shim plate are still lodged in the mold plate 3, tap the back of the spacer plate and the shim plate will fallout of the front.

2) Then tap on the front of the insulation plate until it pushes out the spacer plate and then the insulation plate.
3) Orient the spacer plate and the insulation plate so that they form an upside down triangle with their bolt patterns and the spacer plate’s counter sink holes are visible. Align those two bolt patterns together and place two 9/64 bolts in the inner most two vertical counter sunk holes.

4) Orient the brass mold insert so that the two 3/32 allen bolt holes are horizontal. Orient the thermoblock so that the counter sunk holes are facing you and the inner 9/64 allen bolt holes are vertical.
Figure 131: Back side of the b-side mold insert.

5) In the previously set orientation place the thermoblock on top of the mold insert and align their 3/32 bolt holes.

Figure 132: Back side of the b-side thermal block and mold insert.
6) Insert two 3/32 bolts into the outer most counter sunk holes and tighten them together but do not over tighten or you will strip the thread.

![Image](image1.png)

Figure 133: Assembling the b-side thermal assembly.

7) Take the locating ring and cold sprue out of plate 1 and lay plate 1/plate2 assembly with insert face up.

![Image](image2.png)

Figure 134: Assembling the b-side.

8) Take the thermoblock/mold insert assembly and align the alignment structures on the two mold inserts. The cartridge heater holes on the thermoblock should be oriented parallel to the I-bolt directly above the mold insert assembly. Place wooden wedges on the face of plate 2.
9) With plate 3 oriented its punch on the top left corner, attach four 3/8 bolts to the back of it and, with two people, slowly lower it onto the locating pins of plate 2 until it reaches the wedges or gets stuck on the locating pins.
10) If plate 3 becomes stuck on the locating pins, place a 2x4 across the top and tap on the 2x4 with a hammer until it slides down to the wedges. When it gets to the wedges, one person carefully removes the wedges while the other person supports plate 3 to prevent it from falling on the first person’s fingers.

![Assembling the b-side](image1)

**Figure 137:** Assembling the b-side.

11) Plate 3 should slide down until it makes contact with plate 2. If it does not, tap on the 2x4 with a plastic hammer until plate 3 is flush with plate 2. Then unscrew the four 3/8 bolts.

![Assembling the b-side](image2)

**Figure 138:** Assembling the b-side.

12) Place the shim plate in the cavity and make sure the bolt holes line up with the inner vertical bolt holes on the thermoblock.
13) Orient the insulation plate so that the outer through holes form an upside down triangle and fit it in the cavity. Tap on it with a hammer until just before it is flush with the shim plate. Use a flat head screw driver through the center hole to push the shim plate so that the shim plate through holes line up with the thermoblock holes. Tap the insulation plate until it reaches the shim plate. Readjust the shim plate with the flat head screw driver if needed.
14) Orient the spacer plate with counter sunk holes up and with the outer most tapped hole in an upside down orientation. Place the spacer plate in the cavity and use the plastic hammer to tap it until it is flush with the mold die surface. Place two 9/64 bolts in the inner most counter sunk holes and tighten them but do not overtighten them.

Figure 141: Assembling the b-side.

15) Stand up the plate 1/plate 2/plate 3 assembly and place plate 4 adjacent so that all the plate numbers are aligned and on the top left corner. Push plate 4 and 3 together. Insert three 3/16 bolts in the back of plate 4 and tighten them.

Figure 142: Assembling the b-side.
16) Bring over two wedges and the ejector plate assembly. Orient the ejector plate assembly so that the up punches are visible on the ejector plates. Slide the wedges under the ejector plate and use them to get the ejector plate to the correct height so that you can fit the ejector pin and the ejector back pins in their holes on the back of plate 4. Need to constantly readjust all the pins individually so that they line up with the holes. When they all line up you can easily push the ejector plate up to rest on the leader pins.
17) Use the plastic hammer to bring the ejector plate as far forward as it will go. Then orient the plate 5/plate 6 assembly so that its plate numbers are in the top left corner and push it until it is flush with or about an 1/8” from plate 4.

![Assembling the b-side.](image1)

Figure 145: Assembling the b-side.

18) Place the four 3/8 bolts in the back of plate 6 and tighten until snug.
19) Insert the cold sprue into the front of plate 1 and follow the “put the A side back together” instructions 14-17 (featured earlier in this document) to attach the locating ring and hammer in the cold sprue.
12 Loading and Unloading Mold Die into the Injection Molding Machine

1) Ensure machine platens are fully in Mold Open position

Figure 147: Shows the injection molding machine plenums fully open.

2) Place mold safety strap on mold die

Figure 148: Proper position of the safety strap.
3) Lift mold die into space between machine platens using engine hoist

Figure 149: The mold die being installed into the injection molding machine.

4) Place tie bar protectors onto tie bars
5) Carefully lower mold die between tie bars with sprue side facing A-side of machine

6) Maneuver mold’s locating ring into A-side platen
Figure 152: Loading the mold die into the injection molding machine.
7) Install mold die clamps and tighten down and torque-set A-side mold bolts

Figure 153: Loading the mold die into the injection molding machine.
Figure 154: Loading the mold die into the injection molding machine.

8) Unhook hoist chain and move hoist

Figure 155: Loading the mold die into the injection molding machine.

9) Install ejector rod in back of B-side of the mold die
10) Close gate/door and close mold die in manual operating mode (p. 130)
11) Install clamps and torque-set bolts on B-side of mold

Figure 158: Installing the mold die clamps.

12) In setting mode, bring the machine ejector plate forward to touch ejector rod. Then attach the Ejector Rod to Ejector plate on machine using bolt, black spacer, and lock washer. Hand tighten the bolt.

Figure 159: Attaching the ejector rod to the ejector plate.
13) Remove safety strap

Figure 160: Attaching the ejector rod to the ejector plate.

Figure 161: Location of the safety strap.
14) Close gate and switch to manual operating mode (p. 130)

15) Open mold in manual mode

16) Switch back to setting mode

17) Set zero offset for ejector pins

18) Switch back to manual mode
13 Injection Molding Parameters

13.1 5 μm Insert (Parameters at the start of injection molding 5 μm insert)

13.1.1 Barrel Temperatures (°F)

Table 7: 5 micron insert barrel temperatures.

<table>
<thead>
<tr>
<th>Barrel Heater</th>
<th>Set Temperature (°F)</th>
<th>Allowable Range of Variation (°F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nozzle</td>
<td>500</td>
<td>+21</td>
</tr>
<tr>
<td>Zone 1</td>
<td>527</td>
<td>+15</td>
</tr>
<tr>
<td>Zone 2</td>
<td>509</td>
<td>+15</td>
</tr>
<tr>
<td>Zone 3</td>
<td>491</td>
<td>+15</td>
</tr>
<tr>
<td>Zone 4</td>
<td>140</td>
<td>+20</td>
</tr>
</tbody>
</table>

13.1.2 Clamping Force

Clamping Force 10 short tons
Start Clamping Force Buildup 0.04 in

13.1.3 Injection Table

Table 8: 5 micron insert injection table.

<table>
<thead>
<tr>
<th>Profile Point</th>
<th>Volume of Polymer in Barrel (cuin)</th>
<th>Velocity (cuin/s)</th>
<th>Volume of Polymer in Barrel (cuin)</th>
<th>Maximum Pressure (Alarm) (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. PP</td>
<td>0.950</td>
<td>6.200</td>
<td>0.95</td>
<td>8000</td>
</tr>
<tr>
<td>2. PP</td>
<td>0.900</td>
<td>5.00</td>
<td>0.4</td>
<td>8000</td>
</tr>
<tr>
<td>3. PP</td>
<td>0.400</td>
<td>2.500</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7. PP</td>
<td>0</td>
<td>1.000</td>
<td>0</td>
<td>8000</td>
</tr>
</tbody>
</table>

Delay 1 sec
Peak injection pressure 2176 psi
13.1.4 Holding Pressure Table

Table 9: 5 micron insert holding pressure table.

<table>
<thead>
<tr>
<th>Profile Points</th>
<th>Time (s)</th>
<th>Pressure (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. PP</td>
<td>0</td>
<td>2300</td>
</tr>
<tr>
<td>2. PP</td>
<td>0.1</td>
<td>2300</td>
</tr>
<tr>
<td>3. PP</td>
<td>1.25</td>
<td>2000</td>
</tr>
<tr>
<td>4. PP</td>
<td>3.00</td>
<td>2000</td>
</tr>
<tr>
<td>5. PP</td>
<td>5.00</td>
<td>1000</td>
</tr>
<tr>
<td>Holding Pressure Time</td>
<td>10.00</td>
<td>0</td>
</tr>
</tbody>
</table>

Switchover to holding pressure at volume 0.625 cuin
Cooling time 0 sec

13.1.5 Metering

Table 10: 5 micron insert metering.

<table>
<thead>
<tr>
<th>Profile Points</th>
<th>Volume (cuin)</th>
<th>Circum-v</th>
<th>Volume (cuin)</th>
<th>Backpressure (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. PP</td>
<td>0</td>
<td>6.0</td>
<td>0</td>
<td>1000</td>
</tr>
<tr>
<td>2. PP</td>
<td>0.75</td>
<td>6.0</td>
<td>0.75</td>
<td>1000</td>
</tr>
<tr>
<td>Metering Volume</td>
<td>0.85</td>
<td>0</td>
<td>0.85</td>
<td>0</td>
</tr>
</tbody>
</table>

Delay 3 sec
Decompression
   After metering volume 0.100 cuin 2 cuin/s
13.2 25 μm Insert (Parameters at the start of injection molding 25 μm insert)

13.2.1 Barrel Temperatures (°F)

Table 11: 25 micron insert barrel temperatures.

<table>
<thead>
<tr>
<th>Barrel Heater</th>
<th>Set Temperature (°F)</th>
<th>Allowable Range of Variation (°F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nozzle</td>
<td>500</td>
<td>+21 -10</td>
</tr>
<tr>
<td>Zone 1</td>
<td>527</td>
<td>+15 -15</td>
</tr>
<tr>
<td>Zone 2</td>
<td>509</td>
<td>+15 -15</td>
</tr>
<tr>
<td>Zone 3</td>
<td>491</td>
<td>+15 -15</td>
</tr>
<tr>
<td>Zone 4</td>
<td>140</td>
<td>+20 -20</td>
</tr>
</tbody>
</table>

13.2.2 Clamping Force

Clamping Force 10 short tons

Start Clamping Force Buildup 0.04 in

13.2.3 Injection Table

Table 12: 25 micron insert injection table.

<table>
<thead>
<tr>
<th>Profile Point</th>
<th>Volume of Polymer in Barrel (cuin)</th>
<th>Velocity (cuin/s)</th>
<th>Volume of Polymer in Barrel (cuin)</th>
<th>Maximum Pressure (Alarm) (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. PP</td>
<td>0.950</td>
<td>5.000</td>
<td>0.95</td>
<td>8000</td>
</tr>
<tr>
<td>2. PP</td>
<td>0.900</td>
<td>3.000</td>
<td>0.4</td>
<td>8000</td>
</tr>
<tr>
<td>3. PP</td>
<td>0.400</td>
<td>2.000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7. PP</td>
<td>0</td>
<td>1.000</td>
<td>0</td>
<td>8000</td>
</tr>
</tbody>
</table>

Delay 1 sec

13.2.4 Holding Pressure Table

Table 13: 25 micron insert holding pressure table.

<table>
<thead>
<tr>
<th>Profile Points</th>
<th>Time (s)</th>
<th>Pressure (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. PP</td>
<td>0</td>
<td>2000</td>
</tr>
<tr>
<td>Profile Points</td>
<td>Volume (cuin)</td>
<td>Circum-v</td>
</tr>
<tr>
<td>---------------</td>
<td>--------------</td>
<td>----------</td>
</tr>
<tr>
<td>1. PP</td>
<td>0</td>
<td>6.0</td>
</tr>
<tr>
<td>2. PP</td>
<td>0.75</td>
<td>6.0</td>
</tr>
</tbody>
</table>

Metering Volume

| Holding Pressure Time | 10.00 | 0 |

Switchover to holding pressure at volume 0.625 cuin

Cooling time 15 sec

13.2.5 Metering

Table 14: 25 micron insert metering table.

Delay 3 sec
Decompression
After metering volume 0.100 cuin 2 cuin/s

13.3 50 µm Insert (Parameters at the start of injection molding 50 µm insert)

13.3.1 Barrel Temperatures (ºF)

Table 15: 50 micron insert barrel temperatures.

<table>
<thead>
<tr>
<th>Barrel Heater</th>
<th>Set Temperature (ºF)</th>
<th>Allowable Range of Variation (ºF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nozzle</td>
<td>495</td>
<td>+21 -10</td>
</tr>
<tr>
<td>Zone 1</td>
<td>527</td>
<td>+15 -15</td>
</tr>
<tr>
<td>Zone 2</td>
<td>509</td>
<td>+15 -15</td>
</tr>
<tr>
<td>Zone 3</td>
<td>491</td>
<td>+15 -15</td>
</tr>
</tbody>
</table>
13.3.2 Clamping Force

Clamping Force 9 short tons

Start Clamping Force Buildup 0.04 in

13.3.3 Injection Table

Table 16: 50 micron insert injection table

<table>
<thead>
<tr>
<th>Profile Point</th>
<th>Volume of Polymer in Barrel (cuin)</th>
<th>Velocity (cuin/s)</th>
<th>Volume of Polymer in Barrel (cuin)</th>
<th>Maximum Pressure Alarm Settings</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. PP</td>
<td>0.950</td>
<td>4.750</td>
<td>0.95</td>
<td>3000</td>
</tr>
<tr>
<td>2. PP</td>
<td>0.900</td>
<td>3.000</td>
<td>0.4</td>
<td>3000</td>
</tr>
<tr>
<td>3. PP</td>
<td>0.400</td>
<td>2.000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7. PP</td>
<td>0</td>
<td>1.000</td>
<td>0</td>
<td>3000</td>
</tr>
</tbody>
</table>

Delay 0.5 sec

13.3.4 Holding Pressure Table

Table 17: 50 micron insert holding pressure table.

<table>
<thead>
<tr>
<th>Profile Points</th>
<th>Time (s)</th>
<th>Pressure (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. PP</td>
<td>0</td>
<td>2000</td>
</tr>
<tr>
<td>2. PP</td>
<td>0.1</td>
<td>2000</td>
</tr>
<tr>
<td>3. PP</td>
<td>1.25</td>
<td>2000</td>
</tr>
<tr>
<td>4. PP</td>
<td>3.00</td>
<td>2000</td>
</tr>
<tr>
<td>5. PP</td>
<td>5.00</td>
<td>1000</td>
</tr>
</tbody>
</table>

Holding Pressure Time 15.00
Switchover to holding pressure at volume 0.625 cuin

Cooling time 10 sec

13.3.5 Metering

Table 18: 50 micron metering table.

<table>
<thead>
<tr>
<th>Profile Points</th>
<th>Volume (cuin)</th>
<th>Circum-v</th>
<th>Volume (cuin)</th>
<th>Backpressure (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. PP</td>
<td>0</td>
<td>6.0</td>
<td>0</td>
<td>1200</td>
</tr>
<tr>
<td>2. PP</td>
<td>0.75</td>
<td>6.0</td>
<td>0.75</td>
<td>1200</td>
</tr>
</tbody>
</table>

Metering Volume 0.85 0 0.85 0

Delay 2 sec
Decompression
After metering volume 0.100 cuin 2 cuin/s

13.4 100 μm Insert (Parameters at the start of injection molding 100 μm insert)

13.4.1 Barrel Temperatures (°F)

Table 19: 100 micron insert barrel temperatures.

<table>
<thead>
<tr>
<th>Barrel Heater</th>
<th>Set Temperature (°F)</th>
<th>Allowable Range of Variation (°F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nozzle</td>
<td>495</td>
<td>+21</td>
</tr>
<tr>
<td>Zone 1</td>
<td>527</td>
<td>+15</td>
</tr>
<tr>
<td>Zone 2</td>
<td>509</td>
<td>+15</td>
</tr>
<tr>
<td>Zone 3</td>
<td>491</td>
<td>+15</td>
</tr>
<tr>
<td>Zone 4</td>
<td>140</td>
<td>+20</td>
</tr>
</tbody>
</table>

13.4.2 Clamping Force

Clamping Force 11 short tons

Start Clamping Force Buildup 0.04 in

13.4.3 Injection Table

Table 20: 100 micron insert injection table.

<table>
<thead>
<tr>
<th>Injection Profile Parameters</th>
<th>Maximum Pressure Alarm Settings</th>
</tr>
</thead>
</table>

167
### Table 1: Profile Points and Volume Parameters

<table>
<thead>
<tr>
<th>Profile Point</th>
<th>Volume of Polymer in Barrel (cuin)</th>
<th>Velocity (cuin/s)</th>
<th>Volume of Polymer in Barrel (cuin)</th>
<th>Maximum Pressure (Alarm) (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. PP</td>
<td>0.950</td>
<td>5.000</td>
<td>0.95</td>
<td>3000</td>
</tr>
<tr>
<td>2. PP</td>
<td>0.900</td>
<td>3.000</td>
<td>0.4</td>
<td>3000</td>
</tr>
<tr>
<td>3. PP</td>
<td>0.400</td>
<td>2.000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7. PP</td>
<td>0</td>
<td>1.000</td>
<td>0</td>
<td>3000</td>
</tr>
</tbody>
</table>

Delay 0.5 sec

### 13.4.4 Holding Pressure Table

Table 21: 100 micron holding pressure table.

<table>
<thead>
<tr>
<th>Profile Points</th>
<th>Time (s)</th>
<th>Pressure (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. PP</td>
<td>0</td>
<td>1900</td>
</tr>
<tr>
<td>2. PP</td>
<td>0.1</td>
<td>1950</td>
</tr>
<tr>
<td>3. PP</td>
<td>1.25</td>
<td>1950</td>
</tr>
<tr>
<td>4. PP</td>
<td>3.00</td>
<td>1950</td>
</tr>
<tr>
<td>5. PP</td>
<td>5.00</td>
<td>1000</td>
</tr>
<tr>
<td>Holding Pressure Time</td>
<td>15.00</td>
<td>0</td>
</tr>
</tbody>
</table>

Switchover to holding pressure at volume 0.625 cuin

Cooling time 10 sec

### 13.4.5 Metering

Table 22: 100 micron insert metering table.

<table>
<thead>
<tr>
<th>Profile Points</th>
<th>Volume (cuin)</th>
<th>Circum-v</th>
<th>Volume (cuin)</th>
<th>Backpressure (psi)</th>
</tr>
</thead>
</table>

168
1. PP  
   Metering Volume 0.85  
   2. PP  
   Metering Volume 0.85  
   Delay 2 sec  
   Decompression  
   After metering volume 0.100 cuin 2 cuin/s  

13.5 Re-manufactured 50 μm Insert (Parameters at the start and finish of injection molding the re-manufactured 50 μm insert)

13.5.1 Barrel Temperatures (°F)

Table 23: Re-manufactured 50 micron insert barrel temperatures.

<table>
<thead>
<tr>
<th>Barrel Heater</th>
<th>Set Temperature (°F)</th>
<th>Allowable Range of Variation (°F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nozzle</td>
<td>500</td>
<td>+21 -10</td>
</tr>
<tr>
<td>Zone 1</td>
<td>527</td>
<td>+15 -15</td>
</tr>
<tr>
<td>Zone 2</td>
<td>509</td>
<td>+15 -15</td>
</tr>
<tr>
<td>Zone 3</td>
<td>491</td>
<td>+15 -15</td>
</tr>
<tr>
<td>Zone 4</td>
<td>140</td>
<td>+20 -20</td>
</tr>
</tbody>
</table>

13.5.2 Clamping Force

Clamping Force 9 short tons  
Start Clamping Force Buildup 0.04 in  

13.5.3 Injection Table

Table 24: Re-manufactured 50 micron insert injection table.

<table>
<thead>
<tr>
<th>Injection Profile Parameters</th>
<th>Maximum Pressure Alarm Settings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Profile Point</td>
<td>Volume of Polymer in Barrel (cuin)</td>
</tr>
<tr>
<td>1. PP</td>
<td>0.950</td>
</tr>
<tr>
<td>Profile Points</td>
<td>Time (s)</td>
</tr>
<tr>
<td>----------------</td>
<td>----------</td>
</tr>
<tr>
<td>1. PP</td>
<td>0</td>
</tr>
<tr>
<td>2. PP</td>
<td>0.1</td>
</tr>
<tr>
<td>3. PP</td>
<td>1.25</td>
</tr>
<tr>
<td>4. PP</td>
<td>3.00</td>
</tr>
<tr>
<td>5. PP</td>
<td>5.00</td>
</tr>
<tr>
<td>Holding Pressure Time</td>
<td>15.00</td>
</tr>
</tbody>
</table>

Switch over to holding pressure at volume 0.625 cuin

Cooling time 10 sec

### 13.5.5 Metering

Table 26: Re-manufactured 50 micron insert metering table.

<table>
<thead>
<tr>
<th>Profile Points</th>
<th>Volume (cuin)</th>
<th>Circum-v</th>
<th>Volume (cuin)</th>
<th>Backpressure (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. PP</td>
<td>0</td>
<td>6.0</td>
<td>0</td>
<td>1200</td>
</tr>
<tr>
<td>2. PP</td>
<td>0.75</td>
<td>6.0</td>
<td>0.75</td>
<td>1200</td>
</tr>
<tr>
<td>Metering Volume</td>
<td>0.85</td>
<td>0</td>
<td>0.85</td>
<td>0</td>
</tr>
</tbody>
</table>
Delay 2 sec
Decompression
  After metering volume  0.100 cuin  2 cuin/s
14 Layouts of Injection Mold Inserts

14.1 Motivation

The modified pressure test experiments used injection molding to manufacture the polymer chips. This manufacturing technique was selected to increased repeatability of the location, size, and shape of the chips alignment features and through-holes. The design of the mold inserts were based on the microset lab standards (Louisiana State University) developed for the lab’s 3 inch mold die. These experiments utilized the world-to-chip press fit fluidic interconnection developed by Dr. Taehyun Park between a 1/16” OD x 0.03” ID fluorinated ethylene propylene (FEP) tubing (1520, Upchurch Scientific, Oak Harbor, WA) capillary tube and a through holes and kinematic structures developed by Dr. Byoung Hee You (to align the adjacent through-holes and set the gap distance) to speed up the assembly process. Kinematic alignment standards were measured using the Nikon Measurescope MM-11 (Melville, NY) with a Diagnostic Instruments, Inc. microscope camera (Sterling Heights, MI), and SPOT Advanced Imaging Software to quantify misalignment in the assembly. The a-side and b-side mold inserts were milled from ½” and 3/8” thick sheets of (Alloy 353) brass using conventional metal removal techniques for rough machining and micromilling to create the cavity features and a-side and b-side mold insert alignment structures.

14.2 3in Mold Die Overview

In the late 1990’s, the 3 inch modular mold die was designed and build by CoorsTek in conjunction with Louisiana State University students as a prototype mold die platform to allow for the fabrication of inexpensive, interchangeable (modular), low production, microstructured mold cavities to produce ceramic and polymer microstructured parts. Traditionally, mold dies are manufactured completely from tool steel and designed to produce large volumes of a single part design. This design leads to a more integrated approach to designing the die. For instance, the
cavity of the mold die is machined directly into one of the tool steel plates in the die, and the
ejector rod placement is specifically designed for the die. This approach is excellent at producing
millions of parts on one die but is cost prohibitive for the iterative design purposes of research.
The 3 inch mold die developed for the µset lab modified a standard size injection mold die to
accept a modular cavity assembly on the a-side and b-side of the mold die. The reasoning for
modifying a standard size mold die was availability of the standard mold die bases, the ability of
the mold die to withstand the clamping force without yielding, and the ease of attachment to
standard injection molding plenums and equipment (themolator, cold sprues, clamps, ejector
rods). The modular interchangeable components of the modular cavity included the spacer plate,
the insulation plate, the thermal block, and mold insert. The spacer plate allows for adjustment of
height of the mold insert. The insulation plate reduces the heat transferred to the injection mold
die and allows the mold inserts to reach higher temperatures for lower power input. The thermal
block’s capacitance and high thermal conductivity creates a constant temperature boundary
condition for the mold insert cavity. The interchangeable mold inserts decoupled the mold die
base design from the design of the mold insert cavity (a novel invention) allowing the µset lab to
leverage all additive and subtractive manufacturing techniques available to create mold cavities
in the mold inserts.

14.3 µSET Lab Standards for 3in Mold Die Inserts

Over the years, the µSET lab has developed standards for the designs of 3 inch mold
inserts to enable faster turnaround times for the designs and higher initial success for mold insert
designs. These standards build upon previous µSET students’ successful injection molding insert
designs. The a-side inserts and b-side inserts have different standardized features in their designs.
The a-side standard features are the insert-level alignment pins (pins have standard diameters of
0.07874 inches (2mm) rising 1.6 mm above the insert thickness of 0.365 inches placed on
vertices of square with center coincident with the insert’s center and edge length of 2.3622 in. (60 mm)), the through-hole for the cold sprue (center of through-hole is coincident with insert center and has standard diameter of 0.750 in. (19.05 mm), the four blind tapped 6-32 holes for mounting the insert to the thermal assembly (placed on vertices of square with center coincident with the insert’s center and edge length of 1.5 in. (38.1mm)), the four blind tapped 4-40 holes for mounting the insert to the KERN micromilling machine (placed 1.25 in. away from center at 0°, 90°, 180°, and 270°), and the length (2.990 in. (75.946 mm)), width (2.990 in. (75.946 mm)), and thickness dimensions (0.365 in. (9.271 mm)). The b-side standard features include the reamed 3/8” hole for the ejector pin (with center coincident with the insert center), the four mold insert alignment slots (slot with radius of 0.039567 in. (1.005 mm) and 0.03937 in. (1.000 mm) between the centers of the semicircles with slot axes pointed toward the center of the insert and have a depth of 0.07086 in. (1.8 mm)), the 0.07362 in. (1.87 mm) deep cavity that has a 45° taper from a diameter of 2.58626 in. (65.691 mm) at the bottom of the cavity to a diameter of 2.67717 in. (68 mm) at the top of the cavity, a 0.7804 in. (19.8222 mm) flat (located 1.28032 in. (32.52 mm) away from the center of the insert at 270°), the length (2.900 in. (73.66 mm)), width (2.900 in. (73.66 mm)), and thickness dimensions (0.3650 in. (9.271 mm). This 45° taper is created using a 5 mm diameter solid carbide 90° two flute spotting drill mounted in the micromilling machine. This taper makes it easier to eject (de-mold) parts by reducing de-molding forces along the rim of the part. The cavity is always on the b-side of the insert because the molded part needs to stick on the b-side after the polymer solidifies because the ejector pins are located on this side of the mold die. The ejector pins are located on this side of the mold die because this is the standard side of the injection molding machine for the injection molding
machine’s ejector rod assembly that actuates the ejector plate with the ejector pin. The drawings for these standard 3in mold inserts are shown in Figure 163-Figure 166.

The material used was alloy 353 brass which is a highly leaded engravers brass that can be purchased through McMaster Carr. Two sheets of alloy 353 need to be purchased to create both a-side and b-side mold inserts. A 3/8” thick sheet is used to make b-side inserts and a 1/2” sheet is used to make a-side inserts (due to the insert-level alignment pins). This material is the lab standard material used for inserts because it is easily machined. Other harder materials could be used in future work provided that the micromachinist reconnects the coolant to the KERN micromilling machine. Harder materials are less prone to damage due to accidental scratching and will have a longer part lifespan (greater than 100 parts) than alloy 353.

Figure 163: 5 μm B-side mold insert design.
Figure 164: 25 μm B-side mold insert design.

Figure 165: 50 micro B-side mold insert design.
Figure 166: 100 micro B-side mold insert design.
15 Injection Holding Time Experiment

When injection molding a part, standard practice dictates that approximately 95% of the part volume is filled by the injection parameters and 5% of the part volume is filled with the holding parameters. The switchover from injection volume flow control to holding pressure control can be triggered by time, volume, or injection pressure. The standard practice in industry is to use the switchover by time parameter to locate a good volume (a volume that creates a partially filled part (a “short”)) to use as a switchover point. This is achieved by setting the holding pressure to 0 psi for all profile points and switchover time to a time that is higher than necessary (i.e. 1 sec) to create a full part and then for each successive part reducing the switchover time (by 0.1 increments) until a part is produced that is about 95% filled. The machine measures and reports the volume of polymer injected into the cavity on the holding pressure page. The volume recorded by the machine for the 95% filled part should be recorded and then entered into the switchover by volume setting on the holding pressure page. The machine should then be switched to switchover by volume for all future parts. The next step is to find out how much holding pressure to use. The goal is to match the holding pressure value to the injection pressure value at the switchover point. The injection molding machine displays graph of the melt pressure that is helpful in determining this value. It is an iterative process to select a stable holding pressure value. The next step is to determine the holding time for the part. For each new mold insert design, experiments must be run to determine the length of time necessary for the mass of the part to converge. Table 27 shows the masses of parts from five different holding times: 2.5 seconds, 5 seconds, 10 seconds, 15 seconds, and 20 seconds. Figure 167 shows the average mass of the parts at the five levels of holding pressure.
Table 27: Holding time experiments to determine when mass converges. (Mass of parts in grams)

<table>
<thead>
<tr>
<th>Sample #</th>
<th>Holding time = 2.5 seconds Mass in grams</th>
<th>Holding time = 5 seconds Mass in grams</th>
<th>Holding time = 10 seconds Mass in grams</th>
<th>Holding time = 15 seconds Mass in grams</th>
<th>Holding time = 20 seconds Mass in grams</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7.6741</td>
<td>7.8073</td>
<td>7.8228</td>
<td>7.8412</td>
<td>7.8549</td>
</tr>
<tr>
<td>2</td>
<td>7.6542</td>
<td>7.8106</td>
<td>7.8313</td>
<td>7.8403</td>
<td>7.8482</td>
</tr>
<tr>
<td>3</td>
<td>7.6689</td>
<td>7.815</td>
<td>7.8195</td>
<td>7.8368</td>
<td>7.8565</td>
</tr>
<tr>
<td>4</td>
<td>7.6599</td>
<td>7.8138</td>
<td>7.8192</td>
<td>7.8357</td>
<td>7.8503</td>
</tr>
<tr>
<td>5</td>
<td>7.6478</td>
<td>7.8125</td>
<td>7.8224</td>
<td>7.8413</td>
<td>7.8486</td>
</tr>
<tr>
<td>6</td>
<td>7.6553</td>
<td>7.8105</td>
<td>7.8271</td>
<td>7.8383</td>
<td>7.8544</td>
</tr>
<tr>
<td>7</td>
<td>x</td>
<td>7.8145</td>
<td>7.8188</td>
<td>7.8669</td>
<td>7.8543</td>
</tr>
<tr>
<td>8</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>7.8501</td>
</tr>
<tr>
<td>St. Dev.</td>
<td>0.009824391</td>
<td>0.002739656</td>
<td>0.004662</td>
<td>0.010789</td>
<td>0.003207</td>
</tr>
<tr>
<td>Mean</td>
<td>7.660033333333333</td>
<td>7.812028571</td>
<td>7.823014</td>
<td>7.842929</td>
<td>7.852163</td>
</tr>
</tbody>
</table>

Figure 167: Plot of the average mass of parts produced at five different holding times. Mass is in grams.
16 Preliminary Pressure Test Experimental Assembly

The superhydrophobic portions of these two samples were each sawed into four approximately equal pieces (~2cm x 2 cm) using a MicroLux Tools Tablesaw (Berkeley Heights, NJ). Through-holes were drilled in the middle of these superhydrophobic surfaces approximately 1 mm from the edge with a #67 jobber drill bit using the MicroLux Tools variable speed miniature drill press (Berkeley Heights, NJ). Four 5 inch sections of Upchurch Scientific (Oak Harbor, WA) 1/32 x 0.0035 inch PEEK capillary tubing were cut and attached to the PMMA side of the through-holes about half way through the samples of four of the samples (two from the sample with contact angle 147° ±22° and two from the sample with contact angle of 144° ±14°) using Pacer Z-Poxy 5 minute resin and hardener (Rancho Cucamonga, CA). Precision color coded shims from Precision Brand (Downers Grove, IL), 25 µm and 102 µm in thickness were each cut with scissors into four pairs of 5 mm by 10 mm strips. One pair of these strips was placed adjacent to the through-hole on the superhydrophobic surface of each of the samples with attached capillary tube. An additional 2 inch piece of 1/32 x 0.0032 inch PEEK tubing was used to concentrically align the top and bottom superhydrophobic sample through-holes. Using this 2” piece of 1/32 inch tube, the two superhydrophobic surfaces were both brought into contact with the shims and two Staples Brand (Framingham, MA) 3/5” mini binder clips were used to hold the samples in a fixed orientation. The binder clip contacts were then adjusted to be positioned directly over the shims and the 2” piece of 1/32” tube was removed. The mini binder clips where chosen for their lower clamping force, their curved contacts that created a line loading condition, and to take advantage of Saint-Venant’s principle [73] by applying the majority of the load on the shims. These devices were then used with the experimental apparatus (See Figure 76).
Figure 168: Experimental apparatus for preliminary pressure test experiment. Top: T-740 AMETEK portable pneumatic tester (Berwyn, PA) capable of applying small amounts of pressure, Bottom Left: Upchurch Scientific P-727 TEE junction (Oak Harbor, WA) attached to a 0 to 5 psi ASDX005A2 Honeywell pressure transducer (Golden Valley, MN) connected to LabVIEW (National Instruments Corp., Austin, TX), Bottom Right: An Upchurch Scientific 5 inch long 1/32 x 0.0032 inch PEEK tube was attached to an assembled device with shims sandwiched between the superhydrophobic samples.
17 Design of Kinematic Alignment Structures

17.1 Overview

Previously, You [69] investigated using kinematic alignment structures as assembly features for positioning adjacent component chips in modular microfluidic systems. This work draws upon his work by using his design for alignment standards for measuring misalignment in the horizontal direction.

17.2 Kinematic Alignment Structures

The kinematic alignment structures used in the modified pressure test experiment were three pairs of adjacent v-grooves with ball bearings sandwiched between them. Nominally, the v-grooves and ball bearings contacted each other at two point contacts as shown in the cross-section of one kinematic alignment structure (Figure 169).

![Cross-section of one ball and v-groove coupling](image)

Figure 169: Cross-section of one ball and v-groove coupling

Each disk had six point contacts between the three ball bearings and three v-grooves constraining all six degrees of freedom for each disk. A second disk was flipped and its v-grooves were passively aligned and mated with the ball bearing/disk assembly to create a microfluidic assembly. This microfluidic assembly was then grouted with Pacer two part (resin and hardener) Z-Poxy epoxy to permanently fix the two adjacent chips, kinematically coupled with the v-grooves and ball bearings, together through the middle through hole.
The design of the disk to be flipped and aligned with another identical disk was influenced by manufacturing costs and time. The more inserts required, the longer the wait, and the greater the tooling and material costs. This allowed for a-side mold insert, the mold insert closest to the nozzle of the injection molding machine, to be the same for all the gap distances while only requiring the machining of new b-side inserts, the mold insert closest to the ejector pins. The ability of a microfluidic disk to flipped and aligned with another disk produced by the same mold insert is predicated on the axis of symmetry of the v-groove triangle aligning with the axis of symmetry of the disk (due to the symmetry of the through holes with respect to the axis of symmetry of the disks). Consequently, the use of symmetry allowed all of the disks across the gap distance spectrum to be flipped and aligned with disks from different mold inserts. This translates to fewer b-side mold inserts being manufactured because certain intermediate gap distances can be created from combinations of chips from other gap distances. After comparing different combinations of mold insert gap distances, b-side mold inserts for gap distances of 5 µm, 25 µm, 50 µm, and 100 µm were selected. These inserts will allow the experiments to test disk assemblies with gap distances of 5 µm, 27.5 µm, 50 µm, 52.5 µm, 75 µm, 100 µm.

Table 28: Gap distances generated by combining samples from different mold inserts.

<table>
<thead>
<tr>
<th>Gap Distance (µm)</th>
<th>5</th>
<th>15</th>
<th>25</th>
<th>35</th>
<th>45</th>
<th>50</th>
<th>55</th>
<th>65</th>
<th>75</th>
<th>85</th>
<th>95</th>
<th>100</th>
<th>105</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 µm</td>
<td>5</td>
<td>10</td>
<td>15</td>
<td>20</td>
<td>25</td>
<td>27.5</td>
<td>30</td>
<td>35</td>
<td>40</td>
<td>45</td>
<td>50</td>
<td>52.5</td>
<td>55</td>
</tr>
<tr>
<td>15 µm</td>
<td>10</td>
<td>15</td>
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<td>55</td>
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<td>27.5</td>
<td>32.5</td>
<td>37.5</td>
<td>42.5</td>
<td>47.5</td>
<td>50</td>
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<td>57.5</td>
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<tr>
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<td>30</td>
<td>35</td>
<td>40</td>
<td>45</td>
<td>50</td>
<td>52.5</td>
<td>55</td>
<td>60</td>
<td>65</td>
<td>70</td>
<td>75</td>
<td>77.5</td>
<td>80</td>
</tr>
<tr>
<td>65 µm</td>
<td>35</td>
<td>40</td>
<td>45</td>
<td>50</td>
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<td>57.5</td>
<td>60</td>
<td>65</td>
<td>70</td>
<td>75</td>
<td>80</td>
<td>82.5</td>
<td>85</td>
</tr>
<tr>
<td>75 µm</td>
<td>40</td>
<td>45</td>
<td>50</td>
<td>55</td>
<td>60</td>
<td>62.5</td>
<td>65</td>
<td>70</td>
<td>75</td>
<td>80</td>
<td>85</td>
<td>87.5</td>
<td>90</td>
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<tr>
<td>85 µm</td>
<td>45</td>
<td>50</td>
<td>55</td>
<td>60</td>
<td>65</td>
<td>67.5</td>
<td>70</td>
<td>75</td>
<td>80</td>
<td>85</td>
<td>90</td>
<td>92.5</td>
<td>95</td>
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<tr>
<td>95 µm</td>
<td>50</td>
<td>55</td>
<td>60</td>
<td>65</td>
<td>70</td>
<td>72.5</td>
<td>75</td>
<td>80</td>
<td>85</td>
<td>90</td>
<td>95</td>
<td>97.5</td>
<td>100</td>
</tr>
<tr>
<td>100 µm</td>
<td>52.5</td>
<td>57.5</td>
<td>62.5</td>
<td>67.5</td>
<td>72.5</td>
<td>75</td>
<td>77.5</td>
<td>82.5</td>
<td>87.5</td>
<td>92.5</td>
<td>97.5</td>
<td>100</td>
<td>102.5</td>
</tr>
</tbody>
</table>
The placement of the kinematic alignment structures can amplify the effects of deflection and flatness of the disks on the gap distance. When evaluating the placement of the kinematic alignment structures, several factors came into consideration. From an experimental standpoint, the kinematic alignment structures need to be placed close to through-holes to reduce the error due to tilt of the chips and reduce the effects due to errors caused by lack of flatness. From a manufacturing standpoint, the kinematic alignment structures needed to be placed far enough away from the edge so that the milling bit could fit between the edge of the cavity and the v-grooves, in the mold they appear as triangular prisms protruding from the base of the cavity.

17.3 Ball Bearings

The ball bearings were supplied by Boca Bearings Company (Boynton Beach, FL) and have a diameter of 1/32” (0.8 mm). They are made of Silicon Nitride (Si₃N₄). They are grade 5 which means they have an allowable deviation from spherical form, “greatest radial distance in any radial plane between a sphere circumscribed around the ball surface and any point on the ball surface”[70], of 0.13 μm [70].

17.4 V-groove Geometry

The triangular prism extends from the base of the cavity and features a flat instead of its peak to increase its manufacturability. The gap distance between the two disks and the width of the flat drives the width of the triangular prism at the base of the cavity and the height of the flat from the bottom of the cavity. On the mold insert the v-groove are positive features so the depth of the tapered groove is actually the height of the triangular prism. The height of the triangular prism for different gap distances can be defined using the geometry of the sphere and the v-groove.
Figure 170 shows the derivation of the gap distances and Table 29 shows the heights of the triangular prisms for different gap distances.

Figure 170: Cross-section of kinematic couple between a v-groove and a ball bearing defining the gap distance (d) between experimental chips.

Equations 1 relates gap distance (d), the radius of the ball bearing (R), and flat width (twice the distance E) to the height of the triangular prism flat (F) and the width of the triangular prism at the base of the cavity (W):

\[
\begin{align*}
C &= \frac{1}{\sqrt{2}} R \\
H &= 2C - \frac{d}{2} \\
W &= 2H \\
F &= H - E
\end{align*}
\]  
(1)
Table 29 shows the width at the base and the height of the flat with a triangular prism flat distance (E) of 0.05 mm (per machinist’s specification), a ball bearing radius (R) of 0.4 mm, and varying the gap distances:

Table 29: Dimensions of prism necessary to achieve various assembly gap distances.

<table>
<thead>
<tr>
<th>Gap Distance (D)</th>
<th>Width at Base of Cavity (W)</th>
<th>Height of Flat (F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 µm</td>
<td>1.126 mm</td>
<td>0.513 mm</td>
</tr>
<tr>
<td>15 µm</td>
<td>1.116 mm</td>
<td>0.508 mm</td>
</tr>
<tr>
<td>25 µm</td>
<td>1.106 mm</td>
<td>0.503 mm</td>
</tr>
<tr>
<td>35 µm</td>
<td>1.096 mm</td>
<td>0.498 mm</td>
</tr>
<tr>
<td>45 µm</td>
<td>1.086 mm</td>
<td>0.493 mm</td>
</tr>
<tr>
<td>55 µm</td>
<td>1.076 mm</td>
<td>0.488 mm</td>
</tr>
<tr>
<td>65 µm</td>
<td>1.066 mm</td>
<td>0.483 mm</td>
</tr>
<tr>
<td>75 µm</td>
<td>1.056 mm</td>
<td>0.478 mm</td>
</tr>
<tr>
<td>85 µm</td>
<td>1.046 mm</td>
<td>0.473 mm</td>
</tr>
<tr>
<td>95 µm</td>
<td>1.036 mm</td>
<td>0.468 mm</td>
</tr>
<tr>
<td>105 µm</td>
<td>1.026 mm</td>
<td>0.463 mm</td>
</tr>
<tr>
<td>115 µm</td>
<td>1.016 mm</td>
<td>0.458 mm</td>
</tr>
<tr>
<td>125 µm</td>
<td>1.006 mm</td>
<td>0.453 mm</td>
</tr>
</tbody>
</table>

There is an upper limit for the length of the flat above which the assembly ceases to be determinate and becomes under-constrained. This limit is occurs when the condition in Equation 2 is met.

\[ R = 2C - E \]  \hspace{1cm} (2)

Where R is the radius of the sphere, C is half the distance from the center of the sphere to the vertex of the triangle created by the v-groove, and E is the flat distance.

This results in an upper limit for the length of the flat (twice the distance of E) of approximately 0.28 mm for the ball bearings with radius of 0.4 mm.
18 Hydrobead-P Data

Hydrobead-P was selected as the superhydrophobic surface because it was commercially available, it had a uniform contact angle over the whole sample, it had a uniform flatness, it was thin, and it could be spin coated. Several experiments were performed on the superhydrophobic surface before it was adopted. Observations using the Scanning Electron Microscope (SEM) (FEI Quanta3d FEG, Helios Nanolab, Hillsboro, OR), contact angle measurements, and thickness measurements.

18.1 SEM Observations

A piece of scotch tape was used to mask a section of and injection molded cyclic olefin copolymer sample. Hydrobead-P was then spin coated onto the samples surface and placed in a constant temperature oven set at 100°C for 1 hour to cure. The tape was then removed and the surface was tested with water droplets to ensure it was superhydrophobic. Then, 20 nm of platinum was sputtered onto the surface of the sample. The sample was then cut into several pieces to observe the transition between the masked area and the area with the superhydrophobic coating. The edges of these samples were then sputtered with 80 nm of platinum. The SEM scans were performed by Junseo Choi. The resulting images are featured in Figure 84- Figure 180.

Figure 171: Example of Hydrobead-P surface spin coated on COC.
Figure 172: Figure 3: Hydrobead-P spin coated on COC.

Figure 173: Side view of thickness of the hydrobead-P coating over the COC polymer. The bare COC polymer is on the bottom and in the middle of the image is the Hydrobead-P.
Figure 174: Zoomed in on portion of Hydrobead-P in image 4.

Figure 175: Another zoomed in portion of the Hydrobead-P from image 4.
Figure 176: Side view of the transition from the raw COC surface on the left (notice the micromilling marks) and the superhydrophobic surface on the right. There appears to be a burr resulting from the removal of the scotch tape.

Figure 177: Top view of Hydrobead-P spin coated on COC substrate.
Figure 178: Zoomed in top view of hydrobead-P spin coated on COC substrate.

Figure 179: Top view of Hydrobead-P spin coated on COC substrate.
18.2 Contact Angle Measurements

Thirteen injection molded COC samples were spin coated with Hydrobead-P and then cured in the oven at 100°C for 1 hour. The contact angle of each of the samples were measured sixteen times across the surface using the sessile drop technique on the VCA Optima (Billerica, MA) in Dr. McCarley’s lab. Table 30 shows the resulting measurements.

Table 30: Contact angle measurements of Hydrobead-P using sessile drop method with VCA Optima.

<table>
<thead>
<tr>
<th>Sample #</th>
<th>Contact Angle Measurements (in degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>124.5 124.7 151.4 151.1 152.6 152.4 121.6 120.5 154.2 154 155.2 152 152.5 147.4 147.4 145.9 146.2</td>
</tr>
<tr>
<td>2</td>
<td>148.2 148.1 156.7 156.7 153 152.4 152.3 152 151.2 151.4 150.9 151 154.5 154.2 154.6 154.4</td>
</tr>
<tr>
<td>3</td>
<td>154.2 154.5 152.5 151.6 152.3 151.8 152.3 152.4 155.5 155.5 154.9 154.8 151.8 151.9 147.8 148.4</td>
</tr>
<tr>
<td>4</td>
<td>152.9 153.1 149.1 150.2 152.4 152.4 152.8 152.9 150 150 150.8 150.9 151.4 152.1 156.6 156.9</td>
</tr>
<tr>
<td>5</td>
<td>150.9 150.3 154.1 154 155.8 156.3 154.9 155.2 150 150.6 152 152.6 153.6 153.4 150.6 150.8</td>
</tr>
<tr>
<td>6</td>
<td>142.8 141.7 152.8 152.8 152.5 153.4 153.6 153.5 155.9 156 147.4 147.5 155.3 154.8 149.3 149.4</td>
</tr>
<tr>
<td>7</td>
<td>105.5 104.5 154 154 145.7 145.6 120.1 121.6 148.3 147.3 152.3 152.5 156.5 156.2 155.3 155.4</td>
</tr>
<tr>
<td>8</td>
<td>155.7 155.5 151.6 151.7 154.7 154.5 154.7 154.3 150.7 150.7 152 151.3 153.3 152.7 151.8 151.7</td>
</tr>
<tr>
<td>9</td>
<td>147.4 147.4 144.7 144.5 153.9 154.2 151.8 151.2 154.4 154.8 144.3 143.8 155.5 155.4 152.9 152.6</td>
</tr>
<tr>
<td>10</td>
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</tr>
<tr>
<td>11</td>
<td>154.4 153.9 157 157 156 156.2 153.4 153.8 154.3 154.5 153.7 153.5 152.6 152.2 154.3 153.9</td>
</tr>
<tr>
<td>12</td>
<td>138.9 139.5 149 150.3 149 149.2 147.1 146.2 144.9 144.7 147.8 148 152.8 152.9 138.2 138.7</td>
</tr>
<tr>
<td>13</td>
<td>153.1 152.6 150.8 150.3 152 153.1 155.4 155.3 145.7 145.7 144.2 145.8 148.7 149.3 149.3 150</td>
</tr>
</tbody>
</table>
18.3 Thickness Measurements

Twelve of the samples used for the contact angle measurement experiments had portions of the chip that were masked from the application of Hydrobead-P with scotch tape. The scotch tape was removed with tweezers and the thickness of the Hydrobead-P was measured using the Nikon Measurescope MM-11 (Melville, NY) optical microscope by focusing on area that was masked by tape, taking it as a reference elevation and then focusing on the peaks of the Hydrobead-P. Table 31 shows the thickness measurements resulting from the optical microscope.

Table 31: Thickness measurements of spin coated Hydrobead-P using optical microscope.

<table>
<thead>
<tr>
<th>Sample #</th>
<th>Thickness Measurements (μm)</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>4.5</td>
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<tr>
<td>2</td>
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<td>3.5</td>
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<tr>
<td>8</td>
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<tr>
<td>9</td>
<td>1.5</td>
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<td>11</td>
<td>1</td>
</tr>
<tr>
<td>12</td>
<td>3</td>
</tr>
</tbody>
</table>
19 Elephant Ear Leaf Superhydrophobic Surface Fabrication

From Farshchian [65] and Farshchian et al [74], the process steps used to create the superhydrophobic surfaces were: to cut an elephant ear leaf (Colocasia Esculenta) into a 40 mm by 50 mm squares and paste them on a flat PMMA substrate (~50 mm by 100 mm by 3.2 mm); mix, vacuum, and cast polydimethylsiloxane (PDMS) (Sylgard™ 184, Dow Corning, Midland, MI) onto the elephant ear leaf segments; peel the PDMS stamp off, and coat another PMMA substrate (~50 mm by 100 mm by 3.2 mm) with UV-resin; press the PDMS stamp onto UV-resin and expose it to UV light through the top of the PDMS stamp using an UV-lamp; and then peel off the PDMS stamp from the imprinted UV-resin on the substrate. More detailed information is presented in Farshchian [65] and in Farshchian et al [74].

Figure 181: Image of a 4 cm by 4 cm the PDMS nanoimprinted elephant ear leaf pattern used in preliminary pressure test experiments.

Figure 182: SEM image of nanoimprinted elephant ear leaf pattern courtesy of Bahador Farshchian [65].
Figure 183: Patterning process used by Farshchian [65] to create PDMS nanopatterned surface courtesy of Bahador Farshchian.
20 Detailed Experimental Procedures

20.1 Start-up Procedure

The start-up procedure consisted of tasks needed to initialize the experimental apparatus. First, the pressure relief valve was pulled on to ensure the pressurized liquid column is not under pressure. Then, the pressurized liquid column was disconnected from the experimental apparatus by disengaging the liquid column’s compression fittings and the pressurized liquid column was filled approximately three quarters full with deionized water. Next, a gloved finger was placed over the hole of the top compression fitting, the pressurized liquid column was oriented vertical, and then the downstream ¼” OD high density polyethylene tubing was connected to the bottom compression fitting. Next the upstream ¼” OD high density polyethylene tubing was connected to the top compression fitting. After that, the valve on the ultra high purity nitrogen cylinder was opened and checked to make sure the multi-stage cylinder regulator was set at 25 psi. Then, the power cord of the Cole-Parmer dual valve pressure controller was plug in, the laptop with LabVIEW 2012 was powered up, the NI USB-6212 was plugged in, the 11621A BK Precision DC regulated power supply for the ASDX pressure sensors was turned on, and the power supply was set to 5.0 V. Next, the correct range of ASDX series pressure sensor was plugged into the 1/16” OD Neoprene tubing connected to the P-727 microfluidic tee from Upchurch Scientific. Then, the LabVIEW 2012 experimental program and the program NI MAX were opened.

20.2 Interconnect Assembly Priming Procedure

The interconnect assemblies initially begin without any liquid in them. The process of filling the assembly with liquid before the experiment begins is called priming the assembly. The priming procedure begins by opening the upstream and downstream P-732 microfluidic ball valves from Upchurch Scientific. Then, the interconnect assembly is connected to the P-727 microfluidic tee using the Vacutight headless fitting and Vacutight ferrule. Next, in the NI MAX
program click on the NI USB-6212 under devices and interfaces, and then set the pressure controller’s set point voltage to 0.05 V which corresponds to 0.05 psi. Wait until the assembly is filled with deionized water. If during the priming procedure the fluid stops flowing, increase the pressure to 0.075 psi. Once the assembly including the outlet tube is primed, shut the upstream P-732 microfluidic ball valve and using NI MAX set the pressure controller’s set point voltage to 0 V which corresponds to 0 psi. Then, with the downstream P-732 microfluidic ball valve open connect the assembly’s outlet tube to the downstream P-732 microfluidic ball valve using the super flangeless nut with ¼-28 thread and the super flangeless ferrule. Next, close the downstream microfluidic ball valve.

20.3 Testing Procedure

The testing procedure produced the time varying pressure measurements used to quantify the maximum rupture pressure of the interconnect assemblies. First, with the Cole-Parmer pressure controller set to 0 psi and the downstream P-732 valve closed, open the upstream P-732 ball valve. Then, enter in the ASDX pressure sensor type, and enter the pressure set point in the experiment’s LabVIEW program to correspond to a 10% less than the maximum pressure of the sensor. Next, set the delay to be 120 ms, set the increment to be 0.002 psi, and ensure the “Ramp On” toggle switch is activated. Then, click the run program arrow. Wait a second or two and then activate the burst control toggle switch. Then, watch the assembly for indications of rupture. If rupture is observed, close the upstream P-732 microfluidic ball valve, click the stop button in the experiment’s LabVIEW program, set the pressure controller pressure to zero using NI MAX, open the upstream and downstream microfluidic ball valves, and then save the data file. Most often the burst control caught the rupture for 0-1 psi range pressure sensor and shut the system down automatically. However, sometimes it did not. With the 0-5 psi pressure sensor, the experiment’s LabVIEW program rarely caught the rupture with the burst control subroutine. If
rupture does not occur during the pressure ramp up phase, close the upstream microfluidic ball valve, set the pressure controller to zero using NI MAX, open the upstream microfluidic ball valve to equalize the pressure, and change out the ASDX 0-1 psi pressure sensor for the ASDX 0-5 psi pressure sensor. Then, run the testing procedure again with the ASDX 0-5 psi pressure sensor. After that, run the priming procedure for the next interconnect assembly.

20.4 Gap Distance and Misalignment Measurement Procedure

The gap distance and misalignment were measured using the Nikon Measurescope MM-11 (Melville, NY) with a Diagnostic Instruments, Inc microscope camera (Sterling Heights, MI) with SPOT advanced imaging software, and a QUADRA-CHEK 2000 (Metronics, Schaumburg, IL). First, remove the inlet and outlet tubing from the interconnect assembly and set units of the QUADRA-CHEK 2000 to millimeters. Next, position the assembly on the optical microscope with the flat closest to the interconnect toward the 10X objective. Then, focus the 10X objective on the gap and then switch to the 50X objective and refine the focus on the gap. Using the optical microscope’s micrometers and looking at the SPOT advanced live video stream, align the cross hairs with the base edge of the gap. Then, using the buttons on the microscope’s micrometers, zero out the measurements displayed on the QUADRA-CHEK 2000. After that, using the microscope’s micrometers, scroll until the cross hairs are aligned with the top of the gap. Record the measurement displayed on the QUADRA-CHEK 2000. Repeat for nine additional gap distance measurements. Then, with a similar procedure, measure the left and right offset of the through-holes by using the tooling marks on the edge of the assembly. Repeat for nine additional offset measurements. After that, measure the up and down offset of the assembly by measuring the two pairs of alignment standards ten times each.
21 Complete Description of Experimental Apparatus

The experimental apparatus consisted of three different branches that were attached to the bronze 3/8” NPT 3-way valve. These branches were the CO₂ priming branch, the pressurized liquid column branch, and the microfluidic system branch. The CO₂ priming branch and the pressurized liquid column branch were the two upstream branches while the microfluidic system branch was the downstream branch. The CO₂ priming branch was not used for any experiments with this thesis but may be necessary for future modular microfluidic systems to rid the system of gases, such as nitrogen and argon that are insoluble in water.

Figure 184: CO₂ Priming Branch
Figure 185: Pressurized Liquid Column Branch
21.1 Microfluidic System Branch

Figure 186: Microfluidic System Branch

21.2 Experimental Apparatus Parts List

The experimental apparatus consisted of several components. A parts list is described in Table 32.
<table>
<thead>
<tr>
<th>Number of Parts Used</th>
<th>Part Name</th>
<th>Company</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>cylinder of research grade carbon dioxide, size 35</td>
<td>Airgas</td>
<td>Dallas, TX</td>
</tr>
<tr>
<td>1</td>
<td>cylinder of ultra high purity nitrogen, size 35</td>
<td>Airgas</td>
<td>Dallas, TX</td>
</tr>
<tr>
<td>1</td>
<td>multi-stage nitrogen regulator</td>
<td>Harris</td>
<td>Mason, OH</td>
</tr>
<tr>
<td>1</td>
<td>multi-stage CO2 regulator</td>
<td>Harris</td>
<td>Mason, OH</td>
</tr>
<tr>
<td>2</td>
<td>45° Flare x 3/8” MNPT</td>
<td>Parker</td>
<td>Cleveland, OH</td>
</tr>
<tr>
<td>2</td>
<td>3/8” NPT Brass Union</td>
<td>Grainger</td>
<td>Lake Forest, IL</td>
</tr>
<tr>
<td>3</td>
<td>Bronze Ball Valve, 3/8” NPT Female</td>
<td>McMaster-Carr</td>
<td>Elmhurst, IL</td>
</tr>
<tr>
<td>19</td>
<td>1/4&quot; OD 0.170” ID high density polyethylene tubing</td>
<td>Advanced Technology Products</td>
<td>Milford Center, OH</td>
</tr>
<tr>
<td>3</td>
<td>3/8&quot; NPT to 1/2” tube compression fittings, Nickel Plated Brass</td>
<td>Parker</td>
<td>Cleveland, OH</td>
</tr>
<tr>
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<td>3/8&quot; female NPT to 1/8” male NPT adaptors</td>
<td>McMaster-Carr</td>
<td>Elmhurst, IL</td>
</tr>
<tr>
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<td>1/8&quot; female NPT to 3/8” male NPT adapter</td>
<td>McMaster-Carr</td>
<td>Elmhurst, IL</td>
</tr>
<tr>
<td>1</td>
<td>20 μm air filter</td>
<td>McMaster-Carr</td>
<td>Elmhurst, IL</td>
</tr>
<tr>
<td>1</td>
<td>68027-60, 0-5 psig, dual valve pressure controller</td>
<td>Cole-Parmer</td>
<td>Vernon Hills, IL</td>
</tr>
<tr>
<td>1</td>
<td>3/8&quot; female NPT tee, brass</td>
<td>McMaster-Carr</td>
<td>Elmhurst, IL</td>
</tr>
<tr>
<td>1</td>
<td>25psi ASME Code Brass Pop Safety Valve, 3/8” NPT</td>
<td>McMaster-Carr</td>
<td>Elmhurst, IL</td>
</tr>
<tr>
<td>4 ½ in</td>
<td>1” OD, Sch 40, PVC with pressure rating of 450 psi</td>
<td>Lowe’s</td>
<td>Mooresville, NC</td>
</tr>
<tr>
<td>2</td>
<td>1” OD tube to 3/4” male NPT PVC. adapter</td>
<td>Lowe’s</td>
<td>Mooresville, NC</td>
</tr>
<tr>
<td>2</td>
<td>½” female NPT 90° elbow, Sch 40, PVC</td>
<td>Lowe’s</td>
<td>Mooresville, NC</td>
</tr>
<tr>
<td>2</td>
<td>⅜” male NPT to ½” female NPT adapter, Sch 40, PVC</td>
<td>Lowe’s</td>
<td>Mooresville, NC</td>
</tr>
<tr>
<td>1</td>
<td>⅜” male NPT to 3/8” female NPT adapter, brass</td>
<td>McMaster-Carr</td>
<td>Elmhurst, IL</td>
</tr>
<tr>
<td>1</td>
<td>3-way ball valve, 3/8” female NPT, bronze</td>
<td>McMaster-Carr</td>
<td>Elmhurst, IL</td>
</tr>
<tr>
<td>1</td>
<td>U-501, 1/4” male NPT to ½”-28 male adapter</td>
<td>Upchurch Scientific</td>
<td>Oak Harbor, WA</td>
</tr>
<tr>
<td>2</td>
<td>P-752, microtubing ball valves</td>
<td>Upchurch Scientific</td>
<td>Oak Harbor, WA</td>
</tr>
<tr>
<td>1</td>
<td>P-727, microtubing tee</td>
<td>Upchurch Scientific</td>
<td>Oak Harbor, WA</td>
</tr>
<tr>
<td>2</td>
<td>P-844, Vacutight headless fitting</td>
<td>Upchurch Scientific</td>
<td>Oak Harbor, WA</td>
</tr>
<tr>
<td>2</td>
<td>P-840, Vacutight ferrate</td>
<td>Upchurch Scientific</td>
<td>Oak Harbor, WA</td>
</tr>
<tr>
<td>2</td>
<td>L1-T15, super flangeless nut with ½”-28 thread</td>
<td>Upchurch Scientific</td>
<td>Oak Harbor, WA</td>
</tr>
<tr>
<td>2</td>
<td>P-250, super flangeless ferrate</td>
<td>Upchurch Scientific</td>
<td>Oak Harbor, WA</td>
</tr>
<tr>
<td>23 ½</td>
<td>1/16” OD x 0.03” ID fluorinated ethylene propylene (FEP) tubing</td>
<td>Upchurch Scientific</td>
<td>Oak Harbor, WA</td>
</tr>
<tr>
<td>1/8”</td>
<td>1/16” OD Nipples tubing</td>
<td>Unknown</td>
<td>Unknown</td>
</tr>
<tr>
<td>1</td>
<td>0-1 psi, ANO2VAVD014V0A12</td>
<td>Honeywell S&amp;C</td>
<td>Golden Valley, MN</td>
</tr>
<tr>
<td>1</td>
<td>0-5 psig, ANO2VAVD023V0A12</td>
<td>Honeywell S&amp;C</td>
<td>Golden Valley, MN</td>
</tr>
<tr>
<td>1</td>
<td>NT USB-6212</td>
<td>National Instruments</td>
<td>Austin, TX</td>
</tr>
</tbody>
</table>
22 Modified Pressure Test Raw Data: Gap Distance and Lateral Offset Measurements

Gap distances were measured at ten different locations less than 1 mm from the through-hole along the flat next to the through-hole (See Figure 187). The variation in gap distances measurements gives an indication of the roughness around the through hole. The offset measurements needed a direction to be specified as positive to give an orientation of the offset. Figure 188 shows the directions selected for positive and negative offset. Each sample had a sample name written on one side of the assembly. As a convention, this name was always oriented toward the microscope operator. The average, standard deviation, and 95% confidence interval based on the Student t distribution were calculated for the gap distance and offset measurements. Additionally, the maximum pressure predicted from the first generation model for the low gap distance from the confidence interval and high gap distance from the confidence interval were stated for each assembly. This value can be compared to the graph of the assemblies maximum pressure.

Figure 187: Overview of the gap distance and offset measurement locations.
Figure 188: An example of the rule adopted for the offset direction for the right, left, and top alignment measurements.

22.1 30 μm Insert Assemblies

22.1.1 Sample B (Unclamped)

Table 33: Gap distance and offset measurements for sample B.

<table>
<thead>
<tr>
<th>Replicate #</th>
<th>Gap distance (μm)</th>
<th>Left alignment structure</th>
<th>Right Alignment structure</th>
<th>Top Alignment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>115</td>
<td>-41</td>
<td>-15</td>
<td>23</td>
</tr>
<tr>
<td>2</td>
<td>112</td>
<td>-33</td>
<td>-13</td>
<td>19</td>
</tr>
<tr>
<td>3</td>
<td>120</td>
<td>-28</td>
<td>-24</td>
<td>18</td>
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<tr>
<td>4</td>
<td>115</td>
<td>-30</td>
<td>-24</td>
<td>17</td>
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<tr>
<td>5</td>
<td>56</td>
<td>-33</td>
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<td>20</td>
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<tr>
<td>6</td>
<td>60</td>
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<td>7</td>
<td>80</td>
<td>-38</td>
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<tr>
<td>8</td>
<td>72</td>
<td>-38</td>
<td>-25</td>
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<td>9</td>
<td>74</td>
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<td>-22</td>
<td>18</td>
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<td>10</td>
<td>78</td>
<td>-44</td>
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<td>23</td>
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<td>11</td>
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<td>14</td>
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<td>15</td>
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<td>16</td>
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<td>18</td>
<td>52</td>
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<td>19</td>
<td>60</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>55</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>average</td>
<td>55.4</td>
<td>-34.2</td>
<td>-20</td>
<td>19.7</td>
</tr>
<tr>
<td>stdev</td>
<td>3.134042473</td>
<td>5.769652406</td>
<td>3.972125096</td>
<td>2.002775851</td>
</tr>
<tr>
<td>(+-) 95%</td>
<td>7.089204074</td>
<td>13.05095374</td>
<td>8.984946967</td>
<td>4.530278976</td>
</tr>
<tr>
<td>Gap High</td>
<td>1995.667252</td>
<td>Pascals</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gap Low</td>
<td>2581.362111</td>
<td>Pascals</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 189: Pressure measurement for sample B.

### 22.1.2 Sample C (Unclamped)

Table 34: Gap distance and offset measurements for sample C.

<table>
<thead>
<tr>
<th>Replicate #</th>
<th>Gap distance (μm)</th>
<th>Left alignment structure</th>
<th>Right Alignment structure</th>
<th>Top Alignment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>127</td>
<td>122</td>
<td>-39</td>
<td>68</td>
</tr>
<tr>
<td>2</td>
<td>111</td>
<td>120</td>
<td>-35</td>
<td>66</td>
</tr>
<tr>
<td>3</td>
<td>119</td>
<td>118</td>
<td>-46</td>
<td>67</td>
</tr>
<tr>
<td>4</td>
<td>141</td>
<td>113</td>
<td>-37</td>
<td>68</td>
</tr>
<tr>
<td>5</td>
<td>139</td>
<td>115</td>
<td>-40</td>
<td>67</td>
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<tr>
<td>6</td>
<td>134</td>
<td>121</td>
<td>-32</td>
<td>72</td>
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<tr>
<td>7</td>
<td>141</td>
<td>128</td>
<td>-31</td>
<td>65</td>
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<tr>
<td>8</td>
<td>132</td>
<td>124</td>
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</tr>
<tr>
<td>10</td>
<td>145</td>
<td>129</td>
<td>-36</td>
<td>74</td>
</tr>
<tr>
<td>average</td>
<td>131.9</td>
<td>120.8</td>
<td>36.4</td>
<td>68.9</td>
</tr>
<tr>
<td>stdev</td>
<td>10.66093596</td>
<td>5.181162461</td>
<td>4.788875999</td>
<td>2.923088169</td>
</tr>
<tr>
<td>(+-) 95%</td>
<td>24.11503714</td>
<td>11.71978949</td>
<td>10.83243751</td>
<td>6.612025439</td>
</tr>
<tr>
<td>Gap High</td>
<td>799.331016</td>
<td>Pascals</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gap Low</td>
<td>1157.004232</td>
<td>Pascals</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
22.1.3 Sample D (Unclamped)

Table 35: Gap distance and offset measurements for sample D.

<table>
<thead>
<tr>
<th>Replicate #</th>
<th>Gap distance (μm)</th>
<th>Left alignment structure</th>
<th>Right Alignment structure</th>
<th>Top Alignment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>40</td>
<td>6</td>
<td>56</td>
</tr>
<tr>
<td>2</td>
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<td>50</td>
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<tr>
<td>10</td>
<td>10</td>
<td>57</td>
<td>6</td>
<td>61</td>
</tr>
<tr>
<td>average</td>
<td>average</td>
<td>49.9</td>
<td>5.2</td>
<td>-48.8</td>
</tr>
<tr>
<td>stdev</td>
<td>stdev</td>
<td>7.309810759</td>
<td>2.573367875</td>
<td>21.60144028</td>
</tr>
<tr>
<td>(+-) 95%</td>
<td>(+-) 95%</td>
<td>16.53479194</td>
<td>5.820958134</td>
<td>48.86245792</td>
</tr>
<tr>
<td>Gap High</td>
<td>1877.143805</td>
<td>Pascals</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gap Low</td>
<td>3737.655641</td>
<td>Pascals</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 190: Pressure measurement for sample C.
22.1.4 Sample E (Unclamped)

Table 36: Gap distance and offset measurements for sample E.

<table>
<thead>
<tr>
<th>Replicate #</th>
<th>Gap distance (μm)</th>
<th>Left alignment structure</th>
<th>Right Alignment structure</th>
<th>Top Alignment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>73</td>
<td>-11</td>
<td>9</td>
<td>7</td>
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<tr>
<td>2</td>
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<tr>
<td>3</td>
<td>77</td>
<td>-18</td>
<td>17</td>
<td>6</td>
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<tr>
<td>4</td>
<td>71</td>
<td>-6</td>
<td>12</td>
<td>8</td>
</tr>
<tr>
<td>5</td>
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<td>6</td>
<td>74</td>
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<td>7</td>
<td>78</td>
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<tr>
<td>8</td>
<td>72</td>
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<td>8</td>
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<tr>
<td>9</td>
<td>76</td>
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<td>9</td>
</tr>
<tr>
<td>10</td>
<td>72</td>
<td>-9</td>
<td>18</td>
<td>7</td>
</tr>
<tr>
<td>average</td>
<td>74.4</td>
<td>-11.9</td>
<td>-16.8</td>
<td>7.3</td>
</tr>
<tr>
<td>stdev</td>
<td>2.366431913</td>
<td>4.263540521</td>
<td>4.263540521</td>
<td>1.251665557</td>
</tr>
<tr>
<td>(+-) 95%</td>
<td>5.352868988</td>
<td>9.644128659</td>
<td>9.644128659</td>
<td>2.83126749</td>
</tr>
<tr>
<td>Gap High</td>
<td>1563.676138</td>
<td>Pascals</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gap Low</td>
<td>1806.123677</td>
<td>Pascals</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 191: Pressure measurement for sample D.
22.1.5 Sample F (Unclamped)

Table 37: Gap distance and offset measurements for sample F.

<table>
<thead>
<tr>
<th>Replicate #</th>
<th>Gap distance (μm)</th>
<th>Left alignment structure</th>
<th>Right Alignment structure</th>
<th>Top Alignment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>128</td>
<td>-19</td>
<td>25</td>
<td>N/A</td>
</tr>
<tr>
<td>2</td>
<td>125</td>
<td>-13</td>
<td>-13</td>
<td>N/A</td>
</tr>
<tr>
<td>3</td>
<td>128</td>
<td>-24</td>
<td>0</td>
<td>N/A</td>
</tr>
<tr>
<td>4</td>
<td>118</td>
<td>-2</td>
<td>16</td>
<td>N/A</td>
</tr>
<tr>
<td>5</td>
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<tr>
<td>8</td>
<td>123</td>
<td>-12</td>
<td>-4</td>
<td>N/A</td>
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<tr>
<td>9</td>
<td>116</td>
<td>-10</td>
<td>-7</td>
<td>N/A</td>
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<tr>
<td>10</td>
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<tr>
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<td>121.7</td>
<td>-11.4</td>
<td>-3.9</td>
<td></td>
</tr>
<tr>
<td>stdev</td>
<td>4.967673276</td>
<td>6.883151733</td>
<td>13.64998982</td>
<td></td>
</tr>
<tr>
<td>(+- 95%)</td>
<td>11.23687695</td>
<td>15.56968922</td>
<td>30.87627698</td>
<td></td>
</tr>
<tr>
<td>Gap High</td>
<td>938.0967946</td>
<td>Pascals</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gap Low</td>
<td>1128.952855</td>
<td>Pascals</td>
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<td></td>
</tr>
</tbody>
</table>

Figure 192: Pressure measurement for sample E.
22.1.6 Sample G (Unclamped)

Table 38: Gap distance and offset measurements for sample G.

<table>
<thead>
<tr>
<th>Replicate #</th>
<th>Gap distance (μm)</th>
<th>Left alignment structure</th>
<th>Right Alignment structure</th>
<th>Top Alignment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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<td>20</td>
<td>-7</td>
<td>N/A</td>
</tr>
<tr>
<td>2</td>
<td>137</td>
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<td>N/A</td>
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<td>N/A</td>
</tr>
<tr>
<td>4</td>
<td>131</td>
<td>0</td>
<td>8</td>
<td>N/A</td>
</tr>
<tr>
<td>5</td>
<td>131</td>
<td>-6</td>
<td>14</td>
<td>N/A</td>
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<td>N/A</td>
</tr>
<tr>
<td>9</td>
<td>131</td>
<td>0</td>
<td>20</td>
<td>N/A</td>
</tr>
<tr>
<td>10</td>
<td>133</td>
<td>9</td>
<td>13</td>
<td>N/A</td>
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<td>average</td>
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<td>-2.7</td>
<td>N/A</td>
</tr>
<tr>
<td>stdev</td>
<td>2.936362073</td>
<td>12.80624847</td>
<td>10.83256408</td>
<td></td>
</tr>
<tr>
<td>(+/-) 95%</td>
<td>6.642051009</td>
<td>28.96773405</td>
<td>24.50325994</td>
<td></td>
</tr>
<tr>
<td>Gap High</td>
<td>894.3332176</td>
<td>Pascals</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gap Low</td>
<td>988.5041659</td>
<td>Pascals</td>
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<td></td>
</tr>
</tbody>
</table>

Figure 193: Pressure measurement for sample F.

Sample F Pressure Regulator and Sensor Reading

- Pressure at Interconnect
- Pressure Regulator Pressure

Plot showing pressure over time with a peak at around 2000 Pascals.
Figure 194: Pressure measurement for sample G.

### 22.1.7 Sample H (Unclamped)

Table 39: Gap distance and offset measurements for sample H.

<table>
<thead>
<tr>
<th>Replicate #</th>
<th>Gap distance (μm)</th>
<th>Left alignment structure</th>
<th>Right Alignment structure</th>
<th>Top Alignment</th>
</tr>
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<tbody>
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<td>126</td>
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<td>70</td>
<td>-35</td>
<td>18</td>
<td>123</td>
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<td>70</td>
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<td>134</td>
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<td>76</td>
<td>-47</td>
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<td>120</td>
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<td>75</td>
<td>-48</td>
<td>8</td>
<td>133</td>
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<tr>
<td>7</td>
<td>70</td>
<td>-51</td>
<td>20</td>
<td>121</td>
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<td>66</td>
<td>-38</td>
<td>3</td>
<td>131</td>
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<td>124</td>
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<td>10</td>
<td>73</td>
<td>-49</td>
<td>5</td>
<td>127</td>
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<td>71.2</td>
<td>-45.8</td>
<td>-10.9</td>
<td>126.2</td>
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<tr>
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<td>6.854844191</td>
<td>4.962078418</td>
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<tr>
<td>(+-) 95%</td>
<td>6.976028211</td>
<td>17.48239691</td>
<td>15.50565756</td>
<td>11.22422138</td>
</tr>
<tr>
<td>Gap High</td>
<td>1595.216091</td>
<td>Pascals</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gap Low</td>
<td>1941.761848</td>
<td>Pascals</td>
<td></td>
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</tr>
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</table>
Figure 195: Pressure measurement for sample H.

### 22.1.8 Sample I (Unclamped)

Table 40: Gap distance and offset measurements for sample I.

<table>
<thead>
<tr>
<th>Replicate #</th>
<th>Gap distance (μm)</th>
<th>Left alignment structure</th>
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<th>Top Alignment</th>
</tr>
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<tbody>
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<td>1</td>
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<td>-7</td>
<td>32</td>
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<td>2</td>
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<td>19</td>
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<td>N/A</td>
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<td>4</td>
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<td>-7</td>
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<td>N/A</td>
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<td>5</td>
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<td>N/A</td>
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<td>6</td>
<td>40</td>
<td>19</td>
<td>22</td>
<td>N/A</td>
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<td>7</td>
<td>34</td>
<td>15</td>
<td>11</td>
<td>N/A</td>
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<tr>
<td>8</td>
<td>31</td>
<td>-3</td>
<td>39</td>
<td>N/A</td>
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<tr>
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<td>3.864367132</td>
<td>12.12710463</td>
<td>12.92026832</td>
<td></td>
</tr>
<tr>
<td>(+-) 95%</td>
<td>8.741198453</td>
<td>27.43151067</td>
<td>29.22564693</td>
<td></td>
</tr>
<tr>
<td>Gap High</td>
<td>2750.427038</td>
<td>Pascals</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gap Low</td>
<td>4476.418626</td>
<td>Pascals</td>
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<td></td>
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</tbody>
</table>
Figure 196: Pressure measurement for sample I.

### 22.1.9 Sample J (Unclamped)

Table 41: Gap distance and offset measurements for sample J.

<table>
<thead>
<tr>
<th>Replicate #</th>
<th>Gap distance (μm)</th>
<th>Left alignment structure</th>
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<th>Top Alignment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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<td>85</td>
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<td>-7</td>
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<tr>
<td>2</td>
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</tr>
<tr>
<td>6</td>
<td>127</td>
<td>81</td>
<td>-14</td>
<td>-16</td>
</tr>
<tr>
<td>7</td>
<td>135</td>
<td>88</td>
<td>-6</td>
<td>-11</td>
</tr>
<tr>
<td>8</td>
<td>128</td>
<td>61</td>
<td>2</td>
<td>-12</td>
</tr>
<tr>
<td>9</td>
<td>128</td>
<td>56</td>
<td>-4</td>
<td>-7</td>
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<tr>
<td>10</td>
<td>132</td>
<td>83</td>
<td>-13</td>
<td>-16</td>
</tr>
<tr>
<td>average</td>
<td>129.7</td>
<td>71.4</td>
<td>5.1</td>
<td>-11.5</td>
</tr>
<tr>
<td>stdev</td>
<td>3.093002856</td>
<td>13.26817412</td>
<td>5.10881591</td>
<td>4.196559437</td>
</tr>
<tr>
<td>(+- 95%)</td>
<td>6.99637246</td>
<td>30.01260986</td>
<td>11.55614159</td>
<td>9.492617447</td>
</tr>
<tr>
<td>Gap High</td>
<td>912.2967633</td>
<td>Pascals</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gap Low</td>
<td>1016.332285</td>
<td>Pascals</td>
<td></td>
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</tbody>
</table>
Figure 197: Pressure measurement for sample J.

22.1.10 Sample K (Unclamped)

Table 42: Gap distance and offset measurements for sample K.

<table>
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<tr>
<th>Replicate #</th>
<th>Gap distance (μm)</th>
<th>Left alignment structure</th>
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<th>Top Alignment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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<td>0</td>
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<td>2</td>
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<td>6</td>
<td>N/A</td>
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<tr>
<td>4</td>
<td>78</td>
<td>20</td>
<td>9</td>
<td>N/A</td>
</tr>
<tr>
<td>5</td>
<td>97</td>
<td>11</td>
<td>6</td>
<td>N/A</td>
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<tr>
<td>average</td>
<td>87.9</td>
<td>13.3</td>
<td>-12</td>
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<tr>
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<td>5.89632654</td>
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<tr>
<td>(+-) 95%</td>
<td>13.33749063</td>
<td>9.540409404</td>
<td>17.84289663</td>
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</tr>
<tr>
<td>Gap High</td>
<td>1231.832766</td>
<td>Pascals</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gap Low</td>
<td>1672.524962</td>
<td>Pascals</td>
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</table>
Figure 198: Pressure measurement for sample K.

### 22.1.11 Sample L (Unclamped)

Table 43: Gap distance and offset measurements for sample L.

<table>
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<tr>
<th>Replicate #</th>
<th>Gap distance (μm)</th>
<th>Left alignment structure</th>
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<th>Top Alignment</th>
</tr>
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<tbody>
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<td>1</td>
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<td>2</td>
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<td>-35</td>
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<td>24</td>
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<tr>
<td>3</td>
<td>97</td>
<td>-12</td>
<td>20</td>
<td>16</td>
</tr>
<tr>
<td>4</td>
<td>93</td>
<td>-14</td>
<td>21</td>
<td>23</td>
</tr>
<tr>
<td>5</td>
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</tr>
<tr>
<td>6</td>
<td>99</td>
<td>-7</td>
<td>16</td>
<td>21</td>
</tr>
<tr>
<td>7</td>
<td>101</td>
<td>-26</td>
<td>17</td>
<td>16</td>
</tr>
<tr>
<td>8</td>
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<tr>
<td>10</td>
<td>101</td>
<td>-23</td>
<td>15</td>
<td>26</td>
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<tr>
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<td>98.4</td>
<td>-24.3</td>
<td>-14.8</td>
<td>19.7</td>
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<tr>
<td>stdev</td>
<td>4.671426144</td>
<td>11.58591098</td>
<td>4.131182236</td>
<td>4.137900702</td>
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<tr>
<td>(+/-) 95%</td>
<td>10.56676594</td>
<td>26.20733065</td>
<td>9.344734218</td>
<td>9.359931389</td>
</tr>
<tr>
<td>Gap High</td>
<td>1144.4559</td>
<td>Pascals</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gap Low</td>
<td>1419.82314</td>
<td>Pascals</td>
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</table>
Figure 199: Pressure measurement for sample L.

### 22.1.12 Sample M (Unclamped)

Table 44: Gap distance and offset measurements for sample M.

<table>
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<tr>
<th>Replicate #</th>
<th>Gap distance (μm)</th>
<th>Left alignment structure</th>
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<th>Top Alignment</th>
</tr>
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<tbody>
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<td>40</td>
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<td>109</td>
<td>-7</td>
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<td>46</td>
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<td>3</td>
<td>106</td>
<td>-4</td>
<td>4</td>
<td>43</td>
</tr>
<tr>
<td>4</td>
<td>116</td>
<td>-4</td>
<td>5</td>
<td>44</td>
</tr>
<tr>
<td>5</td>
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<td>44</td>
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<td>46</td>
</tr>
<tr>
<td>9</td>
<td>108</td>
<td>-3</td>
<td>5</td>
<td>44</td>
</tr>
<tr>
<td>10</td>
<td>108</td>
<td>7</td>
<td>2</td>
<td>46</td>
</tr>
<tr>
<td>average</td>
<td>109.5</td>
<td>-1.3</td>
<td>-4.6</td>
<td>44</td>
</tr>
<tr>
<td>stdev</td>
<td>2.758824226</td>
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<td>2.59058123</td>
<td>1.825741858</td>
</tr>
<tr>
<td>(±) 95%</td>
<td>6.2404604</td>
<td>13.82310485</td>
<td>5.859894743</td>
<td>4.129828084</td>
</tr>
<tr>
<td>Gap High</td>
<td>1077.476776</td>
<td>Pascals</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gap Low</td>
<td>1207.710771</td>
<td>Pascals</td>
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</table>
Figure 200: Pressure measurement for sample M.

### 22.1.13 Sample N (Unclamped)

Table 45: Gap distance and offset measurements for sample N.

<table>
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<th>Replicate #</th>
<th>Gap distance (μm)</th>
<th>Left alignment structure</th>
<th>Right Alignment structure</th>
<th>Top Alignment</th>
</tr>
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<tbody>
<tr>
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<td>-157</td>
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<tr>
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<td>3</td>
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<td>-56</td>
<td>74</td>
<td>-156</td>
</tr>
<tr>
<td>4</td>
<td>239</td>
<td>-68</td>
<td>82</td>
<td>-152</td>
</tr>
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<td>5</td>
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<td>6</td>
<td>235</td>
<td>-62</td>
<td>71</td>
<td>-139</td>
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<td>-63</td>
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<td>86</td>
<td>-151</td>
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<td>9</td>
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<td>-156</td>
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<td>10</td>
<td>244</td>
<td>-60</td>
<td>65</td>
<td>-150</td>
</tr>
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<td>average</td>
<td>239.7</td>
<td>-60.1</td>
<td>-71.6</td>
<td>-152</td>
</tr>
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<td>10.03549257</td>
<td>7.717224602</td>
</tr>
<tr>
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<td>8.666081214</td>
<td>9.623474238</td>
<td>22.70028419</td>
<td>17.45636205</td>
</tr>
</tbody>
</table>

Gap High 502.1122753 Pascals

Gap Low 539.7807335 Pascals
Figure 201: Pressure measurement for sample N.

### 22.1.14 Sample O (Unclamped)

Table 46: Gap distance and offset measurements for sample O.

<table>
<thead>
<tr>
<th>Replicate #</th>
<th>Gap distance (μm)</th>
<th>Left alignment structure</th>
<th>Right Alignment structure</th>
<th>Top Alignment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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<td>5</td>
<td>14</td>
<td>37</td>
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<tr>
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</tr>
<tr>
<td>3</td>
<td>89</td>
<td>8</td>
<td>50</td>
<td>37</td>
</tr>
<tr>
<td>4</td>
<td>97</td>
<td>19</td>
<td>23</td>
<td>47</td>
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<tr>
<td>5</td>
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<td>91</td>
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<tr>
<td>average</td>
<td>90.7</td>
<td>14.1</td>
<td>-26.9</td>
<td>45.1</td>
</tr>
<tr>
<td>stdev</td>
<td>3.888730155</td>
<td>11.29847581</td>
<td>17.06490876</td>
<td>5.685263602</td>
</tr>
<tr>
<td>(+/-) 95%</td>
<td>8.796307612</td>
<td>25.55715227</td>
<td>38.60082362</td>
<td>12.86006627</td>
</tr>
</tbody>
</table>

Gap High | 1253.389811 | Pascals |
Gap Low | 1522.613383 | Pascals |
Figure 202: Pressure measurement for sample O.

### 22.1.15 Sample P (Unclamped)

Table 47: Gap distance and offset measurements for sample P.

<table>
<thead>
<tr>
<th>Replicate #</th>
<th>Gap distance (μm)</th>
<th>Left alignment structure</th>
<th>Right Alignment structure</th>
<th>Top Alignment</th>
</tr>
</thead>
<tbody>
<tr>
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<td>2</td>
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<tr>
<td>3</td>
<td>121</td>
<td>-47</td>
<td>-11</td>
<td>N/A</td>
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<td>10</td>
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<td>115.8</td>
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<tr>
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<td>11.54941076</td>
<td>2.40370085</td>
<td></td>
</tr>
<tr>
<td>(+)- 95%</td>
<td>5.416218755</td>
<td>26.12476714</td>
<td>5.437171323</td>
<td></td>
</tr>
<tr>
<td>Gap High</td>
<td>1028.803401</td>
<td>Pascals</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gap Low</td>
<td>1129.764325</td>
<td>Pascals</td>
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</table>
Figure 203: Pressure measurement for sample P.

22.1.16 Sample Q (Unclamped)

Table 48: Gap distance and offset measurements for sample Q.

<table>
<thead>
<tr>
<th>Replicate #</th>
<th>Gap distance (μm)</th>
<th>Left alignment structure</th>
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<th>Top Alignment</th>
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<td>1</td>
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<td>3</td>
<td>N/A</td>
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<td>-3</td>
<td>N/A</td>
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<td>7</td>
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<td>5.016638981</td>
<td>14.12995243</td>
<td>5.321862665</td>
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</tr>
<tr>
<td>(+- 95%)</td>
<td>11.34763738</td>
<td>31.96195239</td>
<td>12.03805335</td>
<td></td>
</tr>
<tr>
<td>Gap High</td>
<td>1372.712178</td>
<td>Pascals</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gap Low</td>
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<td>Pascals</td>
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</table>
Figure 204: Pressure measurement for sample Q.

### 22.1.17 Sample R (Unclamped)

Table 49: Gap distance and offset measurements for sample R.

<table>
<thead>
<tr>
<th>Replicate #</th>
<th>Gap distance (μm)</th>
<th>Left alignment structure</th>
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<th>Top Alignment</th>
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<tr>
<td>1</td>
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<td>-33</td>
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<td>N/A</td>
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<td>3</td>
<td>103</td>
<td>-20</td>
<td>-21</td>
<td>N/A</td>
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<tr>
<td>4</td>
<td>103</td>
<td>-9</td>
<td>-13</td>
<td>N/A</td>
</tr>
<tr>
<td>5</td>
<td>100</td>
<td>-6</td>
<td>-33</td>
<td>N/A</td>
</tr>
<tr>
<td>6</td>
<td>101</td>
<td>-7</td>
<td>-37</td>
<td>N/A</td>
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<td>7</td>
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<td>8</td>
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<td>-9</td>
<td>-46</td>
<td>N/A</td>
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<td>100</td>
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<td>-34</td>
<td>N/A</td>
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<td>10</td>
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<td>N/A</td>
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<td>average</td>
<td>101.4</td>
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</tr>
<tr>
<td>stdev</td>
<td>3.687817783</td>
<td>5.152130088</td>
<td>10.97471842</td>
<td></td>
</tr>
<tr>
<td>(+-) 95%</td>
<td>8.341843825</td>
<td>11.65411826</td>
<td>24.82481307</td>
<td></td>
</tr>
<tr>
<td>Gap High</td>
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<td>Pascals</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gap Low</td>
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<td>Pascals</td>
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</table>
Figure 205: Pressure measurement for sample R.

### 22.1.18 Sample S (Unclamped)

Table 50: Gap distance and offset measurements for sample S.

<table>
<thead>
<tr>
<th>Replicate #</th>
<th>Gap distance (μm)</th>
<th>Left alignment structure</th>
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<th>Top Alignment</th>
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<tbody>
<tr>
<td>1</td>
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<tr>
<td>2</td>
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<tr>
<td>3</td>
<td>56</td>
<td>-28</td>
<td>-21</td>
<td>-4</td>
</tr>
<tr>
<td>4</td>
<td>52</td>
<td>-24</td>
<td>-24</td>
<td>-25</td>
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<tr>
<td>5</td>
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<td>-17</td>
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<td>10</td>
<td>59</td>
<td>-32</td>
<td>-25</td>
<td>-23</td>
</tr>
<tr>
<td>average</td>
<td>59.6</td>
<td>-28.1</td>
<td>18.2</td>
<td>-17.3</td>
</tr>
<tr>
<td>stdev</td>
<td>6.501281925</td>
<td>4.357624225</td>
<td>5.613475849</td>
<td>6.12916525</td>
</tr>
<tr>
<td>(+-95%)</td>
<td>14.70589971</td>
<td>9.856945998</td>
<td>12.69768237</td>
<td>13.8641718</td>
</tr>
</tbody>
</table>

Gap High: 1678.300897 Pascals
Gap Low: 2777.818407 Pascals
22.1.19 Sample T (Unclamped)

Table 51: Gap distance and offset measurements for sample T.

<table>
<thead>
<tr>
<th>Replicate #</th>
<th>Gap distance (μm)</th>
<th>Left alignment structure</th>
<th>Right Alignment structure</th>
<th>Top Alignment</th>
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<tr>
<td>1</td>
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<td>22</td>
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<tr>
<td>2</td>
<td>56</td>
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<td>25</td>
<td>-30</td>
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<tr>
<td>3</td>
<td>52</td>
<td>15</td>
<td>15</td>
<td>-29</td>
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<tr>
<td>4</td>
<td>56</td>
<td>9</td>
<td>20</td>
<td>-28</td>
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<tr>
<td>5</td>
<td>54</td>
<td>7</td>
<td>17</td>
<td>-24</td>
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<td>13</td>
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<td>3.091206165</td>
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<tr>
<td>(+- 95%)</td>
<td>6.992308346</td>
<td>16.19959832</td>
<td>8.064628349</td>
<td>5.33158513</td>
</tr>
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Gap High: 2044.645653 Pascals
Gap Low: 2652.920272 Pascals

Figure 206: Pressure measurement for sample S.
22.1.20 Sample U (Unclamped)

Table 52: Gap distance and offset measurements for sample U.

<table>
<thead>
<tr>
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<th>Gap distance (μm)</th>
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<th>Top Alignment</th>
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<td>1</td>
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<td>2</td>
<td>57</td>
<td>19</td>
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<td>N/A</td>
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<tr>
<td>3</td>
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<td>N/A</td>
</tr>
<tr>
<td>4</td>
<td>65</td>
<td>0</td>
<td>-17</td>
<td>N/A</td>
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<tr>
<td>5</td>
<td>60</td>
<td>-19</td>
<td>-9</td>
<td>N/A</td>
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<td>8</td>
<td>59</td>
<td>-22</td>
<td>-9</td>
<td>N/A</td>
</tr>
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<td>52</td>
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<td>-9</td>
<td>N/A</td>
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<td>10</td>
<td>58</td>
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<td>11.1</td>
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</tr>
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<td>(+-) 95%</td>
<td>8.692282577</td>
<td>38.87672551</td>
<td>6.525476871</td>
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<tr>
<td>Gap High</td>
<td>1818.100426</td>
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<td>Gap Low</td>
<td>2435.329369</td>
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</table>
Figure 208: Pressure measurement for sample U.

22.1.21 Sample V (Unclamped)

Table 53: Gap distance and offset measurements for sample V.

<table>
<thead>
<tr>
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<th>Gap distance (μm)</th>
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<th>Top Alignment</th>
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<td>14</td>
<td>23</td>
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<td>68</td>
<td>16</td>
<td>14</td>
<td>N/A</td>
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<td>19</td>
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<td>2.716206505</td>
<td>10.14396372</td>
<td>12.87719776</td>
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</tr>
<tr>
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<td>6.144059114</td>
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</tr>
<tr>
<td>Gap High</td>
<td>1604.079586</td>
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<tr>
<td>Gap Low</td>
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</table>
Figure 209: Pressure measurement for sample V.

22.1.22 Sample W (Unclamped)

Table 54: Gap distance and offset measurements for sample W.

<table>
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<tr>
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<th>Gap distance (μm)</th>
<th>Left alignment structure</th>
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<th>Top Alignment</th>
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<td>-5</td>
</tr>
<tr>
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<td>-12</td>
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<td>-17</td>
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<td>-22</td>
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<td>-12</td>
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<td>10</td>
<td>76</td>
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<td>-14</td>
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<td>70.3</td>
<td>-0.5</td>
<td>14.4</td>
<td>-12.9</td>
</tr>
<tr>
<td>stdev</td>
<td>3.301514804</td>
<td>9.348202442</td>
<td>3.470510689</td>
<td>4.175324339</td>
</tr>
<tr>
<td>(+-) 95%</td>
<td>7.468026486</td>
<td>21.14563392</td>
<td>7.850295179</td>
<td>9.444583654</td>
</tr>
<tr>
<td>Gap High</td>
<td>1603.585224</td>
<td>Pascals</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gap Low</td>
<td>1984.780219</td>
<td>Pascals</td>
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</table>
Figure 210: Pressure measurement for sample W.

### 22.1.23 Sample X (Unclamped)

Table 55: Gap distance and offset measurements for sample X.

<table>
<thead>
<tr>
<th>Replicate #</th>
<th>Gap distance (µm)</th>
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<th>Right Alignment structure</th>
<th>Top Alignment</th>
</tr>
</thead>
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<td>0</td>
<td>N/A</td>
</tr>
<tr>
<td>2</td>
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<td>16</td>
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<td>31</td>
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<td>21</td>
<td>11</td>
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<td>23</td>
<td>N/A</td>
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<tr>
<td>7</td>
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<td>average</td>
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<tr>
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<td>11.33529395</td>
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</tr>
<tr>
<td>(+- 95%)</td>
<td>10.66583572</td>
<td>7.16895016</td>
<td>25.64043491</td>
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</tr>
<tr>
<td>Gap High</td>
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<td></td>
<td></td>
<td>Pascals</td>
</tr>
<tr>
<td>Gap Low</td>
<td>2201.986376</td>
<td></td>
<td></td>
<td>Pascals</td>
</tr>
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</table>
Figure 211: Pressure measurement for sample X.

### 22.1.24 Sample Y (Unclamped)

#### Table 56: Gap distance and offset measurements for sample Y.

<table>
<thead>
<tr>
<th>Replicate #</th>
<th>Gap distance (μm)</th>
<th>Left alignment structure</th>
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<th>Top Alignment</th>
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<tbody>
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<td>5</td>
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<td>-16</td>
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<td>-33</td>
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<td>N/A</td>
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<td>N/A</td>
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<td>-28</td>
<td>-22</td>
<td>N/A</td>
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<td>9</td>
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<td>2</td>
<td>N/A</td>
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<tr>
<td>10</td>
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<td>10.46900186</td>
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</tr>
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<td>(+-) 95%</td>
<td>4.422324095</td>
<td>26.0855669</td>
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<td></td>
</tr>
<tr>
<td>Gap High</td>
<td>1736.335599</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Gap Low</td>
<td>1980.188318</td>
<td>Pascals</td>
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</table>
Figure 212: Pressure measurement for sample Y.

### 22.1.25 Sample Z (Clamped)

#### Table 57: Gap distance and offset measurements for sample Z.

<table>
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<th>Replicate #</th>
<th>Gap distance (μm)</th>
<th>Left alignment structure</th>
<th>Right Alignment structure</th>
<th>Top Alignment</th>
</tr>
</thead>
<tbody>
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<td>1</td>
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<td>41</td>
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<td>N/A</td>
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<td>34</td>
<td>-9</td>
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<tr>
<td>average</td>
<td>32.1</td>
<td>25.7</td>
<td>8.9</td>
<td></td>
</tr>
<tr>
<td>stdev</td>
<td>5.152130088</td>
<td>10.15491124</td>
<td>2.424412873</td>
<td></td>
</tr>
<tr>
<td>(+-) 95%</td>
<td>11.65411826</td>
<td>22.97040922</td>
<td>5.484021918</td>
<td></td>
</tr>
</tbody>
</table>

| Gap High    | 2850.192464       | Pascals                  |                           |               |
| Gap Low     | 6099.402301       | Pascals                  |                           |               |
Figure 213: Pressure measurement for sample Z.

22.1.26 Sample Alpha

Table 58: Gap distance and offset measurements for sample Alpha.

<table>
<thead>
<tr>
<th>Replicate #</th>
<th>Gap (μm)</th>
<th>Distance</th>
<th>Left alignment structure</th>
<th>Right Alignment structure</th>
<th>Top Alignment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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</tr>
<tr>
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</tr>
<tr>
<td>3</td>
<td>22</td>
<td>-18</td>
<td>0</td>
<td>-42</td>
<td></td>
</tr>
<tr>
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<td>18</td>
<td>-17</td>
<td>-23</td>
<td>-39</td>
<td></td>
</tr>
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<td>0</td>
<td>-43</td>
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<td>20</td>
<td>-13</td>
<td>-23</td>
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<td>19</td>
<td>-22</td>
<td>-22</td>
<td>-41</td>
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<td>11.6</td>
<td>-40.8</td>
<td></td>
</tr>
<tr>
<td>stdev</td>
<td>1.398411798</td>
<td>3.604010112</td>
<td>10.80329168</td>
<td>4.184627954</td>
<td></td>
</tr>
<tr>
<td>(+-) 95%</td>
<td>3.163207486</td>
<td>8.152270874</td>
<td>24.43704578</td>
<td>9.465628431</td>
<td></td>
</tr>
<tr>
<td>Gap High</td>
<td>5576.46564</td>
<td>Pascals</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gap Low</td>
<td>7776.346675</td>
<td>Pascals</td>
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</table>
Figure 214: Pressure measurement for sample Alpha.

### 22.1.27 Sample Beta

Table 59: Gap distance and offset measurements for sample Beta.

<table>
<thead>
<tr>
<th>Replicate #</th>
<th>Gap distance (μm)</th>
<th>Left alignment structure</th>
<th>Right Alignment structure</th>
<th>Top Alignment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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<td>3</td>
<td>22</td>
<td>4</td>
<td>-18</td>
<td>-92</td>
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<td>25</td>
<td>-4</td>
<td>-30</td>
<td>-92</td>
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<td>6</td>
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<td>7</td>
<td>25</td>
<td>5</td>
<td>-22</td>
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<td>25.3</td>
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<tr>
<td>stdev</td>
<td>5.598610939</td>
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<td>2.898275349</td>
</tr>
<tr>
<td>(±) 95%</td>
<td>12.66405794</td>
<td>12.48319813</td>
<td>14.53480463</td>
<td>6.55589884</td>
</tr>
</tbody>
</table>

Gap High: 3284.887467 Pascals
Gap Low: 9869.280627 Pascals
Figure 215: Pressure measurement for sample Beta.

### 22.1.28 Sample Chi

Table 60: Gap distance and offset measurements for sample Chi.

<table>
<thead>
<tr>
<th>Replicate #</th>
<th>Gap distance (µm)</th>
<th>Left alignment structure</th>
<th>Right Alignment structure</th>
<th>Top Alignment</th>
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<tbody>
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<td>11</td>
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<td>-49</td>
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<tr>
<td>3</td>
<td>9</td>
<td>57</td>
<td>-29</td>
<td>-41</td>
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<td>12</td>
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<td>-45</td>
<td>-44</td>
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<td>-46</td>
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<td>-37</td>
<td>-47</td>
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<tr>
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<td>-28</td>
<td>-46</td>
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</tr>
<tr>
<td>10</td>
<td>17</td>
<td>60</td>
<td>-35</td>
<td>-46</td>
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<tr>
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<td>57.4</td>
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<tr>
<td>stdev</td>
<td>4.168666187</td>
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<td>5.16935414</td>
<td>2.766867463</td>
</tr>
<tr>
<td>(+-) 95%</td>
<td>9.429522915</td>
<td>8.610138582</td>
<td>11.69307906</td>
<td>6.2586542</td>
</tr>
<tr>
<td>Gap High</td>
<td>5462.560852</td>
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<td></td>
</tr>
<tr>
<td>Gap Low</td>
<td>31408.73388</td>
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</tbody>
</table>
Figure 216: Pressure measurement for sample Chi.

### 22.1.29 Sample Delta

Table 61: Gap distance and offset measurements for sample Delta.

<table>
<thead>
<tr>
<th>Replicate #</th>
<th>Gap distance (μm)</th>
<th>Left alignment structure</th>
<th>Right Alignment structure</th>
<th>Top Alignment</th>
</tr>
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<tbody>
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<td>-32</td>
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<td>-31</td>
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<td>-33</td>
</tr>
<tr>
<td>10</td>
<td>14</td>
<td>35</td>
<td>-30</td>
<td>-32</td>
</tr>
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<td>14.5</td>
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<td>33.6</td>
<td>-34.7</td>
</tr>
<tr>
<td>stdev</td>
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<td>4.552166761</td>
<td>8.771164879</td>
<td>3.368151488</td>
</tr>
<tr>
<td>(+-) 95%</td>
<td>9.492617447</td>
<td>10.29700121</td>
<td>19.84037496</td>
<td>7.618758665</td>
</tr>
<tr>
<td>Gap High</td>
<td>5197.751284</td>
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<td></td>
</tr>
<tr>
<td>Gap Low</td>
<td>24904.75949</td>
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</tbody>
</table>
Figure 217: Pressure measurement for sample Delta.

### 22.1.30 Sample Epsilon

Table 62: Gap distance and offset measurements for sample Epsilon

<table>
<thead>
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<th>Replicate #</th>
<th>Gap distance (μm)</th>
<th>Left alignment structure</th>
<th>Right Alignment structure</th>
<th>Top Alignment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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<tr>
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<td>-25</td>
</tr>
<tr>
<td>10</td>
<td>27</td>
<td>-20</td>
<td>16</td>
<td>-25</td>
</tr>
<tr>
<td>average</td>
<td>21.2</td>
<td>-20.7</td>
<td>-13.2</td>
<td>-25.7</td>
</tr>
<tr>
<td>stdev</td>
<td>3.190262964</td>
<td>3.164033993</td>
<td>3.425395354</td>
<td>3.433495142</td>
</tr>
<tr>
<td>(+-) 95%</td>
<td>7.216374824</td>
<td>7.157044893</td>
<td>7.748244291</td>
<td>7.766566011</td>
</tr>
<tr>
<td>Gap High</td>
<td>4388.584361</td>
<td>Pascals</td>
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<td></td>
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<tr>
<td>Gap Low</td>
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</tbody>
</table>
Figure 218: Pressure measurement for sample Epsilon.

### 22.1.31 Sample Phi

Table 63: Gap distance and offset measurements for sample Phi.

<table>
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<tr>
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<th>Gap distance (μm)</th>
<th>Left alignment structure</th>
<th>Right Alignment structure</th>
<th>Top Alignment</th>
</tr>
</thead>
<tbody>
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</tr>
<tr>
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<td>6.539622823</td>
</tr>
<tr>
<td>(+-) 95%</td>
<td>5.379355389</td>
<td>12.00731684</td>
<td>12.12041808</td>
<td>14.79262683</td>
</tr>
<tr>
<td>Gap High</td>
<td>4259.235099</td>
<td>Pascals</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gap Low</td>
<td>6733.44048</td>
<td>Pascals</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 219: Pressure measurement for sample Phi

22.2  25 μm Insert Assemblies

22.2.1 Sample Gamma (Unclamped)

Table 64: Gap distance and offset measurements for sample Gamma.

<table>
<thead>
<tr>
<th>Replicate #</th>
<th>Gap distance (μm)</th>
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<th>Top Alignment</th>
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<tbody>
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<td>5.050852513</td>
</tr>
<tr>
<td>(+-) 95%</td>
<td>53.79619594</td>
<td>27.01383234</td>
<td>10.62043193</td>
<td>11.42502839</td>
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<td>Gap High</td>
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<td>Pascals</td>
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<td></td>
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<tr>
<td>Gap Low</td>
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<td>Pascals</td>
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</table>
Figure 220: Pressure measurement for sample Gamma.

### 22.2.2 Sample Eta (Unclamped)

Table 65: Gap distance and offset measurements for sample Eta.

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<th>Replicate #</th>
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<th>Top Alignment</th>
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<tbody>
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<td>5</td>
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<td>-67.9</td>
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<tr>
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<td>2.514402955</td>
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<td>5.963779562</td>
</tr>
<tr>
<td>(+-) 95%</td>
<td>6.894050885</td>
<td>5.687579485</td>
<td>95.64839948</td>
<td>13.49006937</td>
</tr>
</tbody>
</table>

Gap High: 1715.513947 Pascals
Gap Low: 2117.063896 Pascals
Figure 221: Pressure measurement for sample Eta.

### 22.2.3 Sample Iota (Unclamped)

Table 66: Gap distance and offset measurements for sample Iota.

<table>
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<tr>
<th>Replicate #</th>
<th>Gap distance (μm)</th>
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<th>Top Alignment</th>
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<tbody>
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<td>stdev</td>
<td>2.170509413</td>
<td>4.391911758</td>
<td>21.04624538</td>
<td>4.954235001</td>
</tr>
<tr>
<td>(+-) 95%</td>
<td>4.909692292</td>
<td>9.934504396</td>
<td>47.60660704</td>
<td>11.20647957</td>
</tr>
<tr>
<td>Gap High</td>
<td>3324.67825</td>
<td>Pascals</td>
<td></td>
<td></td>
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<tr>
<td>Gap Low</td>
<td>4503.657361</td>
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</table>
Figure 222: Pressure measurement for sample Iota.

22.2.4 Sample Kappa (Unclamped)

Table 67: Gap distance and offset measurements for sample Kappa.

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<tr>
<th>Replicate #</th>
<th>Gap distance (μm)</th>
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<th>Top Alignment</th>
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<td>111</td>
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<td>42</td>
<td>111</td>
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<td>7.483236332</td>
<td>6.167148482</td>
<td>19.81169974</td>
<td>6.894050885</td>
</tr>
<tr>
<td>Gap High</td>
<td>2772.314051</td>
<td>Pascals</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gap Low</td>
<td>4154.600393</td>
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</tr>
</tbody>
</table>
Figure 223: Pressure measurement for sample Kappa.

### 22.2.5 Sample Lambda (Unclamped)

Table 68: Gap distance and offset measurements for sample Lambda.

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<th>Gap distance (μm)</th>
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<td>-2</td>
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<td>47</td>
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<td>67</td>
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<td>37</td>
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<td>10</td>
<td>70</td>
<td>-8</td>
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<td>49</td>
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<td>1.8</td>
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<tr>
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<td>7.448970506</td>
<td>25.9402301</td>
<td>22.81519778</td>
<td>13.19176818</td>
</tr>
<tr>
<td>Gap High</td>
<td>1740.536637</td>
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</tr>
<tr>
<td>Gap Low</td>
<td>2197.45191</td>
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</table>
Figure 224: Pressure measurement for sample Lambda.

### 22.2.6 Sample Mu (Unclamped)

Table 69: Gap distance and offset measurements for sample Mu.

<table>
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<th>Replicate #</th>
<th>Gap distance (µm)</th>
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<th>Top Alignment</th>
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<td>222</td>
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<td>77</td>
<td>74</td>
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<td>221</td>
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<td>2.319003617</td>
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<tr>
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<td>7.325838546</td>
<td>16.26963582</td>
<td>20.26142649</td>
<td>5.245586183</td>
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<tr>
<td>Gap High</td>
<td>1507.481342</td>
<td>Pascals</td>
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<td></td>
</tr>
<tr>
<td>Gap Low</td>
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<td>Pascals</td>
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</table>
Figure 225: Pressure measurement for sample Mu.

### 22.2.7 Sample Nu (Unclamped)

Table 70: Gap distance and offset measurements for sample Nu.

<table>
<thead>
<tr>
<th>Replicate #</th>
<th>Gap distance (μm)</th>
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<th>Top Alignment</th>
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<td>183</td>
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<td>25</td>
<td>185</td>
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<td>23.5</td>
<td>184</td>
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<td>6.948221195</td>
<td>2.538591035</td>
</tr>
<tr>
<td>(+-) 95%</td>
<td>6.312921004</td>
<td>54.28590552</td>
<td>15.71687634</td>
<td>5.742292922</td>
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<tr>
<td>Gap High</td>
<td>2266.879414</td>
<td>Pascals</td>
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</tr>
<tr>
<td>Gap Low</td>
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<td>Pascals</td>
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</tbody>
</table>
Figure 226: Pressure measurement for sample Nu.

### 22.2.8 Sample Omicron (Clamped)

Table 71: Gap distance and offset measurements for sample Omicron.

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<th>Gap distance (μm)</th>
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<th>Top Alignment</th>
</tr>
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<tr>
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<td>36</td>
<td>-50</td>
<td>17</td>
<td></td>
</tr>
<tr>
<td>average</td>
<td>8.1</td>
<td>37.7</td>
<td>-32</td>
<td>14.5</td>
</tr>
<tr>
<td>stdev</td>
<td>2.424412873</td>
<td>2.162817093</td>
<td>15.6347192</td>
<td>3.597838857</td>
</tr>
<tr>
<td>(+/-) 95%</td>
<td>5.484021918</td>
<td>4.892292264</td>
<td>35.36573483</td>
<td>8.138311496</td>
</tr>
<tr>
<td>Gap High</td>
<td>9180.466499</td>
<td>Pascals</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gap Low</td>
<td>47671.52256</td>
<td>Pascals</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 227: Pressure measurement for sample Omicron.

### 22.2.9 Sample Theta (Clamped)

Table 72: Gap distance and offset measurements for sample Theta.

<table>
<thead>
<tr>
<th>Replicate #</th>
<th>Gap distance (μm)</th>
<th>Left alignment structure</th>
<th>Right Alignment structure</th>
<th>Top Alignment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>-32</td>
<td>94</td>
<td>0</td>
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<tr>
<td>2</td>
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<td>-29</td>
<td>109</td>
<td>0</td>
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<tr>
<td>3</td>
<td>5</td>
<td>-45</td>
<td>115</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>-38</td>
<td>114</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
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</tr>
<tr>
<td>6</td>
<td>2</td>
<td>-31</td>
<td>112</td>
<td>0</td>
</tr>
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<td>7</td>
<td>4</td>
<td>-39</td>
<td>101</td>
<td>0</td>
</tr>
<tr>
<td>8</td>
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<td>0</td>
</tr>
<tr>
<td>10</td>
<td>5</td>
<td>-31</td>
<td>131</td>
<td>0</td>
</tr>
<tr>
<td>average</td>
<td>5.1</td>
<td>-36.4</td>
<td>112.6</td>
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</tr>
<tr>
<td>stdev</td>
<td>5.42524961</td>
<td>5.758086102</td>
<td>10.35159676</td>
<td>0</td>
</tr>
<tr>
<td>(±) 95%</td>
<td>12.27191462</td>
<td>13.02479076</td>
<td>23.41531188</td>
<td>0</td>
</tr>
<tr>
<td>Gap High</td>
<td>7178.693937</td>
<td>Pascals</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gap Low</td>
<td>N/A</td>
<td>Pascals</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 228: Pressure measurement for sample Theta.

### 22.2.10 Sample Rho (Clamped)

Table 73: Gap distance and offset measurements for sample Rho.

<table>
<thead>
<tr>
<th>Replicate #</th>
<th>Gap distance (μm)</th>
<th>Left alignment structure</th>
<th>Right Alignment structure</th>
<th>Top Alignment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8</td>
<td>-27</td>
<td>67</td>
<td>N/A</td>
</tr>
<tr>
<td>2</td>
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<td>N/A</td>
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<tr>
<td>3</td>
<td>10</td>
<td>-22</td>
<td>77</td>
<td>N/A</td>
</tr>
<tr>
<td>4</td>
<td>7</td>
<td>-26</td>
<td>56</td>
<td>N/A</td>
</tr>
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<td>5</td>
<td>7</td>
<td>-21</td>
<td>68</td>
<td>N/A</td>
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<td>6</td>
<td>8</td>
<td>-29</td>
<td>71</td>
<td>N/A</td>
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<tr>
<td>7</td>
<td>5</td>
<td>-22</td>
<td>66</td>
<td>N/A</td>
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<td>8</td>
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<td>-27</td>
<td>40</td>
<td>N/A</td>
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<td>9</td>
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<td>-18</td>
<td>76</td>
<td>N/A</td>
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<td>10</td>
<td>9</td>
<td>-25</td>
<td>60</td>
<td>N/A</td>
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<td>average</td>
<td>7.9</td>
<td>-24.2</td>
<td></td>
<td>64.9</td>
</tr>
<tr>
<td>stdev</td>
<td>1.370320319</td>
<td>3.359894178</td>
<td>10.82640804</td>
<td></td>
</tr>
<tr>
<td>(+/-) 95%</td>
<td>3.099664562</td>
<td>7.600080631</td>
<td>24.48933499</td>
<td></td>
</tr>
<tr>
<td>Gap High</td>
<td>11337.40556</td>
<td>Pascals</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gap Low</td>
<td>25978.94663</td>
<td>Pascals</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
22.2.11 Sample Sigma (Clamped)

Table 74: Gap distance and offset measurements for sample Sigma

<table>
<thead>
<tr>
<th>Replicate #</th>
<th>Gap distance (μm)</th>
<th>Left alignment structure</th>
<th>Right Alignment structure</th>
<th>Top Alignment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>16</td>
<td>83</td>
<td>-135</td>
<td>102</td>
</tr>
<tr>
<td>2</td>
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<tr>
<td>3</td>
<td>20</td>
<td>85</td>
<td>-137</td>
<td>104</td>
</tr>
<tr>
<td>4</td>
<td>12</td>
<td>95</td>
<td>-107</td>
<td>105</td>
</tr>
<tr>
<td>5</td>
<td>8</td>
<td>90</td>
<td>-107</td>
<td>99</td>
</tr>
<tr>
<td>6</td>
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</tr>
<tr>
<td>8</td>
<td>19</td>
<td>97</td>
<td>-127</td>
<td>102</td>
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<tr>
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<td>20</td>
<td>89</td>
<td>-100</td>
<td>100</td>
</tr>
<tr>
<td>10</td>
<td>13</td>
<td>90</td>
<td>-132</td>
<td>102</td>
</tr>
<tr>
<td>average</td>
<td>15.9</td>
<td>89.3</td>
<td>-116.8</td>
<td>102.4</td>
</tr>
<tr>
<td>stdev</td>
<td>4.040077007</td>
<td>4.643992535</td>
<td>14.33565873</td>
<td>2.118699811</td>
</tr>
<tr>
<td>(+-95%)</td>
<td>9.13865419</td>
<td>10.50471111</td>
<td>32.42726004</td>
<td>4.792498972</td>
</tr>
<tr>
<td>Gap High</td>
<td>4980.605475</td>
<td>Pascals</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gap Low</td>
<td>18444.20647</td>
<td>Pascals</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 229: Pressure measurement for sample Rho.
Figure 230: Pressure measurement for sample Sigma.

### 22.2.12 Sample Tao (Clamped)

Table 75: Gap distance and offset measurements for sample Tao

<table>
<thead>
<tr>
<th>Replicate #</th>
<th>Gap distance (µm)</th>
<th>Left alignment structure</th>
<th>Right Alignment structure</th>
<th>Top Alignment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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<td>-18</td>
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</tr>
<tr>
<td>2</td>
<td>7</td>
<td>-1</td>
<td>53</td>
<td>17</td>
</tr>
<tr>
<td>3</td>
<td>6</td>
<td>-3</td>
<td>80</td>
<td>18</td>
</tr>
<tr>
<td>4</td>
<td>7</td>
<td>4</td>
<td>60</td>
<td>19</td>
</tr>
<tr>
<td>5</td>
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<td>22</td>
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<tr>
<td>10</td>
<td>7</td>
<td>0</td>
<td>56</td>
<td>20</td>
</tr>
<tr>
<td>average</td>
<td>6.8</td>
<td>-3.1</td>
<td>57.9</td>
<td>19.9</td>
</tr>
<tr>
<td>stdev</td>
<td>1.032795559</td>
<td>10.79557523</td>
<td>11.49347641</td>
<td>1.791957341</td>
</tr>
<tr>
<td>(+-) 95%</td>
<td>2.336183554</td>
<td>24.41959116</td>
<td>25.99824364</td>
<td>4.053407505</td>
</tr>
<tr>
<td>Gap High</td>
<td>13649.86347</td>
<td>Pascals</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gap Low</td>
<td>27937.4521</td>
<td>Pascals</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 231: Pressure measurement for sample Tao.

### 22.2.13 Sample Upsilon (Clamped)

Table 76: Gap distance and offset measurements for sample Upsilon.

<table>
<thead>
<tr>
<th>Replicate #</th>
<th>Gap distance (µm)</th>
<th>Left alignment structure</th>
<th>Right Alignment structure</th>
<th>Top Alignment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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<td>75</td>
<td>-111</td>
<td>N/A</td>
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<td>2</td>
<td>4</td>
<td>80</td>
<td>-129</td>
<td>N/A</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>75</td>
<td>-120</td>
<td>N/A</td>
</tr>
<tr>
<td>4</td>
<td>3</td>
<td>72</td>
<td>-114</td>
<td>N/A</td>
</tr>
<tr>
<td>5</td>
<td>6</td>
<td>70</td>
<td>-99</td>
<td>N/A</td>
</tr>
<tr>
<td>6</td>
<td>4</td>
<td>73</td>
<td>-116</td>
<td>N/A</td>
</tr>
<tr>
<td>7</td>
<td>2</td>
<td>72</td>
<td>-117</td>
<td>N/A</td>
</tr>
<tr>
<td>8</td>
<td>3</td>
<td>70</td>
<td>-109</td>
<td>N/A</td>
</tr>
<tr>
<td>9</td>
<td>3</td>
<td>77</td>
<td>-119</td>
<td>N/A</td>
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<tr>
<td>10</td>
<td>2</td>
<td>70</td>
<td>-115</td>
<td>N/A</td>
</tr>
<tr>
<td>average</td>
<td>3.4</td>
<td>73.4</td>
<td>-114.9</td>
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</tr>
<tr>
<td>stdev</td>
<td>1.173787791</td>
<td>3.339993347</td>
<td>7.823753007</td>
<td></td>
</tr>
<tr>
<td>(+-) 95%</td>
<td>2.655107983</td>
<td>7.55506495</td>
<td>17.6973293</td>
<td></td>
</tr>
</tbody>
</table>

Gap High: 20595.44743 Pascals

Gap Low: 167417.0957 Pascals
22.2.14 Sample Omega (Clamped)

Table 77: Gap distance and offset measurements for sample Omega.

<table>
<thead>
<tr>
<th>Replicate #</th>
<th>Gap distance (µm)</th>
<th>Left alignment structure</th>
<th>Right Alignment structure</th>
<th>Top Alignment</th>
</tr>
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<tbody>
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<td>57</td>
<td>30</td>
<td>139</td>
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<tr>
<td>2</td>
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</tr>
<tr>
<td>3</td>
<td>27</td>
<td>57</td>
<td>24</td>
<td>137</td>
</tr>
<tr>
<td>4</td>
<td>25</td>
<td>79</td>
<td>26</td>
<td>130</td>
</tr>
<tr>
<td>5</td>
<td>27</td>
<td>70</td>
<td>26</td>
<td>134</td>
</tr>
<tr>
<td>6</td>
<td>22</td>
<td>69</td>
<td>20</td>
<td>137</td>
</tr>
<tr>
<td>7</td>
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<td>67</td>
<td>15</td>
<td>131</td>
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<td>8</td>
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<td>25.6</td>
<td>71.8</td>
<td>24.6</td>
<td>134.5</td>
</tr>
<tr>
<td>stdev</td>
<td>2.065591118</td>
<td>9.953223933</td>
<td>5.98516685</td>
<td>3.171049598</td>
</tr>
<tr>
<td>(+-) 95%</td>
<td>4.672367109</td>
<td>22.51419254</td>
<td>13.53844741</td>
<td>7.172914192</td>
</tr>
</tbody>
</table>

Gap High 4119.521202 Pascals
Gap Low 5958.994923 Pascals

Figure 232: Pressure measurement for sample Upsilon.
Figure 233: Pressure measurement for sample Omega.

### 22.2.15 Sample Xi (Clamped)

Table 78: Gap distance and offset measurements for sample Xi.

<table>
<thead>
<tr>
<th>Replicate #</th>
<th>Gap distance (μm)</th>
<th>Left alignment structure</th>
<th>Right Alignment structure</th>
<th>Top Alignment</th>
</tr>
</thead>
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<td>-126</td>
<td>28</td>
<td>N/A</td>
</tr>
<tr>
<td>3</td>
<td>18</td>
<td>-145</td>
<td>55</td>
<td>N/A</td>
</tr>
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<td>4</td>
<td>23</td>
<td>-121</td>
<td>45</td>
<td>N/A</td>
</tr>
<tr>
<td>5</td>
<td>25</td>
<td>-111</td>
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<td>N/A</td>
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<td>6</td>
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<td>-118</td>
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<td>N/A</td>
</tr>
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<td>7</td>
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</tr>
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<td>8</td>
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<td>-144</td>
<td>49</td>
<td>N/A</td>
</tr>
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<td>9</td>
<td>21</td>
<td>-141</td>
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<td>N/A</td>
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<td>10</td>
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<td>-119</td>
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</tr>
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<td>average</td>
<td>16.2</td>
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<td>53.9</td>
<td></td>
</tr>
<tr>
<td>stdev</td>
<td>8.024961059</td>
<td>13.016656</td>
<td>17.21401238</td>
<td></td>
</tr>
<tr>
<td>(+-) 95%</td>
<td>18.15246192</td>
<td>29.44367586</td>
<td>38.938096</td>
<td></td>
</tr>
<tr>
<td>Gap High</td>
<td>3630.239325</td>
<td>Pascals</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gap Low</td>
<td>N/A</td>
<td>Pascals</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 234: Pressure measurement for sample Xi.

22.2.16 Sample Psi (Clamped)

Table 79: Gap distance and offset measurements for sample Psi.

<table>
<thead>
<tr>
<th>Replicate #</th>
<th>Gap distance (μm)</th>
<th>Left alignment structure</th>
<th>Right Alignment structure</th>
<th>Top Alignment</th>
</tr>
</thead>
<tbody>
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<td>1</td>
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<td>-48</td>
<td>64</td>
<td>141</td>
</tr>
<tr>
<td>2</td>
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<td>144</td>
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<td>8</td>
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<td>-40</td>
<td>43</td>
<td>140</td>
</tr>
<tr>
<td>9</td>
<td>5</td>
<td>-50</td>
<td>69</td>
<td>143</td>
</tr>
<tr>
<td>10</td>
<td>10</td>
<td>-60</td>
<td>51</td>
<td>139</td>
</tr>
<tr>
<td>average</td>
<td>8.1</td>
<td>-52.9</td>
<td>52.1</td>
<td>141.4</td>
</tr>
<tr>
<td>stdev</td>
<td>3.142893218</td>
<td>6.556591255</td>
<td>15.6875747</td>
<td>2.170509413</td>
</tr>
<tr>
<td>(+-) 95%</td>
<td>7.109224458</td>
<td>14.83100942</td>
<td>35.48529397</td>
<td>4.909692292</td>
</tr>
<tr>
<td>Gap High</td>
<td>8199.47516</td>
<td>Pascals</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gap Low</td>
<td>125868.729</td>
<td>Pascals</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 235: Pressure measurement for sample Psi.

### 22.2.17 Sample Zeta (Clamped)

Table 80: Gap distance and offset measurements for sample Zeta.

<table>
<thead>
<tr>
<th>Replicate #</th>
<th>Gap distance (μm)</th>
<th>Left alignment structure</th>
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<th>Top Alignment</th>
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<tbody>
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<td>1</td>
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<td>41</td>
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<tr>
<td>2</td>
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<td>79</td>
<td>56</td>
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<td>3</td>
<td>10</td>
<td>77</td>
<td>11</td>
<td>N/A</td>
</tr>
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<td>4</td>
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<tr>
<td>5</td>
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<tr>
<td>8</td>
<td>14</td>
<td>30</td>
<td>50</td>
<td>N/A</td>
</tr>
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<td>9</td>
<td>13</td>
<td>76</td>
<td>45</td>
<td>N/A</td>
</tr>
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<td>10</td>
<td>18</td>
<td>40</td>
<td>50</td>
<td>N/A</td>
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<td>average</td>
<td>14.2</td>
<td>57.3</td>
<td>40.3</td>
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</tr>
<tr>
<td>stdev</td>
<td>2.347575582</td>
<td>21.45822816</td>
<td>16.48602101</td>
<td></td>
</tr>
<tr>
<td>(+-) 95%</td>
<td>5.310215965</td>
<td>48.53851209</td>
<td>37.29137953</td>
<td></td>
</tr>
<tr>
<td>Gap High</td>
<td>6391.915823</td>
<td>Pascals</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gap Low</td>
<td>14028.19885</td>
<td>Pascals</td>
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</table>
Figure 236: Pressure measurement for sample Zeta.

### 22.2.18 Sample AA (Clamped)

Table 81: Gap distance and offset measurements for sample AA.

<table>
<thead>
<tr>
<th>Replicate #</th>
<th>Gap distance (μm)</th>
<th>Left alignment structure</th>
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<th>Top Alignment</th>
</tr>
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<tbody>
<tr>
<td>1</td>
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<td>N/A</td>
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<td>-97</td>
<td>N/A</td>
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<td>N/A</td>
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<tr>
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<tr>
<td>8</td>
<td>3</td>
<td>43</td>
<td>-99</td>
<td>N/A</td>
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<td>45</td>
<td>-102</td>
<td>N/A</td>
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<td>10</td>
<td>5</td>
<td>28</td>
<td>-104</td>
<td>N/A</td>
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<td>-99.9</td>
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<tr>
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<td>1.33749351</td>
<td>6.511528238</td>
<td>3.107338983</td>
<td></td>
</tr>
<tr>
<td>(+- 95%)</td>
<td>3.025410319</td>
<td>14.72907688</td>
<td>7.02880078</td>
<td></td>
</tr>
<tr>
<td>Gap High</td>
<td>19715.34681</td>
<td>Pascals</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gap Low</td>
<td>454160.0319</td>
<td>Pascals</td>
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</tbody>
</table>
Figure 237: Pressure measurement for sample AA.

22.2.19 Sample BB (Clamped)

Table 82: Gap distance and offset measurements for sample BB.

<table>
<thead>
<tr>
<th>Replicate #</th>
<th>Gap distance (μm)</th>
<th>Left alignment structure</th>
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<th>Top Alignment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5</td>
<td>17</td>
<td>20</td>
<td>81</td>
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<tr>
<td>2</td>
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<tr>
<td>3</td>
<td>7</td>
<td>17</td>
<td>46</td>
<td>84</td>
</tr>
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<td>4</td>
<td>9</td>
<td>16</td>
<td>28</td>
<td>81</td>
</tr>
<tr>
<td>5</td>
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<td>76</td>
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<td>79</td>
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<tr>
<td>10</td>
<td>7</td>
<td>26</td>
<td>23</td>
<td>79</td>
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<td>17.1</td>
<td>32.7</td>
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<td>3.784471195</td>
<td>11.65284896</td>
<td>3.527668415</td>
</tr>
<tr>
<td>(+-) 95%</td>
<td>5.667552735</td>
<td>8.560473842</td>
<td>26.35874435</td>
<td>7.979585954</td>
</tr>
<tr>
<td>Gap High</td>
<td>8802.342965</td>
<td>Pascals</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gap Low</td>
<td>44028.23653</td>
<td>Pascals</td>
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</tbody>
</table>
Figure 238: Pressure measurement for sample BB.

### 22.2.20 Sample CC (Clamped)

Table 83: Gap distance and offset measurements for sample CC.

<table>
<thead>
<tr>
<th>Replicate #</th>
<th>Gap distance (μm)</th>
<th>Left alignment structure</th>
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<th>Top Alignment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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</tr>
<tr>
<td>2</td>
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</tr>
<tr>
<td>3</td>
<td>8</td>
<td>-171</td>
<td>39</td>
<td>44</td>
</tr>
<tr>
<td>4</td>
<td>9</td>
<td>-164</td>
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<td>47</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>-162</td>
<td>42</td>
<td>36</td>
</tr>
<tr>
<td>6</td>
<td>8</td>
<td>-177</td>
<td>44</td>
<td>45</td>
</tr>
<tr>
<td>7</td>
<td>8</td>
<td>-159</td>
<td>35</td>
<td>30</td>
</tr>
<tr>
<td>8</td>
<td>6</td>
<td>-193</td>
<td>38</td>
<td>46</td>
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<tr>
<td>9</td>
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<td>29</td>
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<tr>
<td>10</td>
<td>7</td>
<td>-179</td>
<td>42</td>
<td>43</td>
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<td>6.8</td>
<td>-170.2</td>
<td>40.6</td>
<td>39.8</td>
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<tr>
<td>stdev</td>
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<td>10.47536793</td>
<td>2.988868236</td>
<td>7.036413228</td>
</tr>
<tr>
<td>(+-) 95%</td>
<td>3.338100298</td>
<td>23.69528226</td>
<td>6.76081995</td>
<td>15.91636672</td>
</tr>
<tr>
<td>Gap High</td>
<td>12300.89015</td>
<td>Pascals</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gap Low</td>
<td>36022.89751</td>
<td>Pascals</td>
<td></td>
<td></td>
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</tbody>
</table>
Figure 239: Pressure measurement for sample CC.

### 22.2.21 Sample DD (Clamped)

Table 84: Gap distance and offset measurements for sample DD.

<table>
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<tr>
<th>Replicate #</th>
<th>Gap distance (μm)</th>
<th>Left alignment structure</th>
<th>Right Alignment structure</th>
<th>Top Alignment</th>
</tr>
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<tbody>
<tr>
<td>1</td>
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<td>-25</td>
<td>11</td>
</tr>
<tr>
<td>2</td>
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</tr>
<tr>
<td>3</td>
<td>20</td>
<td>13</td>
<td>-27</td>
<td>8</td>
</tr>
<tr>
<td>4</td>
<td>16</td>
<td>6</td>
<td>12</td>
<td>6</td>
</tr>
<tr>
<td>5</td>
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<td>8</td>
</tr>
<tr>
<td>6</td>
<td>19</td>
<td>9</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>7</td>
<td>19</td>
<td>15</td>
<td>-18</td>
<td>10</td>
</tr>
<tr>
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<td>12</td>
</tr>
<tr>
<td>10</td>
<td>22</td>
<td>15</td>
<td>9</td>
<td>4</td>
</tr>
<tr>
<td>Average</td>
<td>19.6</td>
<td>12.2</td>
<td>-6.9</td>
<td>6.9</td>
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<tr>
<td>Stdev</td>
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<td>3.293090409</td>
<td>17.89754794</td>
<td>3.446415207</td>
</tr>
<tr>
<td>(+-) 95%</td>
<td>6.844393209</td>
<td>7.448970506</td>
<td>40.48425344</td>
<td>7.795791198</td>
</tr>
<tr>
<td>Gap High</td>
<td>4715.844949</td>
<td>Pascals</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gap Low</td>
<td>9776.693511</td>
<td>Pascals</td>
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</tbody>
</table>
Figure 240: Pressure measurement for sample DD

### 22.2.22 Sample EE (Clamped)

Table 85: Gap distance and offset measurements for sample EE.

<table>
<thead>
<tr>
<th>Replicate #</th>
<th>Gap distance (μm)</th>
<th>Left alignment structure</th>
<th>Right Alignment structure</th>
<th>Top Alignment</th>
</tr>
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<tbody>
<tr>
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</tr>
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<td>107</td>
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<td>3</td>
<td>23</td>
<td>8</td>
<td>59</td>
<td>111</td>
</tr>
<tr>
<td>4</td>
<td>17</td>
<td>-13</td>
<td>29</td>
<td>106</td>
</tr>
<tr>
<td>5</td>
<td>12</td>
<td>-6</td>
<td>56</td>
<td>109</td>
</tr>
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<td>6</td>
<td>17</td>
<td>-13</td>
<td>20</td>
<td>106</td>
</tr>
<tr>
<td>7</td>
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</tr>
<tr>
<td>10</td>
<td>14</td>
<td>-6</td>
<td>22</td>
<td>106</td>
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<tr>
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<td>17.80792583</td>
<td>2.330951165</td>
</tr>
<tr>
<td>(+-) 95%</td>
<td>8.744449783</td>
<td>21.41147595</td>
<td>40.28152822</td>
<td>5.272611535</td>
</tr>
<tr>
<td>Gap High</td>
<td>4751.772629</td>
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<td></td>
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<tr>
<td>Gap Low</td>
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</table>
Figure 241: Pressure measurement for sample EE.

### 22.2.23 Sample FF (Clamped)

Table 86: Gap distance and offset measurements for sample FF.

<table>
<thead>
<tr>
<th>Replicate #</th>
<th>Gap distance (μm)</th>
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<th>Top Alignment</th>
</tr>
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<tbody>
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<tr>
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</tr>
<tr>
<td>3</td>
<td>27</td>
<td>40</td>
<td>-8</td>
<td>4</td>
</tr>
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<td>4</td>
<td>21</td>
<td>44</td>
<td>-9</td>
<td>-4</td>
</tr>
<tr>
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<td>36</td>
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<td>0</td>
</tr>
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<td>-12</td>
<td>0</td>
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<td>31</td>
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<td>0</td>
</tr>
<tr>
<td>8</td>
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<td>10</td>
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<td>-11</td>
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</tr>
<tr>
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<td>7.172914192</td>
<td>21.00536283</td>
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<td>8.42660361</td>
</tr>
<tr>
<td>Gap High</td>
<td>4202.743867</td>
<td>Pascals</td>
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<tr>
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<td>8136.423303</td>
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</table>
Figure 242: Pressure measurement for sample FF.

### 22.2.24 Sample GG (Clamped)

Table 87: Gap distance and offset measurements for sample GG.

<table>
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<tr>
<th>Replicate #</th>
<th>Gap distance (μm)</th>
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<th>Right Alignment structure</th>
<th>Top Alignment</th>
</tr>
</thead>
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</tr>
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<td>22</td>
</tr>
<tr>
<td>10</td>
<td>8</td>
<td>-42</td>
<td>79</td>
<td>20</td>
</tr>
<tr>
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<td>9.8</td>
<td>-48.5</td>
<td>77.5</td>
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</tr>
<tr>
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<td>4.222953153</td>
<td>4.089281382</td>
<td>3.921450979</td>
</tr>
<tr>
<td>(+) 95%</td>
<td>9.761315567</td>
<td>9.552320032</td>
<td>9.249954486</td>
<td>8.870322114</td>
</tr>
<tr>
<td>Gap High</td>
<td>6375.21836</td>
<td>Pascals</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gap Low</td>
<td>3223716.847</td>
<td>Pascals</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 243: Pressure measurement for sample GG.

22.2.25 Sample HH (Clamped)

Table 88: Gap distance and offset measurements for sample HH.

<table>
<thead>
<tr>
<th>Replicate #</th>
<th>Gap distance (μm)</th>
<th>Left alignment structure</th>
<th>Right Alignment structure</th>
<th>Top Alignment</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>4</td>
<td>3</td>
<td>-138</td>
<td>N/A</td>
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<td>2</td>
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<td>18</td>
<td>-113</td>
<td>N/A</td>
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<td>5</td>
<td>-118</td>
<td>N/A</td>
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<td>4</td>
<td>5</td>
<td>21</td>
<td>-139</td>
<td>N/A</td>
</tr>
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<td>5</td>
<td>8</td>
<td>13</td>
<td>-117</td>
<td>N/A</td>
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<td>6</td>
<td>9</td>
<td>19</td>
<td>-133</td>
<td>N/A</td>
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<td>7</td>
<td>5</td>
<td>-126</td>
<td>N/A</td>
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<td>6</td>
<td>20</td>
<td>-136</td>
<td>N/A</td>
</tr>
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<td>9</td>
<td>7</td>
<td>7</td>
<td>-115</td>
<td>N/A</td>
</tr>
<tr>
<td>10</td>
<td>12</td>
<td>20</td>
<td>-141</td>
<td>N/A</td>
</tr>
<tr>
<td>average</td>
<td>6.8</td>
<td>13.1</td>
<td>-127.6</td>
<td></td>
</tr>
<tr>
<td>stdev</td>
<td>2.440400696</td>
<td>7.355270219</td>
<td>11.03731046</td>
<td></td>
</tr>
<tr>
<td>(+-) 95%</td>
<td>5.520186374</td>
<td>16.63762124</td>
<td>24.96639626</td>
<td></td>
</tr>
<tr>
<td>Gap High</td>
<td>10122.22172</td>
<td>Pascals</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gap Low</td>
<td>97442.04592</td>
<td>Pascals</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 244: Pressure measurement for sample HH.

### 22.2.26 Sample II (Clamped)

Table 89: Gap distance and offset measurements for sample II.

<table>
<thead>
<tr>
<th>Replicate #</th>
<th>Gap distance (μm)</th>
<th>Left alignment structure</th>
<th>Right Alignment structure</th>
<th>Top Alignment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>14</td>
<td>22</td>
<td>-39</td>
<td>68</td>
</tr>
<tr>
<td>2</td>
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<td>66</td>
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<td>13</td>
<td>28</td>
<td>-51</td>
<td>70</td>
</tr>
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<td>14</td>
<td>28</td>
<td>-51</td>
<td>65</td>
</tr>
<tr>
<td>5</td>
<td>18</td>
<td>32</td>
<td>-36</td>
<td>63</td>
</tr>
<tr>
<td>6</td>
<td>16</td>
<td>33</td>
<td>-42</td>
<td>69</td>
</tr>
<tr>
<td>7</td>
<td>20</td>
<td>25</td>
<td>-49</td>
<td>68</td>
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<td>22</td>
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<td>65</td>
</tr>
<tr>
<td>10</td>
<td>21</td>
<td>24</td>
<td>-36</td>
<td>66</td>
</tr>
<tr>
<td>average</td>
<td>15.8</td>
<td>28.5</td>
<td>-42.3</td>
<td>66.7</td>
</tr>
<tr>
<td>stdev</td>
<td>4.442221666</td>
<td>4.719934086</td>
<td>6.307843442</td>
<td>2.110818693</td>
</tr>
<tr>
<td>(+/-) 95%</td>
<td>10.04830541</td>
<td>10.6764909</td>
<td>14.26834187</td>
<td>4.774671884</td>
</tr>
</tbody>
</table>

Gap High: 4824.597055 Pascals
Gap Low: 21681.89847 Pascals
Figure 245: Pressure measurement for sample II.

22.3 5 μm Insert Assemblies

22.3.1 Sample JJ (Clamped)

Table 90: Gap distance and offset measurements for sample JJ.

<table>
<thead>
<tr>
<th>Replicate #</th>
<th>Gap (μm)</th>
<th>Left alignment structure</th>
<th>Right Alignment structure</th>
<th>Top Alignment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6</td>
<td>-4</td>
<td>-12</td>
<td>63</td>
</tr>
<tr>
<td>2</td>
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<td>-12</td>
<td>56</td>
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<td>3</td>
<td>16</td>
<td>-10</td>
<td>-5</td>
<td>63</td>
</tr>
<tr>
<td>4</td>
<td>11</td>
<td>-4</td>
<td>-10</td>
<td>60</td>
</tr>
<tr>
<td>5</td>
<td>11</td>
<td>-8</td>
<td>-5</td>
<td>62</td>
</tr>
<tr>
<td>6</td>
<td>11</td>
<td>-8</td>
<td>-10</td>
<td>59</td>
</tr>
<tr>
<td>7</td>
<td>12</td>
<td>-15</td>
<td>-2</td>
<td>61</td>
</tr>
<tr>
<td>8</td>
<td>11</td>
<td>-10</td>
<td>-10</td>
<td>60</td>
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<tr>
<td>9</td>
<td>16</td>
<td>-6</td>
<td>-9</td>
<td>63</td>
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<tr>
<td>10</td>
<td>20</td>
<td>2</td>
<td>-10</td>
<td>59</td>
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<tr>
<td>average</td>
<td>12.8</td>
<td>-7</td>
<td>8.5</td>
<td>60.6</td>
</tr>
<tr>
<td>stdev</td>
<td>3.852848874</td>
<td>4.521553322</td>
<td>3.341656276</td>
<td>2.270584849</td>
</tr>
<tr>
<td>(+-) 95%</td>
<td>8.715144153</td>
<td>10.22775361</td>
<td>7.558826496</td>
<td>5.136062928</td>
</tr>
</tbody>
</table>

Gap High: 5796.273418 Pascals

Gap Low: 30529.26781 Pascals
Figure 246: Pressure measurement for sample JJ.

### 22.3.2 Sample KK (Clamped)

Table 91: Gap distance and offset measurements for sample KK.

<table>
<thead>
<tr>
<th>Replicate #</th>
<th>Gap distance (µm)</th>
<th>Left alignment structure</th>
<th>Right Alignment structure</th>
<th>Top Alignment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8</td>
<td>19</td>
<td>33</td>
<td>40</td>
</tr>
<tr>
<td>2</td>
<td>9</td>
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</tr>
<tr>
<td>3</td>
<td>4</td>
<td>23</td>
<td>21</td>
<td>35</td>
</tr>
<tr>
<td>4</td>
<td>12</td>
<td>4</td>
<td>27</td>
<td>36</td>
</tr>
<tr>
<td>5</td>
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<td>29</td>
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<td>36</td>
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<tr>
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<td>22</td>
<td>32</td>
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<tr>
<td>8</td>
<td>11</td>
<td>11</td>
<td>13</td>
<td>32</td>
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<tr>
<td>10</td>
<td>9</td>
<td>9</td>
<td>27</td>
<td>37</td>
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<tr>
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<td>9</td>
<td>19.3</td>
<td>-23.7</td>
<td>35.7</td>
</tr>
<tr>
<td>stdev</td>
<td>2.748737084</td>
<td>8.932462644</td>
<td>5.396500924</td>
<td>2.540778533</td>
</tr>
<tr>
<td>(+-) 95%</td>
<td>6.217643283</td>
<td>20.2052305</td>
<td>12.20688509</td>
<td>5.747241042</td>
</tr>
<tr>
<td>Gap High</td>
<td>8194.938981</td>
<td></td>
<td></td>
<td>Pascals</td>
</tr>
<tr>
<td>Gap Low</td>
<td>44820.8734</td>
<td></td>
<td></td>
<td>Pascals</td>
</tr>
</tbody>
</table>
Figure 247: Pressure measurement for sample KK.

### 22.3.3 Sample MM (Clamped)

Table 92: Gap distance and offset measurements for sample MM.

<table>
<thead>
<tr>
<th>Replicate #</th>
<th>Gap distance (μm)</th>
<th>Left alignment structure</th>
<th>Right Alignment structure</th>
<th>Top Alignment</th>
</tr>
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<tbody>
<tr>
<td>1</td>
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<td>-37</td>
<td>51</td>
<td>N/A</td>
</tr>
<tr>
<td>2</td>
<td>17</td>
<td>-13</td>
<td>45</td>
<td>N/A</td>
</tr>
<tr>
<td>3</td>
<td>19</td>
<td>-8</td>
<td>50</td>
<td>N/A</td>
</tr>
<tr>
<td>4</td>
<td>16</td>
<td>-12</td>
<td>46</td>
<td>N/A</td>
</tr>
<tr>
<td>5</td>
<td>13</td>
<td>-32</td>
<td>55</td>
<td>N/A</td>
</tr>
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<td>6</td>
<td>13</td>
<td>-12</td>
<td>43</td>
<td>N/A</td>
</tr>
<tr>
<td>7</td>
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<td>-30</td>
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<td>N/A</td>
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<tr>
<td>10</td>
<td>16</td>
<td>-14</td>
<td>53</td>
<td>N/A</td>
</tr>
<tr>
<td><strong>average</strong></td>
<td><strong>16.9</strong></td>
<td><strong>-19.8</strong></td>
<td><strong>-48.5</strong></td>
<td></td>
</tr>
<tr>
<td><strong>sdev</strong></td>
<td>3.034981237</td>
<td>11.43872565</td>
<td>3.778594683</td>
<td></td>
</tr>
<tr>
<td>(+- 95%)</td>
<td>6.865127559</td>
<td>25.87439742</td>
<td>8.547181173</td>
<td></td>
</tr>
<tr>
<td><strong>Gap High</strong></td>
<td>5247.506366</td>
<td>Pascals</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Gap Low</strong></td>
<td>12427.42834</td>
<td>Pascals</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 248: Pressure measurement for sample MM.

### 22.3.4 Sample NN (Clamped)

Table 93: Gap distance and offset measurements for sample NN.

<table>
<thead>
<tr>
<th>Replicate #</th>
<th>Gap distance (µm)</th>
<th>Left alignment structure</th>
<th>Right Alignment structure</th>
<th>Top Alignment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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<td>-15</td>
<td>-13</td>
<td>30</td>
</tr>
<tr>
<td>2</td>
<td>18</td>
<td>-33</td>
<td>-4</td>
<td>28</td>
</tr>
<tr>
<td>3</td>
<td>16</td>
<td>-3</td>
<td>-19</td>
<td>33</td>
</tr>
<tr>
<td>4</td>
<td>14</td>
<td>-12</td>
<td>8</td>
<td>21</td>
</tr>
<tr>
<td>5</td>
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</tr>
<tr>
<td>6</td>
<td>16</td>
<td>-17</td>
<td>-2</td>
<td>22</td>
</tr>
<tr>
<td>7</td>
<td>18</td>
<td>-23</td>
<td>-13</td>
<td>27</td>
</tr>
<tr>
<td>8</td>
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<td>-17</td>
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<td>28</td>
</tr>
<tr>
<td>10</td>
<td>18</td>
<td>-19</td>
<td>-1</td>
<td>26</td>
</tr>
<tr>
<td>average</td>
<td>15.1</td>
<td>-17.1</td>
<td>6.4</td>
<td>27.1</td>
</tr>
<tr>
<td>stdev</td>
<td>2.806737925</td>
<td>7.852105167</td>
<td>8.896940798</td>
<td>3.541813722</td>
</tr>
<tr>
<td>(+-) 95%</td>
<td>6.348841186</td>
<td>17.76146189</td>
<td>20.12488008</td>
<td>8.01158264</td>
</tr>
<tr>
<td>Gap High</td>
<td>5814.190942</td>
<td>Pascals</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gap Low</td>
<td>14250.41652</td>
<td>Pascals</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 249: Pressure measurement for sample NN.

### 22.3.5 Sample OO (Clamped)

Table 94: Gap distance and offset measurements for sample OO.

<table>
<thead>
<tr>
<th>Replicate #</th>
<th>Gap distance (μm)</th>
<th>Left alignment structure</th>
<th>Right Alignment structure</th>
<th>Top Alignment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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<td>0</td>
<td>-3</td>
<td>5</td>
</tr>
<tr>
<td>2</td>
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</tr>
<tr>
<td>3</td>
<td>18</td>
<td>4</td>
<td>16</td>
<td>3</td>
</tr>
<tr>
<td>4</td>
<td>19</td>
<td>-12</td>
<td>11</td>
<td>7</td>
</tr>
<tr>
<td>5</td>
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<td>3</td>
</tr>
<tr>
<td>10</td>
<td>16</td>
<td>4</td>
<td>21</td>
<td>2</td>
</tr>
<tr>
<td>average</td>
<td>16.9</td>
<td>2.1</td>
<td>-11.6</td>
<td>3.8</td>
</tr>
<tr>
<td>stdev</td>
<td>1.370320319</td>
<td>5.801340841</td>
<td>8.461678321</td>
<td>2.043961296</td>
</tr>
<tr>
<td>(+) 95%</td>
<td>3.099664562</td>
<td>13.12263298</td>
<td>19.14031636</td>
<td>4.623440451</td>
</tr>
<tr>
<td>Gap High</td>
<td>6235.487488</td>
<td>Pascals</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gap Low</td>
<td>9036.56717</td>
<td>Pascals</td>
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<td></td>
</tr>
</tbody>
</table>
Figure 250: Pressure measurement for sample OO.

22.3.6 Sample PP (Unclamped)

Table 95: Gap distance and offset measurements for sample PP.

<table>
<thead>
<tr>
<th>Replicate #</th>
<th>Gap distance (μm)</th>
<th>Left alignment structure</th>
<th>Right Alignment structure</th>
<th>Top Alignment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>161</td>
<td>16</td>
<td>-23</td>
<td>46</td>
</tr>
<tr>
<td>2</td>
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<td>9</td>
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<td>48</td>
</tr>
<tr>
<td>3</td>
<td>156</td>
<td>19</td>
<td>-21</td>
<td>47</td>
</tr>
<tr>
<td>4</td>
<td>159</td>
<td>11</td>
<td>-11</td>
<td>51</td>
</tr>
<tr>
<td>5</td>
<td>157</td>
<td>18</td>
<td>-9</td>
<td>47</td>
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<tr>
<td>6</td>
<td>152</td>
<td>6</td>
<td>-10</td>
<td>46</td>
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<tr>
<td>8</td>
<td>162</td>
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<td>9</td>
<td>158</td>
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<td>45</td>
</tr>
<tr>
<td>10</td>
<td>150</td>
<td>19</td>
<td>-12</td>
<td>47</td>
</tr>
<tr>
<td>average</td>
<td>158.6</td>
<td>13.1</td>
<td>14.6</td>
<td>47.2</td>
</tr>
</tbody>
</table>

stdev 5.168279318  5.130518709  5.660781257  1.988857852

(±) 95% 11.69064782  11.60523332  12.8046872  4.498796461

Gap High  732.3224131  Pascals

Gap Low  848.8748762  Pascals
Figure 251: Pressure measurement for sample PP.

### 22.3.7 Sample QQ (Unclamped)

Table 96: Gap distance and offset measurements for sample QQ.

<table>
<thead>
<tr>
<th>Replicate #</th>
<th>Gap distance (µm)</th>
<th>Left alignment structure</th>
<th>Right Alignment structure</th>
<th>Top Alignment</th>
</tr>
</thead>
<tbody>
<tr>
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<td>3</td>
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<td>4</td>
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<tr>
<td>10</td>
<td>95</td>
<td>1</td>
<td>-21</td>
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</tr>
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<td>103.6</td>
<td>2.5</td>
<td>24.4</td>
<td>5.6</td>
</tr>
<tr>
<td>std dev</td>
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<td>3.205897344</td>
<td>2.836272985</td>
<td>2.796823595</td>
</tr>
<tr>
<td>(+- 95%)</td>
<td>20.32166387</td>
<td>7.251739791</td>
<td>6.415649492</td>
<td>6.326414972</td>
</tr>
<tr>
<td>Gap High</td>
<td>1006.34267</td>
<td>Pascals</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gap Low</td>
<td>1497.480184</td>
<td>Pascals</td>
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<td></td>
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</table>
Figure 252: Pressure measurement for sample QQ.

### 22.3.8 Sample RR (Unclamped)

Table 97: Gap distance and offset measurements for sample RR.

<table>
<thead>
<tr>
<th>Replicate #</th>
<th>Gap distance (μm)</th>
<th>Left alignment structure</th>
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<th>Top Alignment</th>
</tr>
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<tbody>
<tr>
<td>1</td>
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<td>0</td>
<td>-21</td>
<td>52</td>
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<tr>
<td>2</td>
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</tr>
<tr>
<td>3</td>
<td>151</td>
<td>1</td>
<td>-17</td>
<td>50</td>
</tr>
<tr>
<td>4</td>
<td>155</td>
<td>2</td>
<td>-4</td>
<td>58</td>
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<tr>
<td>5</td>
<td>161</td>
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<td>-19</td>
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<td>-18</td>
<td>53</td>
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<tr>
<td>8</td>
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<td>0</td>
<td>-6</td>
<td>55</td>
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<td>9</td>
<td>143</td>
<td>-5</td>
<td>-14</td>
<td>56</td>
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<tr>
<td>10</td>
<td>152</td>
<td>0</td>
<td>-6</td>
<td>55</td>
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<td>average</td>
<td>152.3</td>
<td>-0.3</td>
<td>12.3</td>
<td>53</td>
</tr>
<tr>
<td>stdev</td>
<td>4.945255864</td>
<td>1.82878223</td>
<td>6.290204024</td>
<td>2.867441756</td>
</tr>
<tr>
<td>(+- 95%)</td>
<td>11.18616876</td>
<td>4.136705404</td>
<td>14.2284415</td>
<td>6.486153251</td>
</tr>
<tr>
<td>Gap High</td>
<td>762.8024994</td>
<td>Pascals</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gap Low</td>
<td>883.7380224</td>
<td>Pascals</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
22.3.9 Sample SS (Unclamped)

Table 98: Gap distance and offset measurements for sample SS.

<table>
<thead>
<tr>
<th>Replicate #</th>
<th>Gap distance (μm)</th>
<th>Left alignment structure</th>
<th>Right Alignment structure</th>
<th>Top Alignment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>119</td>
<td>0</td>
<td>-12</td>
<td>N/A</td>
</tr>
<tr>
<td>2</td>
<td>129</td>
<td>0</td>
<td>-14</td>
<td>N/A</td>
</tr>
<tr>
<td>3</td>
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<td>N/A</td>
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<tr>
<td>4</td>
<td>129</td>
<td>0</td>
<td>-13</td>
<td>N/A</td>
</tr>
<tr>
<td>5</td>
<td>127</td>
<td>0</td>
<td>-8</td>
<td>N/A</td>
</tr>
<tr>
<td>6</td>
<td>121</td>
<td>0</td>
<td>-4</td>
<td>N/A</td>
</tr>
<tr>
<td>7</td>
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<td>N/A</td>
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<tr>
<td>9</td>
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<td>0</td>
<td>-27</td>
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<td>10</td>
<td>122</td>
<td>0</td>
<td>-11</td>
<td>N/A</td>
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<tr>
<td>average</td>
<td>126.7</td>
<td>0</td>
<td>16</td>
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</tr>
<tr>
<td>stdev</td>
<td>10.76052456</td>
<td>0</td>
<td>10.21980648</td>
<td></td>
</tr>
<tr>
<td>(+/-) 95%</td>
<td>24.34030656</td>
<td>0</td>
<td>23.11720225</td>
<td></td>
</tr>
</tbody>
</table>

Gap High: 825.6581371 Pascals
Gap Low: 1218.327781 Pascals
Figure 254: Pressure measurement for sample SS.

22.3.10 Sample TT (Unclamped)

Table 99: Gap distance and offset measurements for sample TT.

<table>
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<tr>
<th>Replicate #</th>
<th>Gap distance (μm)</th>
<th>Left alignment structure</th>
<th>Right Alignment structure</th>
<th>Top Alignment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>127</td>
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<td>139</td>
</tr>
<tr>
<td>2</td>
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<td>8</td>
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<td>136</td>
</tr>
<tr>
<td>10</td>
<td>119</td>
<td>-18</td>
<td>28</td>
<td>137</td>
</tr>
<tr>
<td>average</td>
<td>122.5</td>
<td>-25.7</td>
<td>-18.3</td>
<td>135.6</td>
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<tr>
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<td>2.915475947</td>
<td>8.165646195</td>
<td>8.124722217</td>
<td>3.373096171</td>
</tr>
<tr>
<td>(+-) 95%</td>
<td>6.594806593</td>
<td>18.47069169</td>
<td>18.37812166</td>
<td>7.629943538</td>
</tr>
<tr>
<td>Gap High</td>
<td>966.0160733</td>
<td>Pascals</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gap Low</td>
<td>1075.945387</td>
<td>Pascals</td>
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</table>
Figure 255: Pressure measurement for sample TT.

### 22.3.11 Sample LL (Clamped)

Table 100: Gap distance and offset measurements for sample LL.

<table>
<thead>
<tr>
<th>Replicate #</th>
<th>Gap distance (μm)</th>
<th>Left alignment structure</th>
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<th>Top Alignment</th>
</tr>
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<tbody>
<tr>
<td>1</td>
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<td>-6</td>
<td>15</td>
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</tr>
<tr>
<td>2</td>
<td>13</td>
<td>-5</td>
<td>-1</td>
<td>N/A</td>
</tr>
<tr>
<td>3</td>
<td>11</td>
<td>-4</td>
<td>17</td>
<td>N/A</td>
</tr>
<tr>
<td>4</td>
<td>15</td>
<td>0</td>
<td>-11</td>
<td>N/A</td>
</tr>
<tr>
<td>5</td>
<td>11</td>
<td>-7</td>
<td>15</td>
<td>N/A</td>
</tr>
<tr>
<td>6</td>
<td>12</td>
<td>-2</td>
<td>-6</td>
<td>N/A</td>
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<tr>
<td>7</td>
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<tr>
<td>10</td>
<td>13</td>
<td>1</td>
<td>-13</td>
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</table>

<table>
<thead>
<tr>
<th></th>
<th>average</th>
<th>stdev</th>
<th>(+- 95%)</th>
<th>Gap High</th>
<th>Gap Low</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>12.1</td>
<td>1.595131482</td>
<td>3.608187412</td>
<td>7939.022809</td>
<td>14685.63476</td>
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<tr>
<td></td>
<td>-5.2</td>
<td>4.104198392</td>
<td>9.283696764</td>
<td>Pascals</td>
<td>Pascals</td>
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<td></td>
<td>-3.9</td>
<td>13.016656</td>
<td>29.44367586</td>
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</tr>
</tbody>
</table>

Gap High: 7939.022809 Pascals
Gap Low: 14685.63476 Pascals
Figure 256: Pressure measurement for sample LL.

### 22.4 50 μm Insert Assemblies

#### 22.4.1 Sample VV (Unclamped)

Table 101: Gap distance and offset measurements for sample VV.

<table>
<thead>
<tr>
<th>Replicate #</th>
<th>Gap distance (μm)</th>
<th>Left alignment structure</th>
<th>Right Alignment structure</th>
<th>Top Alignment</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>52</td>
<td>-7</td>
<td>51</td>
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</tr>
<tr>
<td>2</td>
<td>48</td>
<td>-14</td>
<td>45</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>54</td>
<td>-19</td>
<td>36</td>
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<tr>
<td>4</td>
<td>47</td>
<td>-23</td>
<td>44</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>46</td>
<td>-22</td>
<td>31</td>
<td></td>
</tr>
<tr>
<td>6</td>
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<td></td>
</tr>
<tr>
<td>8</td>
<td>52</td>
<td>-15</td>
<td>45</td>
<td></td>
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<td>50</td>
<td>-26</td>
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<tr>
<td>10</td>
<td>52</td>
<td>-23</td>
<td>36</td>
<td></td>
</tr>
<tr>
<td>average</td>
<td>49.8</td>
<td>-18.6</td>
<td>-43.8</td>
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</tr>
<tr>
<td>stdev</td>
<td>2.616188916</td>
<td>5.561774297</td>
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</tr>
<tr>
<td>(+-95%)</td>
<td>5.917819328</td>
<td>12.58073346</td>
<td>23.86264079</td>
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</table>

Gap High 2238.200627 Pascals
Gap Low 2841.87468 Pascals
Figure 257: Pressure measurement for sample VV.

### 22.4.2 Sample WW (Unclamped)

Table 102: Gap distance and offset measurements for sample WW.

<table>
<thead>
<tr>
<th>Replicate #</th>
<th>Gap distance (μm)</th>
<th>Left alignment structure</th>
<th>Right Alignment structure</th>
<th>Top Alignment</th>
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<tbody>
<tr>
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</tr>
<tr>
<td>2</td>
<td>57</td>
<td>-1</td>
<td>-36</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>56</td>
<td>-5</td>
<td>-11</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>43</td>
<td>-4</td>
<td>-34</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>51</td>
<td>-8</td>
<td>-18</td>
<td></td>
</tr>
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</tr>
<tr>
<td>7</td>
<td>56</td>
<td>-11</td>
<td>-14</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>52</td>
<td>-9</td>
<td>-28</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>39</td>
<td>-5</td>
<td>-13</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>50</td>
<td>-12</td>
<td>-31</td>
<td></td>
</tr>
<tr>
<td>average</td>
<td>52.9</td>
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<td>24.2</td>
<td></td>
</tr>
<tr>
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<td>8.225299724</td>
<td>3.334999584</td>
<td>10.10830242</td>
<td></td>
</tr>
<tr>
<td>(+-) 95%</td>
<td>18.60562798</td>
<td>7.543769058</td>
<td>22.86498007</td>
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</tr>
<tr>
<td>Gap High</td>
<td>1744.025774</td>
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<td></td>
</tr>
<tr>
<td>Gap Low</td>
<td>3636.388445</td>
<td>Pascals</td>
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</table>
22.4.3 Sample XX (Unclamped)

Table 103: Gap distance and offset measurements for sample XX.

<table>
<thead>
<tr>
<th>Replicate #</th>
<th>Gap distance (µm)</th>
<th>Left alignment structure</th>
<th>Right Alignment structure</th>
<th>Top Alignment</th>
</tr>
</thead>
<tbody>
<tr>
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<td>24</td>
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</tr>
<tr>
<td>2</td>
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</tr>
<tr>
<td>3</td>
<td>3</td>
<td>-23</td>
<td>7</td>
<td></td>
</tr>
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<td>5</td>
<td>-30</td>
<td>32</td>
<td></td>
</tr>
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<td>5</td>
<td>11</td>
<td>-37</td>
<td>14</td>
<td></td>
</tr>
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<td>6</td>
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<td></td>
</tr>
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<td>8</td>
<td>22</td>
<td>-32</td>
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<td>7</td>
<td>-28</td>
<td>16</td>
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</tr>
<tr>
<td>10</td>
<td>15</td>
<td>-15</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>average</td>
<td>12.6</td>
<td>-25.7</td>
<td>-14.9</td>
<td></td>
</tr>
<tr>
<td>stdev</td>
<td>6.003702561</td>
<td>7.616502551</td>
<td>10.09345222</td>
<td></td>
</tr>
<tr>
<td>(+/-) 95%</td>
<td>13.58037519</td>
<td>17.22852877</td>
<td>22.83138893</td>
<td></td>
</tr>
<tr>
<td>Gap High</td>
<td>4763.402252</td>
<td>Pascals</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gap Low</td>
<td>N/A</td>
<td>Pascals</td>
<td></td>
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</tr>
</tbody>
</table>
Figure 259: Pressure measurement for sample XX.

22.4.4 Sample YY (Unclamped)

Table 104: Gap distance and offset measurements for sample YY.

<table>
<thead>
<tr>
<th>Replicate #</th>
<th>Gap distance (μm)</th>
<th>Left alignment structure</th>
<th>Right Alignment structure</th>
<th>Top Alignment</th>
</tr>
</thead>
<tbody>
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<td>1</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>24</td>
<td>4</td>
<td>-13</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>26</td>
<td>-12</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>24</td>
<td>-10</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>24</td>
<td>-7</td>
<td>-6</td>
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<td>-12</td>
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</tr>
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<tr>
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<td>6.292853089</td>
<td>6.999206304</td>
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</tr>
<tr>
<td>(+-) 95%</td>
<td>13.03569839</td>
<td>14.23443369</td>
<td>15.83220466</td>
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</tr>
<tr>
<td>Gap High</td>
<td>3904.961045</td>
<td>Pascals</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gap Low</td>
<td>21265.56005</td>
<td>Pascals</td>
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<td></td>
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</table>
Figure 260: Pressure measurement for sample YY.

### 22.4.5 Sample ZZ (Unclamped)

Table 105: Gap distance and offset measurements for sample ZZ.

<table>
<thead>
<tr>
<th>Replicate #</th>
<th>Gap distance (μm)</th>
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<th>Top Alignment</th>
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<tbody>
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<td>1</td>
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<td>24</td>
<td>-47</td>
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<td>12</td>
<td>47</td>
<td>-38</td>
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<td>10</td>
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<td>-49</td>
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<td>49</td>
<td>-35</td>
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<td>34.2</td>
<td>39.2</td>
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<tr>
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<td>10.03106287</td>
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<tr>
<td>(+-) 95%</td>
<td>6.831922394</td>
<td>22.6902642</td>
<td>18.27730838</td>
<td></td>
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Gap High: 9496.527195 Pascals
Gap Low: N/A Pascals
Figure 261: Pressure measurement for sample ZZ.

22.4.6 Sample AAA (Unclamped)

Table 106: Gap distance and offset measurements for sample AAA.

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<thead>
<tr>
<th>Replicate #</th>
<th>Gap distance (μm)</th>
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<th>Top Alignment</th>
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<tbody>
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</tr>
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<td>4</td>
<td>15</td>
<td>-42</td>
<td>39</td>
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<tr>
<td>5</td>
<td>20</td>
<td>-33</td>
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</tr>
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<td>6</td>
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<td>-45</td>
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<td>-38</td>
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<td>21</td>
<td>-42</td>
<td>38</td>
<td></td>
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<td>15</td>
<td>-44</td>
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<tr>
<td>10</td>
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</tr>
<tr>
<td>(+-) 95%</td>
<td>8.120828529</td>
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</tr>
<tr>
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<td>Pascals</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gap Low</td>
<td>15827.5091</td>
<td>Pascals</td>
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</table>
Figure 262: Pressure measurement for sample AAA.

### 22.4.7 Sample BBB (Unclamped)

Table 107: Gap distance and offset measurements for sample BBB.

<table>
<thead>
<tr>
<th>Replicate #</th>
<th>Gap distance (μm)</th>
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<th>Top Alignment</th>
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<td>34</td>
<td>-107</td>
<td>-19</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>43</td>
<td>-118</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>44</td>
<td>-100</td>
<td>-9</td>
<td></td>
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<tr>
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<td>41</td>
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<td></td>
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<tr>
<td>7</td>
<td>33</td>
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<td>-8</td>
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<td></td>
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<td>32</td>
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<td>39.6</td>
<td>-110.6</td>
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<tr>
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<td>5.316640543</td>
<td>13.20101006</td>
<td>9.445163371</td>
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<tr>
<td>(+-) 95%</td>
<td>12.02624091</td>
<td>29.86068476</td>
<td>21.36495955</td>
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</tr>
<tr>
<td>Gap High</td>
<td>2415.586646</td>
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<td></td>
</tr>
<tr>
<td>Gap Low</td>
<td>4522.693396</td>
<td>Pascals</td>
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</table>
Figure 263: Pressure measurement for sample BBB.

### 22.4.8 Sample CCC (Clamped)

Table 108: Gap distance and offset measurements for sample CCC.

<table>
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<tr>
<th>Replicate #</th>
<th>Gap distance (μm)</th>
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<th>Top Alignment</th>
</tr>
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<tbody>
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<td><strong>-59.1</strong></td>
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<td><strong>10.28969279</strong></td>
<td><strong>2.273030283</strong></td>
</tr>
<tr>
<td><strong>(+-) 95%</strong></td>
<td><strong>5.1415945</strong></td>
<td><strong>21.90626293</strong></td>
<td><strong>23.2752851</strong></td>
<td><strong>5.1415945</strong></td>
</tr>
</tbody>
</table>

Gap High: 10712.24892 Pascals

Gap Low: 91804.4414 Pascals
Figure 264: Pressure measurement for sample CCC.

### 22.4.9 Sample DDD (Clamped)

Table 109: Gap distance and offset measurements for sample DDD.

<table>
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<tr>
<th>Replicate #</th>
<th>Gap distance (μm)</th>
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<td>5.375872022</td>
<td>5.375872022</td>
</tr>
<tr>
<td>(+-) 95%</td>
<td>12.16022251</td>
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<td>12.16022251</td>
<td>12.16022251</td>
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<tr>
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<td>Pascals</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gap Low</td>
<td>N/A</td>
<td>Pascals</td>
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</table>
Figure 265: Pressure measurement for sample DDD.

### Table 110: Gap distance and offset measurements for sample EEE.

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<th>Top Alignment</th>
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<td>8</td>
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<td>14</td>
<td>-14</td>
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<td></td>
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<td>9</td>
<td>16</td>
<td>-4</td>
<td>9</td>
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<tr>
<td>10</td>
<td>15</td>
<td>-17</td>
<td>8</td>
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<tr>
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</tr>
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<td>10.71900572</td>
<td>15.46159688</td>
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</tr>
<tr>
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<td></td>
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<tr>
<td>Gap Low</td>
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<td>Pascals</td>
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</table>
22.4.11 Sample FFF (Clamped)

Table 111: Gap distance and offset measurements for sample FFF.

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<th>Top Alignment</th>
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<tr>
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<tr>
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<tr>
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<tr>
<td>10</td>
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</tr>
<tr>
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<td>-60.2</td>
<td>-7.9</td>
<td></td>
</tr>
<tr>
<td>stdev</td>
<td>2.988868236</td>
<td>11.45813636</td>
<td>6.154492487</td>
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</tr>
<tr>
<td>(+-) 95%</td>
<td>6.76081995</td>
<td>25.91830445</td>
<td>13.92146201</td>
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</table>

Gap High 8118.554774 Pascals
Gap Low 67806.11728 Pascals

Figure 266: Pressure measurement for sample EEE.
Figure 267: Pressure measurement for sample FFF.

22.4.12 Sample GGG (Clamped)

Table 112: Gap distance and offset measurements for sample GGG.

<table>
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<tr>
<th>Replicate #</th>
<th>Gap distance (μm)</th>
<th>Left alignment structure</th>
<th>Right Alignment structure</th>
<th>Top Alignment</th>
</tr>
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<tr>
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</tr>
<tr>
<td>3</td>
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<tr>
<td>4</td>
<td>36</td>
<td>-24</td>
<td>-24</td>
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<td>5</td>
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<td>-12</td>
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<td></td>
</tr>
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<td>-13</td>
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<td>30</td>
<td>-12</td>
<td>-12</td>
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<td>10</td>
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<td>-11</td>
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</tr>
<tr>
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<tr>
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<td></td>
</tr>
<tr>
<td>(±) 95%</td>
<td>7.777538325</td>
<td>11.9241709</td>
<td>11.9241709</td>
<td></td>
</tr>
<tr>
<td>Gap High</td>
<td>2874.936268</td>
<td>Pascals</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gap Low</td>
<td>4482.26543</td>
<td>Pascals</td>
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</table>
Figure 268: Pressure measurement for sample GGG.

22.4.13 Sample HHH (Clamped)

Table 113: Gap distance and offset measurements for sample HHH.

<table>
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<tr>
<th>Replicate #</th>
<th>Gap distance (μm)</th>
<th>Left alignment structure</th>
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<th>Top Alignment</th>
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<td>1</td>
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<td>6</td>
<td>-46</td>
<td>-8</td>
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<td>4</td>
<td>19</td>
<td>-52</td>
<td>-10</td>
<td></td>
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<tr>
<td>5</td>
<td>12</td>
<td>-44</td>
<td>-10</td>
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<td>13</td>
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<td>-20</td>
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<td>8</td>
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<td>10</td>
<td>8</td>
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<td>-7</td>
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<tr>
<td>average</td>
<td>9.8</td>
<td>-51.3</td>
<td>8.3</td>
<td></td>
</tr>
<tr>
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<td>3.994440581</td>
<td>12.69339286</td>
<td>7.832269431</td>
<td></td>
</tr>
<tr>
<td>(+-) 95%</td>
<td>9.035424594</td>
<td>28.71245464</td>
<td>17.71659345</td>
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</tr>
<tr>
<td>Gap High</td>
<td>6620.910377</td>
<td>Pascals</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gap Low</td>
<td>163107.0751</td>
<td>Pascals</td>
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</tbody>
</table>
Figure 269: Pressure measurement for sample HHH.

22.4.14 Sample III (Clamped)

Table 114: Gap distance and offset measurements for sample III.

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<tr>
<th>Replicate #</th>
<th>Gap distance (μm)</th>
<th>Left alignment structure</th>
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<th>Top Alignment</th>
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<tbody>
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<tr>
<td>2</td>
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<td>64</td>
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<td>4</td>
<td>8</td>
<td>-168</td>
<td></td>
<td>47</td>
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<tr>
<td>5</td>
<td>10</td>
<td>-170</td>
<td></td>
<td>56</td>
</tr>
<tr>
<td>6</td>
<td>10</td>
<td>-173</td>
<td></td>
<td>59</td>
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<td>7</td>
<td>16</td>
<td>-168</td>
<td></td>
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<td>8</td>
<td>18</td>
<td>-153</td>
<td></td>
<td>60</td>
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<td></td>
<td>44</td>
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<td>10</td>
<td>19</td>
<td>-154</td>
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<td>average</td>
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<td>-163.7</td>
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<td>4.175324339</td>
<td>8.628763269</td>
<td>7.441624673</td>
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<tr>
<td>(+- 95%)</td>
<td>9.444583654</td>
<td>19.51826251</td>
<td>16.83295501</td>
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</tr>
<tr>
<td>Gap High</td>
<td>5788.353126</td>
<td>Pascals</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gap Low</td>
<td>46963.50474</td>
<td>Pascals</td>
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</table>
Figure 270: Pressure measurement for sample III.

22.4.15 Sample JJJ (Clamped)

Table 115: Gap distance and offset measurements for sample JJJ.

<table>
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<th>Replicate #</th>
<th>Gap distance (μm)</th>
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<th>Top Alignment</th>
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<tbody>
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<tr>
<td>2</td>
<td>12</td>
<td>93</td>
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</tr>
<tr>
<td>3</td>
<td>12</td>
<td>104</td>
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</tr>
<tr>
<td>4</td>
<td>10</td>
<td>99</td>
<td>-5</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>12</td>
<td>101</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>6</td>
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<td></td>
</tr>
<tr>
<td>7</td>
<td>10</td>
<td>105</td>
<td>-5</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>10</td>
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<td>-9</td>
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<td>9</td>
<td>8</td>
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<tr>
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<td>10</td>
<td>110</td>
<td>-7</td>
<td></td>
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<tr>
<td>average</td>
<td>10.9</td>
<td>100.7</td>
<td>2.9</td>
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<tr>
<td>stdev</td>
<td>1.523883927</td>
<td>8.602971063</td>
<td>7.202622979</td>
<td></td>
</tr>
<tr>
<td>(+-) 95%</td>
<td>3.447025442</td>
<td>19.45992054</td>
<td>16.29233318</td>
<td></td>
</tr>
<tr>
<td>Gap High</td>
<td>8692.230919</td>
<td>Pascals</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gap Low</td>
<td>16732.60215</td>
<td>Pascals</td>
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</table>
Figure 271: Pressure measurement for sample JJJ.

22.4.16 Sample KKK (Clamped)

Table 116: Gap distance and offset measurements for sample KKK.

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<tr>
<th>Replicate #</th>
<th>Gap distance (μm)</th>
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<th>Top Alignment</th>
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<tbody>
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<td>2</td>
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</tr>
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<td>3</td>
<td>7</td>
<td>98</td>
<td>-29</td>
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<td>4</td>
<td>8</td>
<td>100</td>
<td>-8</td>
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<tr>
<td>5</td>
<td>9</td>
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<td>-15</td>
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</tr>
<tr>
<td>6</td>
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<td></td>
</tr>
<tr>
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<td>8</td>
<td>95</td>
<td>-16</td>
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<td>8</td>
<td>95</td>
<td>-17</td>
<td></td>
</tr>
<tr>
<td>9</td>
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<tr>
<td>10</td>
<td>9</td>
<td>95</td>
<td>-19</td>
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<td>average</td>
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<td>96.3</td>
<td>17.1</td>
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<tr>
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<td>0.966091783</td>
<td>2.49664441</td>
<td>5.704773829</td>
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</tr>
<tr>
<td>(+- 95%)</td>
<td>2.185299613</td>
<td>5.647454967</td>
<td>12.9041984</td>
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</tr>
<tr>
<td>Gap High</td>
<td>11562.74398</td>
<td>Pascals</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gap Low</td>
<td>19440.91705</td>
<td>Pascals</td>
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</table>
Figure 272: Pressure measurement for sample KKK.

22.4.17 Sample LLL (Clamped)

Table 117: Gap distance and offset measurements for sample LLL.

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<th>Gap distance (μm)</th>
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<th>Top Alignment</th>
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</tr>
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<td>34</td>
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<td>3</td>
<td>7</td>
<td>30</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>7</td>
<td>30</td>
<td>5</td>
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<td>5</td>
<td>9</td>
<td>28</td>
<td>2</td>
<td></td>
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<tr>
<td>6</td>
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<td></td>
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<tr>
<td>7</td>
<td>8</td>
<td>30</td>
<td>5</td>
<td></td>
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<tr>
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<td>7</td>
<td>29</td>
<td>8</td>
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<tr>
<td>9</td>
<td>4</td>
<td>24</td>
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<tr>
<td>10</td>
<td>3</td>
<td>35</td>
<td>11</td>
<td></td>
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<tr>
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<td>29</td>
<td>-7.5</td>
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</tr>
<tr>
<td>stdev</td>
<td>1.946506843</td>
<td>3.944053189</td>
<td>5.461989869</td>
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<tr>
<td>(+-) 95%</td>
<td>4.402998478</td>
<td>8.921448313</td>
<td>12.35502108</td>
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</tr>
<tr>
<td>Gap High</td>
<td>11651.65616</td>
<td>Pascals</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gap Low</td>
<td>65739.35588</td>
<td>Pascals</td>
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</table>
Figure 273: Pressure measurement for sample LLL.

### 22.4.18 Sample MMM (Clamped)

Table 118: Gap distance and offset measurements for sample MMM.

<table>
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<th>Replicate #</th>
<th>Gap distance (μm)</th>
<th>Left alignment structure</th>
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<th>Top Alignment</th>
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<td>3</td>
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<td>10</td>
<td>53</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>5</td>
<td>25</td>
<td>59</td>
<td></td>
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<tr>
<td>5</td>
<td>6</td>
<td>5</td>
<td>54</td>
<td></td>
</tr>
<tr>
<td>6</td>
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<td></td>
</tr>
<tr>
<td>7</td>
<td>5</td>
<td>6</td>
<td>50</td>
<td></td>
</tr>
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<td>8</td>
<td>9</td>
<td>20</td>
<td>41</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>11</td>
<td>8</td>
<td>53</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>14</td>
<td>17</td>
<td>55</td>
<td></td>
</tr>
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<td>average</td>
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</tr>
<tr>
<td>stdev</td>
<td>3.134042473</td>
<td>7.578478299</td>
<td>5.96284794</td>
<td></td>
</tr>
<tr>
<td>(+-) 95%</td>
<td>7.089204074</td>
<td>17.14251791</td>
<td>13.48796204</td>
<td></td>
</tr>
<tr>
<td>Gap High</td>
<td>8051.263161</td>
<td>Pascals</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gap Low</td>
<td>95138.88139</td>
<td>Pascals</td>
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</tbody>
</table>
Figure 274: Pressure measurement for sample MMM.

### 22.4.19 Sample NNN (Clamped)

Table 119: Gap distance and offset measurements for sample NNN.

<table>
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<tr>
<th>Replicate #</th>
<th>Gap distance (µm)</th>
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<th>Right Alignment structure</th>
<th>Top Alignment</th>
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<td>11</td>
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<td>84</td>
<td></td>
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<td>4</td>
<td>8</td>
<td>13</td>
<td>95</td>
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<td></td>
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<td>8</td>
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<td>91</td>
<td></td>
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<tr>
<td>8</td>
<td>1</td>
<td>10</td>
<td>84</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>7</td>
<td>10</td>
<td>85</td>
<td></td>
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<tr>
<td>10</td>
<td>10</td>
<td>14</td>
<td>85</td>
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</tr>
<tr>
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<td>10.5</td>
<td>-86.9</td>
<td></td>
</tr>
<tr>
<td>stdev</td>
<td>2.936362073</td>
<td>3.628590176</td>
<td>3.63470922</td>
<td></td>
</tr>
<tr>
<td>(+-) 95%</td>
<td>6.642051009</td>
<td>8.207870979</td>
<td>8.221712255</td>
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</tr>
<tr>
<td>Gap High</td>
<td>8635.037923</td>
<td>Pascals</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gap Low</td>
<td>107697.0221</td>
<td>Pascals</td>
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</tbody>
</table>
22.4.20 Sample OOO (Clamped)

Table 120: Gap distance and offset measurements for sample OOO.

<table>
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<th>Replicate #</th>
<th>Gap distance (μm)</th>
<th>Left alignment structure</th>
<th>Right Alignment structure</th>
<th>Top Alignment</th>
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<td>12</td>
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</tr>
<tr>
<td>2</td>
<td>44</td>
<td>34</td>
<td>29</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>46</td>
<td>37</td>
<td>24</td>
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</tr>
<tr>
<td>4</td>
<td>42</td>
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<td>38</td>
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</tr>
<tr>
<td>5</td>
<td>49</td>
<td>33</td>
<td>41</td>
<td></td>
</tr>
<tr>
<td>6</td>
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<td>7</td>
<td>46</td>
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<td>41</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>49</td>
<td>28</td>
<td>46</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>50</td>
<td>30</td>
<td>42</td>
<td></td>
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<tr>
<td>10</td>
<td>49</td>
<td>22</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td>average</td>
<td>46.1</td>
<td>29.5</td>
<td>-36.6</td>
<td></td>
</tr>
<tr>
<td>stdev</td>
<td>3.314949304</td>
<td>5.8357138</td>
<td>11.83403754</td>
<td></td>
</tr>
<tr>
<td>(+-) 95%</td>
<td>7.498415326</td>
<td>13.20038462</td>
<td>26.76859291</td>
<td></td>
</tr>
<tr>
<td>Gap High</td>
<td>2326.704202</td>
<td>Pascals</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gap Low</td>
<td>3230.635716</td>
<td>Pascals</td>
<td></td>
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</tbody>
</table>

Figure 275: Pressure measurement for sample NNN.
Figure 276: Pressure measurement for sample OOO.

### 22.4.21 Sample PPP (Clamped)

Table 121: Gap distance and offset measurements for sample PPP.

<table>
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<tr>
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<th>Gap distance (μm)</th>
<th>Left alignment structure</th>
<th>Right Alignment structure</th>
<th>Top Alignment</th>
</tr>
</thead>
<tbody>
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<td>0</td>
<td>123</td>
<td></td>
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<tr>
<td>(+-) 95%</td>
<td>15.63709473</td>
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<td></td>
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<tr>
<td>Gap Low</td>
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<td>Pascals</td>
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Figure 277: Pressure measurement for sample PPP.

22.4.22 Sample QQQ (Clamped)

Table 122: Gap distance and offset measurements for sample QQQ.

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<th>Replicate #</th>
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<td>(+-) 95%</td>
<td>11.65411826</td>
<td>22.9642209</td>
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</tr>
<tr>
<td>Gap Low</td>
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</table>
### 22.4.23 Sample RRR (Clamped)

Table 123: Gap distance and offset measurements for sample RRR.

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<td>10</td>
<td>5</td>
<td>37</td>
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<tr>
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<td>17.17564998</td>
<td>18.15246192</td>
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<tr>
<td>Gap High</td>
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<td>Pascals</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gap Low</td>
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### 22.4.24 Sample SSS (Clamped)

Table 124: Gap distance and offset measurements for sample SSS.

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<td>2</td>
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</tr>
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<tr>
<td>Gap High</td>
<td>7307.13244</td>
<td>Pascals</td>
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</tr>
<tr>
<td>Gap Low</td>
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Figure 278: Pressure measurement for sample SSS.

### 22.4.25 Sample TTT (Clamped)

Table 125: Gap distance and offset measurements for sample TTT.

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<td>-9</td>
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<td>(+-) 95%</td>
<td>7.372254038</td>
<td>10.59899814</td>
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<tr>
<td>Gap High</td>
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<tr>
<td>Gap Low</td>
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22.4.26 Sample UUU (Unclamped)

Table 126: Gap distance and offset measurements for sample UUU.

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<td>-66</td>
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<td>-79</td>
<td>-67</td>
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<td>34</td>
<td>-78</td>
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<td>35</td>
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<td>-65</td>
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<td>2.668749187</td>
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<td>6.036710661</td>
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<td>Gap High</td>
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</tr>
<tr>
<td>Gap Low</td>
<td>4859.379345</td>
<td>Pascals</td>
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</table>

Figure 279: Pressure measurement for sample TTT.
Figure 280: Pressure measurement for sample UUU.

22.4.27 Sample VVV (Unclamped)

Table 127: Gap distance and offset measurements for sample VVV.

<table>
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<tr>
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<td>31</td>
<td>-39</td>
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<td>2.951459149</td>
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<td>15.34904005</td>
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<td>3724.373713</td>
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<tr>
<td>Gap Low</td>
<td>8474.403122</td>
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</table>
Figure 281: Pressure measurement for sample VVV.

### 22.4.28 Sample WWW (Unclamped)

**Table 128: Gap distance and offset measurements for sample WWW.**

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<th>Top Alignment</th>
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<td>10</td>
<td>21</td>
<td>73</td>
<td>-19</td>
<td></td>
</tr>
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<td>average</td>
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</tr>
<tr>
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<td>5.602578771</td>
<td></td>
</tr>
<tr>
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<td>15.56968922</td>
<td>9.596853234</td>
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</tr>
</tbody>
</table>

Gap High: 2836.218776 Pascals
Gap Low: 9719.769091 Pascals
Figure 282: Pressure measurement for sample WWW.

### 22.4.29 Sample XXX (Unclamped)

Table 129: Gap distance and offset measurements for sample XXX.

<table>
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<th>Replicate #</th>
<th>Gap distance (µm)</th>
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<th>Top Alignment</th>
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<tr>
<td>3</td>
<td>16</td>
<td>46</td>
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<td></td>
</tr>
<tr>
<td>4</td>
<td>18</td>
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<td>5</td>
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<tr>
<td>10</td>
<td>35</td>
<td>30</td>
<td>-43</td>
<td></td>
</tr>
<tr>
<td>average</td>
<td>25.2</td>
<td>42.1</td>
<td>45</td>
<td></td>
</tr>
<tr>
<td>stdev</td>
<td>7.714344503</td>
<td>7.32499526</td>
<td>5.617433182</td>
<td></td>
</tr>
<tr>
<td>(+- 95%)</td>
<td>17.44984727</td>
<td>16.56913928</td>
<td>12.70663386</td>
<td></td>
</tr>
<tr>
<td>Gap High</td>
<td>2923.988388</td>
<td>Pascals</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gap Low</td>
<td>16090.99361</td>
<td>Pascals</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 283: Pressure measurement for sample XXX.

### 22.4.30 Sample YYY (Unclamped)

Table 130: Gap distance and offset measurements for sample YYY.

<table>
<thead>
<tr>
<th>Replicate #</th>
<th>Gap distance (µm)</th>
<th>Left alignment structure</th>
<th>Right Alignment structure</th>
<th>Top Alignment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>15</td>
<td>28</td>
<td>105</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>18</td>
<td>38</td>
<td>103</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>13</td>
<td>33</td>
<td>106</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>12</td>
<td>44</td>
<td>95</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>19</td>
<td>33</td>
<td>87</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>20</td>
<td>44</td>
<td>94</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>12</td>
<td>33</td>
<td>87</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>14</td>
<td>44</td>
<td>96</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>16</td>
<td>40</td>
<td>92</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>15</td>
<td>43</td>
<td>98</td>
<td></td>
</tr>
<tr>
<td>average</td>
<td>15.4</td>
<td>38</td>
<td>-96.3</td>
<td></td>
</tr>
<tr>
<td>stdev</td>
<td>2.836272985</td>
<td>5.887840578</td>
<td>6.799509786</td>
<td></td>
</tr>
<tr>
<td>(+) 95%</td>
<td>6.415649492</td>
<td>13.31829539</td>
<td>15.38049114</td>
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</tr>
<tr>
<td>Gap High</td>
<td>5716.431142</td>
<td>Pascals</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gap Low</td>
<td>13880.5424</td>
<td>Pascals</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 284: Pressure measurement for sample YYY.

### 22.4.31 Sample ZZZ (Unclamped)

Table 131: Gap distance and offset measurements for sample ZZZ.

<table>
<thead>
<tr>
<th>Replicate #</th>
<th>Gap distance (μm)</th>
<th>Left alignment structure</th>
<th>Right Alignment structure</th>
<th>Top Alignment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>18</td>
<td>-30</td>
<td>-46</td>
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</tr>
<tr>
<td>2</td>
<td>11</td>
<td>-20</td>
<td>-18</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>10</td>
<td>-30</td>
<td>-38</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>9</td>
<td>-14</td>
<td>-13</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>10</td>
<td>-27</td>
<td>-32</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>10</td>
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<td>-30</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>12</td>
<td>-31</td>
<td>-16</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>15</td>
<td>-21</td>
<td>-24</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>15</td>
<td>-20</td>
<td>-24</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>8</td>
<td>-19</td>
<td>-27</td>
<td></td>
</tr>
<tr>
<td>average</td>
<td>11.8</td>
<td>-22.7</td>
<td>26.8</td>
<td></td>
</tr>
<tr>
<td>stdev</td>
<td>3.190262964</td>
<td>6.32543367</td>
<td>10.17404104</td>
<td></td>
</tr>
<tr>
<td>(+- 95%)</td>
<td>7.216374824</td>
<td>14.30813096</td>
<td>23.01368084</td>
<td></td>
</tr>
<tr>
<td>Gap High</td>
<td>6557.909134</td>
<td>Pascals</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gap Low</td>
<td>27207.21118</td>
<td>Pascals</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 285: Pressure measurement for sample ZZZ.
Vita

Christopher Ramsey Brown received his bachelor’s degree in Mechanical Engineering at Louisiana State University in 2009. He joined the Department of Mechanical Engineering at Louisiana State University in August 2009 to pursue a master of science in mechanical engineering with a focus on mechanical systems. He began research into Microsystem technologies as part of the Micro System Engineering Team under the supervision of Dr. Michael C. Murphy. He expects to receive his master’s degree in May 2014 and plans to work as an engineer upon graduation.