Modeling and simulation of surface profile forming process of microlenses and their application in optical interconnection devices

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MODELING AND SIMULATION OF SURFACE PROFILE FORMING PROCESS OF MICROLENSES AND THEIR APPLICATION IN OPTICAL INTERCONNECTION DEVICES

A Dissertation

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 Doctor of Philosophy

in

The Department of Mechanical Engineering

by

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ABSTRACT

Free space micro-optical systems require to integrate microlens array, micromirrors, optical waveguides, beam splitter, etc. on a single substrate. Out-of-plane microlens array fabricated by direct lithography provides pre-alignment during mask fabrication stage and has the advantage of mass manufacturing at low cost. However, this technology requires precise control of the surface profile of microlenses, which is a major technical challenge. The quality control of the surface profile of microlenses limits their applications.

In this dissertation, the surface forming process of the out-of-plane microlenses in UV-lithography fabrication was modeled and simulated using a simplified cellular automata model. The microlens array was integrated with micromirrors on a single silicon substrate to form a free space interconnect system.

The main contributions of this dissertation include: (1) The influences of different processing parameters on the final surface profiles of microlenses were thoroughly analyzed and discussed. A photoresist etching model based on a simplified cellular automata algorithm was established and tested. The forming process and mechanism of the microlens surface profile were explained based on the established model. (2) Microlens arrays with different parameters were designed, fabricated, and tested. The experiment results were compared with the simulation results. The possible causes for the deviation were discussed. (3) A microlens array based beam relay for optical interconnection application was proposed. A sequence of identical microlens array was fabricated on a single silicon substrate simultaneously and its optical performance was tested. A fast replication method for the microlens optical interconnects using PDMS and UV curable polymer was developed. A selective deposition method of micro-optical elements using PDMS ‘lift-off’ technique was realized. No shadow mask was needed during deposition process.

With the continuous advances in the integration of micro-optical systems, direct
lithography of micro-optical elements will be a potential technology to provide both precision alignment and low cost in manufacturing process. Microlenses and microlens array with precisely controlled surface profiles will be an important part in the micro-optical system.
CHAPTER 1. INTRODUCTION

1.1 MEMS and Micro-optics

MEMS is the acronym of Micro-electro-mechanical systems. These systems are in the scale of several microns to several hundred microns. In 1959, Richard Feynman gave a famous lecture ‘There’s Plenty of Room at the Bottom’, predicted the future in the micro technique field [1]. Since 1970s and 1980s, MEMS technology has been greatly developed and widely used in daily lives, such as vehicle accelerometers, display chips, miniaturized sensors, inkjet printers, and etc.

Micro-optics is the integration of optics and MEMS fabrication technology. In general, it is the scaling down of traditional optical devices using micromachining technology, which usually means the optical components are fabricated in sizes from microns to millimeters. Micro-optics systems have been widely used in display systems [2], communication [3, 4], data storage [5], sensors, imaging systems [6-9], and etc. [10]. Micro-optical systems typically consist of elements like microlenses, micromirrors, micro-gratings, beam splitters, and waveguides.

Digital Light Projection (DLP) developed by Texas Instrument is a successful example of the microfabricated micromirrors used for digital projection applications [2]. DLP initially found their applications in projectors for class and meeting. In recent years these projectors have been widely used in cinemas for high quality movie projection. This device consists of a two-dimensional micromirror array fabricated on a CMOS chip. Each mirror can be individually controlled to rotate $\pm 10^\circ$ which stands for ‘on’ and ‘off’ state respectively. The switching time of the mirror (~16$\mu$s) is much shorter than the response time of human eye (~150ms), thus modulation of the incident light can generate around 1000 gray levels. DLP can produce more than 16 million colors with the help of a color wheel or 3-chip setup [11].
Another example of applications of micromirrors is for remote temperature sensing [7]. This thermal sensing chip consists of bimaterial cantilevers and micromachined micromirrors. When heated by an incident thermal radiation, the bimaterial cantilevers will deform due to thermal stress, which is a result of the different coefficients of thermal expansion of the two cantilever materials. Therefore, the displacement of the micromirrors can be detected by interference method or diffraction method. The intensity changes on the CCD camera correspond to the temperature change on the microcantilevers.

A miniaturized Fourier transform spectrometer has been demonstrated using micro beam splitters together and movable micromirrors fabricated on a silicon optical bench [12]. The micro-optical elements were fabricated by using a simple bulk micromachining process.

Microlenses and microlens arrays are key components in micro-optical systems. Applications of microlenses and microlens arrays include: optical communication [13], integral imaging systems [14, 15], laser diode array collimators [16], microfluidic systems [17], and etc.

Figure 1-1 is a schematic diagram of a microlens used as a laser diode to optical fiber coupler. Laser beam emitted from the laser diode is collected by the microlens and then enters the optical fiber. This setup reshapes the laser beam and improves the beam quality. Integration of laser diodes and two dimensional microlenses has been demonstrated on a silicon optical bench [18].
Microlens array can be also used to increase the light collection efficiency of CCD arrays or infrared focal plane array [19, 20]. Wu et al. used microlenses to pattern the intensity of light incident on photoresist and generated an array of microstructures with submicron resolution [21].

1.2 In-plane and Out-of-plane Microlenses

Depending on the relative arrangement between the optical axes of the microlenses and the substrate plane, microlenses can be categorized into in-plane and out-of-plane types.

The optical axes of the in-plane microlenses are perpendicular to the substrate. There are many methods to fabricate in-plane microlenses and microlens arrays: Use the surface tension at reflow temperature of the polymer fabrication [22, 23], hot-embossing to imprint microlenses or microlens array in PMMA [24], isotropic wet-etching of glass [25], gray-tone lithography, and etc. The reflow process is the most popular technique for in-plane refractive microlens fabrication. A schematic diagram of the reflow process is shown in Figure 1-2. Briefly, an array of micro-sized photoresist cylinders is formed after lithography. Then these cylinders are heated above the polymer’s glass transition temperature and will reflow. Due to the surface tension, photoresist cylinders tend to form spherical surface profiles. Plano-convex microlens array has been successfully fabricated and well studied using the reflow method.

Glass etching is another method used for fabrication of microlenses. In this method, a pin-hole is first made in the metal layer coated on glass. HF is then used to etch the metal layer. Finally a chemical smoothing process by BOE is used to form the microlenses.

Gray tone lithography is also used to fabricate diffractive optical elements including lens [26, 27], though the mask fabrication is more complex. Comparing to normal lithography and reflow technique, gray tone mask lithography is able to fabricate microlenses with larger diameters. It also has the potential to fabricate aspheric microlenses.
All these reported technologies are used to produce in-plane microlenses or lens arrays. In applications like free space integrated optics, optical interconnections and on-chip optical detection, it is often desirable to have integrated out-of-plane microlenses or microlens array with their optical axes parallel to the substrate on which the system is fabricated [3]. A conventional method to fabricate such out-of-plane microlenses was using a flexible hinge [28]. In this approach, a microlens suspended on a mechanical hinge is first fabricated using surface-micromachining techniques. Electrostatic force was then used to drive the microlens to the vertical position. This method may be useful for one single lens. However, both the cost and assembly requirement make it not a practical solution for the fabrication of microlens array.

Another way to fabricate out-of-plane microlenses is to use microstereolithography [29]. Stereolithography is one of the 3D printing technologies, which is a very hot topic recently. Its basic principle is to fabricate the final structure in a layer by layer fashion based on polymers.
cured by laser. For complicated structures, it is a process that may take hours to finish. The production rate and the surface quality are the main problems.

Pneumatically-actuated tunable structure is another approach of fabricating out-of-plane microlenses [30, 31]. This kind of microlenses is made of elastomer-based materials such as PDMS filled with gas or liquid using soft lithographic technique. The focal length is controlled by adjusting the pressure of the gases or liquids filled in it. However, the precise control of the focal length often requires syringe pump and pressure sensor connected to the microlenses. It adds the complexity of the device, especially for array structure. In addition, they are normally fabricated piece by piece, not very suitable for batch fabrication.

UV lithography of SU-8 has been widely used in MEMS and MOEMS in recent years. Cured SU-8 polymer has very good optical and mechanical properties, and relatively high thermal stability. It was used as a structural material for MEMS applications including optical components. Our group has been working on fabricating out-of-plane microlenses and microlens arrays using tilted UV lithography technique [32-35]. This fabrication method is based on the direct lithography of a thick photoresist. The lithography method may also be used to fabricate other optical elements like micromirrors and optical waveguides on the same layer. This will greatly reduce the time and cost for the integration of micro-optical elements. Fabrication of microlenses using directly lithography technology requires precise control of the surface profile of microlenses, which is a major technical challenge in this technology. This dissertation is devoted to study the surface forming mechanism of out-of-plane microlenses and microlens arrays in the fabrication process using direct lithography as well as their applications in free space optical interconnections. A simplified cellular automata method was established to study the surface profile forming mechanism of the out-of-plane microlenses.
1.3 Outline of the Dissertation

The research work in this dissertation is organized as follows: In Chapter 2 a detailed description of the fabrication process of the out-of-plane microlens array using direct lithography was presented. The influences of different fabrication steps and parameters on the final surface profile were discussed. The challenge in modeling and simulation of the fabrication process was also discussed.

In Chapter 3, a simplified three-dimensional cellular automata model was established to simulate the forming process of microlenses. This modeling took advantages of the robust and simple algorithm of the cellular automata method. The surface profiles of SU-8 photoresist under different manufacturing conditions were simulated. The evolution of the surface profile of microlenses was modeled in MATLAB.

In Chapter 4, different types of microlenses were fabricated and compared to the simulation results presented in Chapter 3. Optical performances of the fabricated microlenses were also measured.

Chapter 5 compared the surface profiles of microlenses between simulation results and experiment results. It was observed that although there was a deviation between the simulation results and experiment results, the evolution of the surface profile by simulation is in agreement with the practical experiment process. The forming process and mechanism of the microlens surface profile were explained based on the established model.

In Chapter 6, the fabricated out-of-plane microlenses and micromirrors were used in a free-space optical interconnection device. A prototype system was designed and fabricated. A beam relay for optical connections using a series of identical microlens arrays was also fabricated and tested. Different alignment methods for the integration of micro-optical elements were discussed.
Chapter 7 summarized the work that has been done in this dissertation and pointed the future work needs to be done for the integration of micro-optical systems.
CHAPTER 2. FABRICATION PROCESS OF SU-8 OUT-OF-PLANE MICROLENSES

2.1 Properties of SU-8 Photoresist

SU-8 is a chemically amplified negative resist based on epoxy resin. It was originally developed and patented by IBM-Watson Research Center [36] as a photoresist for microelectronic industry, providing a high resolution mask for semiconductor devices. SU-8 consists of three basic components: 1) An epoxy called EPON SU-8 resin (available at Shell Chemicals), 2) a solvent called gamma-butyrolactone (GBL), 3) a photoacid generator from the family of the triarylsulfonium salts. Figure 2-1 shows the structure of a SU-8 molecule contains eight epoxy groups. It should be noted in reality the molecules have a wide variety of sizes and shapes. SU-8 photoresist can be used to fabricate microstructures as high as 2mm with aspect ratio up to 25 using a standard UV-lithography process [34]. Cross-linked SU-8 polymer has a Young’s modulus of $E \approx 4-5$ GPa and high thermal stability (glass-transition temperature $\sim 200^\circ$C and degradation temperature $\sim 380^\circ$C) [37].

Figure 2-1 SU-8 molecular with epoxy groups
Cross-linked SU-8 polymer is transparent in a relatively broad wavelength range as shown in Figure 2-2 based on the measurement of 1.1mm thick SU-8 film [33]. According to the data on Microchem Inc. website, when wavelengths are longer than 400 nm, the transmission of SU-8 can be greater than 95%. These properties made SU-8 polymer suitable for various applications including micro-optical elements. Yang and Wang demonstrated SU-8 polymer based out-of-plane microlens array made with direct UV lithography technique [32]. Dai and Wang reported a method to selectively metalize cured SU-8 surface [38], which can greatly broaden the application scope of SU-8 polymer.

![Figure 2-2 Transmission spectrum of cured 1.1mm thick SU-8 film](image)

2.2 **Fabrication of Out-of-plane SU-8 microlenses based on tilted UV lithography**

Although X-ray lithography can produce high quality and high aspect ratio SU-8 structures, it is more desirable to use UV lithography as an alternative due to its low cost and comparable quality. Details of the fabrication process of out-of-plane SU-8 microlenses has been reported by Yang and Wang [32] [35]. The fabrication flow-chart for SU-8 100 photoresist is shown in Figure 2-3, which includes (1) Substrate pretreatment and spin-coating of photoresist
(2) Soft bake (3) Exposure (4) Post-exposure bake (5) Development. The detailed process conditions of each step are explained in the following sections.

![Fabrication Flowchart of SU-8 Photoresist](image)

**Figure 2-3 The fabrication flowchart of SU-8 photoresist**

### 2.2.1 Substrate pretreatment and spin-coating of photoresist

A 4-inch silicon wafer with one side polished was subsequently cleaned with acetone, isopropyl alcohol (IPA) and DI water. The wafer was then dehydrated on a hotplate or an oven at 120°C for 20 minutes. After that, SU-8 100 photoresist was dispensed onto the wafer and spin-coated at 450 rpm for 30 seconds to obtain a 1000µm thick SU-8 layer. Figure 2-4 shows the spin-coating curve for SU-8 50 and SU-8 100 photoresist with thickness over 200µm calibrated in the CAMD (Center for Advanced Microstructures and Devices) cleanroom of LSU. SU-8 100 has about 73% resin compared with SU-8 50, which has about 69%. Therefore the viscosity of SU-100 is higher than SU-8 50. In this study, SU-8 100 was used because it can generate a thicker resist layer, which is needed for a large array of out-of-plane microlenses. The measured
flatness errors for 1000µm thick SU-8 100 range from 10µm to 100µm. Leaving the film to relax on a very flat-leveled position for several minutes or longer time allows reflowing and enhances planarization.

![Graph showing SU-8 spin-speeds vs. film thickness curve in CAMD cleanroom](image)

**Figure 2-4 SU-8 spin-speeds vs. film thickness curve in CAMD cleanroom**

### 2.2.2 Soft bake

After spin coating, the sample wafer coated with SU-8 resist was soft baked in order to remove the solvent and to promote the adhesion of the resist layer to the substrate. The wafer was soft baked on a well-leveled hot plate. To reduce the stress in thick SU-8 layer, soft bake process with multi-step ramping and stepping of temperature was used. The soft-bake temperature needs to be well controlled because a lower temperature will leave residual solvent content while a higher temperature may initiate thermal cross-linking [39]. Figure 2-5 shows the multi-step baking process used. For thick SU-8 layer the soft bake time is about 1hr per 100µm. The SU-8 layer was slowly ramped up to 105°C in multiple steps and then maintained at 105°C for 12 hours. Any residual solvent will evaporate during the post-exposure baking and result in high film stress. Thus sometimes it requires even longer time to evaporate the solvent. This step is very critical for a good lithography result. Soft bake also helps to smooth the photoresist.
surface. Height deviation across the entire area of the 4-inch wafer was less than 50µm for a
1000µm layer.

Ramp up to 105°C in 30m  
Dwell for 30m  
Ramp to 25°C in 2 hrs  
Relax at 25°C until exposure

Ramp up to 65°C in 30m  
Dwell for 30m  
Ramp to 65°C in 30m  
Dwell for 12hrs

Figure 2-5 Multi-step soft baking process of 1000µm thick SU-8 film

2.2.3 Tilted UV exposure

Figure 2-6 shows the setup for tilted UV exposure. Water immersion lithography method
similar to the one reported by Sato et al [40] was used to reduce the diffraction effect of the
possible air gap between the photoresist layer and mask. As shown in Figure 2-6, a silicon
substrate spin-coated with SU-8 was fixed together with a chromium mask. This setup was
immersed in deionized (DI) water and held at a tilted position. This position can be carefully
adjusted so that after refraction the incident light beam will be projected in with ±45° respect to
the substrate [41]. All UV exposures were performed using an Oriel UV exposure station
(Newport Stratford, Inc. Stratford, CT). During the exposure under UV light, a strong acid
(HSbF6) is generated in the SU-8 photoresist. The photoacid acts as a catalyst in the following
cross-linking reaction. A broadband light source (Mercury-Xenon lamp) was used in the
lithography process of SU-8 photoresist. This light source contains near UV wavelength from
320nm to 450nm. The absorbance of the light decreases and the transmission increases when the
wavelength of the light source increases. The transmission increases from 6% at λ=365nm (i-line)
to about 58% at λ=405nm (h-line). Because of the high absorptions of light with shorter
wavelengths, light source dominated by shorter wavelength components often result in over
exposure at the surface and underexposure at the bottom part of the resist layer. This is the main reason that UV lithography of SU-8 using i-line dominated light source tends to produce T-toppings as commonly observed by many researchers [34]. To overcome this difficulty, an optical filter (4.35mm PMMA sheet) was used to filter out most of the wavelength shorter than 365nm to improve the uniformity of lithography, and therefore enhance the uniformity of the microlens surface profiles and the microlens array. This filter helps to eliminate about 92% of the 365nm wavelength intensity.

To fabricate micro-optical components such as bi-convex spherical microlenses, the opening shape on the photomask need to be ellipse (with long axis equal to $\sqrt{2}$ times of the short axis) [35]. The incident beam will be projected with $\pm 45^\circ$ to the substrate to form cylindrical beams as shown in Figure 2-7(a). The intersections receive double exposure dosage while other regions of the cylinders have single exposure dosage. Due to the combination effect of the etching of single exposed and double exposed regions, smooth surfaces form on the intersection regions after the development process (Figure 2-7(b)). In general, the final surface profile of a
microlens is determined mainly by three factors: the geometrical shapes of the beam propagating in the resist (which determine the basic structure of the microlens), the exposure dosages (which determine the etching rate during the development process) and the development times (which determine the surface profile evolution).

Figure 2-7 (a) Cylindrical beams intersect perpendicular to each other; the intersection regions are double-exposed. (b) After development, the sharp edges are rounded and smooth surface profiles are obtained.

2.2.4 Post-exposure bake (PEB)

After exposure, the SU-8 layer was post-baked to accelerate the cross-linking process. The PEB is responsible for the cross-linking mechanism in the SU-8 layer, which is very slow at ambient temperature. Heating the exposed SU-8 photoresist above its glass transition temperature ($T_g \approx 55^\circ C$) increases the molecular motion and accelerates the cross-linking process. Similar to the soft bake process, multiple steps of temperature changes were used to reduce the stress in PEB. As shown in Figure 2-8, the sample was slowly heated up to $95^\circ C$ and kept for 30 minutes and then slowly cooled down to room temperature. To further reduce the residual stress, a PEB at a lower temperature for a much longer time could also be employed.
2.2.5 Development

After post exposure bake, the sample was immersed in a SU-8 developer (PGMEA, propylene glycol methyl ether acetate). During the development of SU-8, the developer molecules first diffuse into the non-cross-linked SU-8 regions, followed by the diffusion of solvated polymer chains to the developer solution. The exposed SU-8 will also be etched but at a much lower rate, which depends on the cross-linking degree of the photoresist. The required development time is determined by many factors. The exposure dosage decides the state of cross-linking. Thus reducing the exposure time will accelerate development rate. Increasing the temperature and adding an agitation during development will also accelerate the development rate. The soft bake time and temperature also have an influence on the development rate [42].

2.3 The Quality Control Issues in Fabrication of Microlenses

Our preliminary study has demonstrated the feasibility of the out-of-plane microlens fabrication technology and its potential application in integrated micro-optical systems. Although the parameters of the fabricated microlenses are relatively stable under a fixed manufacturing condition, when fabricating a new group of microlenses with different parameters, the surface profile and focal length of the fabricated microlenses usually deviate from the designed parameters significantly. This deviation may make the microlens fabrication technology unsuitable for many applications, such as on-chip detection, optical interconnection or laser
diode to fiber coupler, where the focal lengths need to be precisely controlled. Several factors affecting the final surface profiles and the focal lengths of the microlenses were studied:

(a) The aperture geometry of the openings designed on the photomask. This is the easiest parameter to be accurately controlled because of the high precision in mask design and fabrication.

(b) The exposure dosage used. The development rate is directly affected by the exposure dosage received by SU-8 resist. Higher exposure dosage leads to slower development rate.

(c) The development time. The development time for the forming of microlenses is a critical parameter in the fabrication process. Complete removal of unexposed 1mm thick SU-8 photoresist takes more than 100 minutes. Further smoothing of the lens surface needs extra time. However, several hours of development time may cause damages on the fine features, and most importantly the surface quality of microlenses will be degraded due to the swelling effect.

Increasing the development temperature may accelerate the development process. Ultrasonic stirring accelerates the diffusion and the development process, but at the same time it also causes vibration of the microstructures and results in structure cracking and debonding from the substrate. To place the wafer upside down in the developer helps to increase the development rate with the help of gravitational force.

(d) Because the absorption rate of SU-8 is higher at shorter wavelengths and lower at longer wavelengths and the typical UV light source in an industrial aligner (UV station for lithography) has broadband spectrum, over exposure at the surface of the resist by short wavelength components may results in distortion of the sidewalls.

(e) Other processing parameters such as soft bake time and temperature, the PEB temperature also affect the final surface profile.
To have better control for the surface profiles and the focal lengths of the microlenses, a mathematical model for the surface forming process during development process needs to be developed to run numerical simulations and for computer-aided design and manufacturing. This is essential for precise control of the surface profile, surface quality, and therefore the focal lengths of the microlenses and lens arrays. Research work presented in this dissertation targeted to study the effects of the opening shapes on the photomask, the exposure dosages, and the development conditions. The purpose of the research work on the mathematical model and the numerical simulation tools developed in this dissertation target to be used for computer-aided design and manufacturing for precise surface profile control of microlenses and microlens array.
CHAPTER 3. SIMULATION OF THE SURFACE PROFILE FORMING MECHANISM OF LITHOGRAPHICALLY FABRICATED MICROLENSES

3.1 History of Photolithography Modeling

The SU-8 lithography process mentioned in Chapter 2 includes optical field propagation in the resist, exposure, post-exposure baking (PEB), and the development. Photolithography modeling is an indispensable tool to describe these complicated processes and also serves as a design and manufacturing tool to precisely control of the SU-8 lithography fabrication process. Numerical tools have been widely used in the exposure simulation, the post-exposure bake simulation, and the development simulation.

F. H. Dill et al. pioneered the work of photolithography simulation in the early 1970s. They first attempted to describe lithography process with mathematical equations [43-46]. Dill’s four papers on the topic are still the most cited works in the photolithography modeling area. A review on the history of lithography simulation and the important role of lithographical simulators played in semiconductor industry can be found in reference [47].

Generally, photolithography simulation consists of three basic steps as shown in Figure 3-1: imaging of the photomask, photoresist exposure, and the photoresist development. PEB step may also be included if necessary. In a typical lithography simulation, these three steps determine the final profile of photoresist. The imaging of the photomask step simulates the illumination of the photomask by the incident light source. The light propagates through the optical system and passes through the photomask, resulting in a two dimensional aerial image on top of the photoresist. The exposure step simulates the light propagation within the photoresist as well as the chemical reaction of the photoresist. The development step simulates the isotropic etching process of photoresist.
Most of the reported simulation studies have focused on positive photoresists, as they are the most commonly used resist materials in the IC industry. However, there have been few simulation studies concerning negative photoresists. It is much more difficult to simulate ultrathick chemically amplified negative resists like SU-8. In SU-8 photoresist, large molecules cross-linked while in positive photoresist the photoactive species were destroyed during the exposure process. The development of SU-8 photoresist usually involves diffusion of the developer into the photoresist, while in positive photoresist the development is a surface dissolution process. These differences make the simulation of negative photoresist like SU-8 cannot fit the method used by Dill.

Sensu et al. measured all the parameters in SU-8 lithography process: the photosensitivity parameter for exposure, the crosslinking reaction parameter for PEB and the development parameter [48]. The resist profile is then simulated by inputting all the obtained parameters to a commercial software SOLID-C. This simulation approach requires the measurements of all the parameters each time. Besides, the discrepancy between their model and the actual crosslinking reaction process results in disagreement between simulation results and patterning results.
There have been some simulation methods used in etching process like ray tracing method [49], string method [50, 51] and level set method [52, 53]. A few commercial simulators based on these methods have been developed. In these methods, the simulation usually has two steps: first is the calculation of the development rate and then the advancement of the surface. The advantages and disadvantages of these methods will be briefly discussed.

In ray tracing methods, the developed and undeveloped regions are defined with different etching rates, for example, \( R_1 \) and \( R_2 \). The propagation of the etching vectors are calculated similar to the propagation of light using Snell’s law of refraction. The index of refraction of resist is defined as \( n=R_{\text{max}}R(x,y) \), where \( R_{\text{max}} \) is the maximum value of the local etching rate \( R(x,y) \). The advancement of the etching front can be visualized based on the etching vectors. The ray tracing method is easy to implement. However, the initial rays must be chosen carefully otherwise some regions may not be reached [49].

String method for photoresist etching simulation was first introduced in the 1970s [49]. In this model, the surface is separated by a series of points joined by straight line segments as shown in Figure 3-2. Each point advances along the angle bisector of the two adjoining segments. During the simulation, the algorithm tries to keep the segments equal by adding or deleting points. It often needs ‘delooping’ operation every few time-step to avoid the accumulated errors [51].

![Figure 3-2 Algorithm for string method (redraw after [49])](image)
Level set method was first introduced by Stanley Osher and James Sethian in 1988 [52]. The etching fronts propagation is calculated with curvature-dependent speed based on solving a Hamilton-Jacobi type equation. The surface computation is based on a fixed Cartesian grid. It is a great tool for modeling time-varying objects.

Cellular automata model is based on the removal of cells in a photoresist cubic according to some evolution rules. It has been used by some commercial software in IC industry to simulate the profile of etching process or development. Compared with other methods, cellular methods is the most robust so far thanks to its simple algorithm [54]. It can also be easily extended to three dimensions. This method has been used in simulating high-aspect ratio structures [55-57]. The accuracy of cellular automata method depends on the number of cells. A large number of cells improves accuracy but at the same time costs more computation time. For the same accuracy, the cellular automata method is slower compared with other methods [49]. Thus in the cellular method the tradeoff between accuracy and computation time needs to be carefully balanced.

Three-dimensional (3D) cellular automata (CA) model has been successfully introduced for the simulation of photoresist etching process in recent years [55, 58]. In this chapter, a simplified 3D CA model will be established to simulate the forming process of the surface profile of out-of-plane microlenses fabricated on thick SU-8 resist.

3.2 History and Definition of Cellular Automata Model

A CA model is an idealization of physical system consisting of a regular grid of cells that has a finite number of states. In the CA model, the space and time are discrete. The history of CA model dates back to 1940s when Job Von Neumann tried to imitate the behavior of a human brain in order to build a machine able to solve complex problems [59]. Since then it has been
developed and widely used in a wide variety of fields ranging from statistical physics to social science. CA model has been used as a two dimensional simulator for the etching process in IC fabrication [60]. It was also used to simulate the etching of silicon [61]. Ioannis et al. extended its application to three dimensions to simulate the etching of thick resist [55] and some works have been done on improving the 3D CA model [57, 58].

3.3 CA Model for Numerical Simulation of the Surface Forming Process of the Out-of-Plane Microlenses

In the CA model for our simulation, a three dimensional lattice was used as shown in Figure 3-3.

Figure 3-3 The 3D lattice used in CA model

Each cell may have a state between 0 and 1. The state 0 means the cell is fully etched while the state 1 means the cell is un-etched, while any value between 0 and 1 means the cell is partially etched. \( C^t(i,j,k) \) is defined as the local state of cell \((i, j, k)\) at time \(t\), which can be expressed as

\[
C^t(i,j,k) = Vr/Vc,
\]

(3-1)
where $V_r$ is the remaining volume and $V_c$ is the total cell volume. Each cell has 6 face adjacent
neighbours, 12 edge adjacent neighbours, and 8 corner adjacent neighbours. Each cell is
allocated with an etching rate $R$. Each cell will only interact with its neighbouring cells where
the etchant flows from.

Due to the geometric constraint, the contributions of different type of neighbors on cell $(i, j, k)$ are different. The face adjacent neighbors will have the largest contributions on the cell $(i, j, k)$ while the corner adjacent cells will have the smallest contributions.

Figure 3-4 shows the contribution of one face adjacent cell on cell $(i, j, k)$. The length of
a cell is $a$. Suppose cell $(i, j, k+1)$ is partially etched, the etchant will enter cell $(i, j, k)$ through
the adjacent face to etch cell $(i, j, k)$ only after cell $(i, j, k+1)$ is fully etched. The state of cell $(i, j, k+1)$ is

$$C_{i,j,k+1} = \frac{a^2 s}{a^3} = \frac{s}{a}, \quad (3-2)$$

where $s$ is the remaining height of cell $(i, j, k+1)$.

According to Figure 3-4(a), the time to etch the rest of cell $(i, j, k+1)$ is

$$t_p = \frac{s}{R_{i,j,k+1}} = a \cdot \frac{C_{i,j,k+1}}{R_{i,j,k+1}}, \quad (3-3)$$

where $R_{i,j,k+1}$ is the etching rate of cell $(i, j, k+1)$.

The state of cell $(i, j, k)$ after time $\Delta t (\Delta t > t_p)$ is shown in Figure 3-4(b). The cellular state
change due to the etchant flow from cell $(i, j, k)$ can be expressed as

$$E_{i,j,k} = R_{i,j,k} \left( \Delta t - t_p \right) a^2 / a^3 = R_{i,j,k} \left( \Delta t - t_p \right) / a. \quad (3-4)$$

Replacing equation (3-2) in equation (3-3), the state change of cell $(i, j, k)$ becomes

$$E_{i,j,k} = R_{i,j,k} \left( \frac{\Delta t}{a} - \frac{C_{i,j,k+1}}{R_{i,j,k+1}} \right). \quad (3-5)$$

There are total 6 face adjacent cells inside a CA lattice, thus the total contributions of
face adjacent cells can be expressed as
where the indices \( l, m, \) and \( n \) are the face adjacent neighbors of cell (i, j, k).

![Figure 3-4 Contribution of a face adjacent neighbor on cell (i, j, k)](image)

Etchant will also flow from edge adjacent cells. The situation is similar to the case of face adjacent neighbors, but the etchant will enter cell (i, j, k) through the common edge between cell (i-1, j, k+1) and cell (i, j, k) instead of the common face, therefore a restriction parameter needs to be added to equation (3-5). The state change of cell (i, j, k) contributed by an edge adjacent neighbor can be expressed as

\[
E_{i,j,k} = d \cdot R_{i,j,k} \Delta t/a - C_{i-1,j,k+1}/R_{i-1,j,k+1},
\]

(3-7)

where \( d \) is a model fitting parameter which shows the geometric restriction of edge adjacent cells. A proper value of \( d \) is 0.18 for a homogenous etch-rate distribution [55]. The total contributions of edge adjacent cells will be

\[
E_{i,j,k} = d \cdot R_{i,j,k} \sum (\Delta t/a - C_{p,q,r}/R_{p,q,r}),
\]

(3-8)

where the indices \( p, q, \) and \( r \) are the edge adjacent neighbors of cell (i, j, k).
The contributions corner adjacent cells will be neglected since they will not significantly change the states of the cell \((i, j, k)\).

According to the above rules, the new state of each cell will be updated based on the current state of itself minus the total etched part due to the etchant flow from its neighbors. This new state of cell \((i, j, k)\) at time \(t+\Delta t\) can be express as
\[
C^{t+\Delta t}(i, j, k) = C^t(i, j, k) - E_{\text{neighbor}}.
\]
This is called the cellular automata rule, which is the total contribution of face adjacent neighbors and edge adjacent neighbors
\[
C^{t+\Delta t}(i, j, k) = C^t(i, j, k) - R_{i,j,k} \sum (\Delta t/a - C_{l,m,n}/R_{l,m,n})
- d \cdot R_{i,j,k} \sum (\Delta t/a - C_{p,q,r}/R_{p,q,r}),
\]
where \(C^{t+\Delta t}(i, j, k)\) is the state of the cell \((i, j, k)\) at time \(t+\Delta t\) and \(C^t(i, j, k)\) is the state of cell \((i, j, k)\) at time \(t\). The selection of time step \(\Delta t\) greatly affects the accuracy of the program as a large time step will reduce the accuracy [55]. A good choice for the time step is \(1/4R_{\text{max}}\), where \(R_{\text{max}}\) is the maximum etching rate. Equation (3-9) is the general cellular updating rule for all the cells inside a lattice.
Based on the previous analysis of SU-8 photoresist development, the etching rate of cell \((i, j, k)\) will be determined by the following factors: (1) Exposure dosage, each etch cell will be assigned with a exposure dosage before iteration, cells with a lower dosage will be etched at a higher rate than cells with a higher dosage. The exposure dosage will determine the local etching rate \(R_{i,j,k}\) at each cell. (2) Geometric type, during the iteration according to each cell’s geometric type, the cell state is a geometrical related parameters, if one of its neighbors is total etched, the etchant will start to attack cell \((i, j, k)\). At a time \(t\), some neighbors of cell \((i, j, k)\) are fully etched while some are partially etched. The more fully etched neighbors it has, the faster the etching speed of cell \((i, j, k)\). Suppose at time \(t\) cell \((i, j, k+1)\) is fully etched as shown in Figure 3-6(a), at a time \(t+\Delta t\) (Figure 3-6(b)) the state change of cell \((i, j, k)\) can be expressed as

\[
E_{i,j,k} = R_{i,j,k} \Delta t a^2 / a^3 = R_{i,j,k} \Delta t / a.
\] (3-10)

Because cell \((i, j, k)\) can have a maximum of 6 fully etched neighbors at time \(t\), the maximum value of \(E_{i,j,k}\) is \(6R_{i,j,k} \Delta t / a\). The minimum value of \(E_{i,j,k}\) is zero, which means no etch of cell \((i, j, k)\) at all. The etching rate of the central cell contributed by its fully etched face adjacent neighbors can be expressed as

\[
E_{i,j,k} = R_{i,j,k} \cdot \Sigma_{\text{face}} \Delta t / a.
\] (3-11)

Similarly, equation (3-9) can be rewrote as

\[
C^{t+\Delta t}(i, j, k) = C^t(i, j, k) - R_{i,j,k} \Sigma_{\text{face}} \Delta t / a - d \cdot R_{i,j,k} \Sigma_{\text{edge}} \Delta t / a
\] (3-12)

The numbers of the face adjacent neighbors and edge adjacent neighbors need to be checked before each update. Once \(C^{t+\Delta t}(i, j, k) \ll 0\) which means cell \((i, j, k)\) is fully etched, it needs to be set to zero and will be occupied by etchant. It then serves as a neighboring cell for the etching of other cells. The state of each cell will be updated after each time step \(\Delta t\). The final state of each cell will determine the final surface profile after a given number of iteration steps.
Equation (3-12) doesn’t include the current states of the neighbors of the central cell, which simplifies the algorithm. However, it may reduce resolution at the same time. Suppose at time $t$ the central cell has fully etched neighbors and partially etched neighbors, only the contributions of fully etched neighbors are counted. At time $t+\Delta t$ the partially etched neighbors may be already fully etched and make contributions in etching of cell $(i, j, k)$. However, their contributions were not counted until time $t+\Delta t$. This will reduce the resolution of the algorithm but can be compensated by take a smaller time step $\Delta t$.

3.4 Parameters for Numerical Simulations using CA Model

As stated before, the three parameters directly related to the final surface profile of the microlenses are the geometric opening shapes on the photomask, the exposure dosages of the single exposed regions and double exposed regions, the development times. The influences of soft bake and PEB are not considered in the simulation.

The geometric shapes on the photomask define the basic types of the microlens to be fabricated, such as bi-convex, plano-convex, bi-concave, and plano-concave. Figure 3-7 shows the bi-convex and plano-convex opening shapes on the photomask. In the mask design there is
no gap between two adjacent cylinders. However, this gap can be adjusted for particular design purpose. This topic will be covered in Chapter 4. The diffraction effect of light beam in the photoresist will change the light intensity distribution. This is not considered in our study here.

The lithography light used for the out-of-plane microlens fabrication is an $h$-line ($\lambda=405\text{nm}$) dominated broadband UV light to improve the exposure uniformity.

![Image](image.png)

Figure 3-7 The mask patterns for the bi-convex and plano-convex microlens arrays

Figure 3-8 shows the developing rates of exposed SU-8 resist under different exposure dosage ($h$-line). The etching rate of SU-8 resist mainly depends on the degree of cross-linking of the exposed photoresist, therefore the resist exposed with less dosage is always developed at a higher rate for the negative resists such as SU-8. Figure 3-8 were used to determine the different etching rates of single exposed regions and double exposed regions. In the numerical simulations, the unexposed regions, the single exposed regions, and the double exposed regions were allocated with different etching rates. In our model the flow of the etchant (SU-8 developer) is considered to be infinite and the developer density is considered to be uniform. The development time is adjusted by changing the total time steps in the program.

In the development process, the gravity or using mechanical stirrings such as ultrasonic agitation also affect the etching rate. When the wafer is positioned in a face-down orientation, the diffusion and removal of the dissolved SU-8 from the boundary regions of the developer and the un-cross-linked SU-8 are accelerated by the gravity force. Wafer positioned in the face-down
orientation therefore has a much higher development rate than that of the face-up case. In the suggested parameters provided by MicroChem Inc., the etching rate of unexposed SU-100 used for high aspect ratio structures is about 10µm/min when facing-up and with no agitation. Our measured time for the fully etching of 1000µm unexposed SU-8 (facing-up and no agitation) is around 100-110min, thus the etching rate is about 9-10µm/min. In our simulation and experiment, all the samples were positioned in a face-up orientation and no agitations were used.

![Etching Rate vs. Exposure dosage](image)

**Figure 3-8** Experiment results of the relationship between exposure dosage and etching rate

A flow chart of the simulation process is schematically shown in Figure 3-9. The simulation process is as follows: 1) divide the resist into 100x100x100 identical cubical cells and set the timer to zero; 2) input the opening shape, the etching rate, and the development time into the program. An interactive window is created in MATLAB to input the parameters as shown in Figure 3-10; 3) take a time step t=t+Δt, and update the states of each cell based on the cellular automata rule; 4) end the updating after a given number of iteration steps and export the results. The simulation was done in MATLAB and the surface points were exported to engineering software Pro/E to get the surface profile.
Figure 3-11 is the starting etching state, 100x100x100 grid is defined inside the photoresist cube. The following simulation starts from this photoresist cube.

Figure 3-9 Flow chart of the simulation process

Figure 3-10 Interactive window for input parameters
3.5 Simulations of Microlens Surface Profiles using Different Photomask Opening Shapes

Suppose the development dosage and development time are fixed, different opening shape on the mask will result in different lens types, for example, bi-convex lens, plano-convex lens, bi-concave lens, and plano-concave lens. Since the bi-concave and plano-concave are the inverses of the bi-convex and plano-convex, only the simulation of bi-convex and plano-convex will be presented here. The exposure dosage was set to be 3500mJ/cm$^2$ and 400 iteration steps were used.

Figure 3-12 shows the initial etching of a bi-convex lens. In this situation, two cylinders intersect with each other and the intersection is used to form the lens base. The regions inside these two cylinders are assumed to have uniform exposure dosage, while the intersected regions have double exposure dosage. In the practical lithography process to form the microlenses, an exposure dosage less than full dosage on the intersections were used. Both the single exposed regions and double exposed regions have less dosage than that required to fully cure SU-8 resist,
therefore both of these two areas can be developed with different etch ratio but much slower than that of the unexposed SU-8 resist.

Figure 3-12 Initial etching of bi-convex lens (Photoresist cubic divided into 100x100x100 cells)

The development process helps to etch the single exposed regions and round the edges of the double exposed regions. If the processing parameters are well controlled, the final surface profile tends to become a spherical surface after the development. In the corresponding simulation, the double exposed regions and single exposed regions are allocated with different etching rates based on the experimental data shown in Figure 3-8. The unexposed regions are allocated with an etching rate based on the standard etching rate of unexposed SU-8 photoresist. After a given development time (400 iteration steps), the final surface profile becomes bi-convex lens. Figure 3-13(a) shows simulation results of the surface points generated in MATLAB. Figure 3-13(b) shows the surface profile generated in Pro/E by importing the surface points from MATLAB. The simulation result shows in a practical lithography with less than full dosage, the edges of the intersection were smoothed. It also can be noticed that the diameter of the single exposed cylinders decreased due to the etching of the single exposed regions.
Figure 3-13 (a) Surface profile of a bi-convex microlens pixel simulated in MATLAB and (b) exported to Pro/E

Figure 3-14 shows the initial etching of a plano-convex microlens pixel. The cross section of the incident beam projected in the photoresist is the combination of half circle and half square. After etching of 400 iteration steps, the surface profile has become a plano-convex microlens as shown in Figure 3-15.

Figure 3-14 Initial etching of plano-convex lens

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The results of the bi-convex and plano-convex modeling showed that the CA model successfully simulated the influences of different opening shapes on the final surface profile. Since this paper focused on the fabrication of bi-convex microlenses, most of the simulations are based on an opening shape of ellipse. However, other geometric shapes like parabola, circle, and hyperbola can be also simulated depending on the requirements for the microlens’ surface profile.

![Figure 3-15 The surface profile of plano-convex lens after etching](image)

### 3.6 Simulations of Microlens Surface Profiles under Different Exposure Dosages

If the opening shapes on the photomask have been chosen, the exposure dosages and the development times will determine the surface profile of the microlenses. Since bi-convex microlenses are the most commonly used lens type in micro-optics, the numerical simulations of bi-convex microlenses were conducted and presented in the following section.

As discussed previously, Figure 3-8 shows the relationship between the exposure dosage and etching rate. This relationship was to be used to provide the etching rates in numerical simulations under different exposure dosages. The simulations were performed under three typical conditions. The first one is that both the single exposed and double exposed regions were assumed to be overexposed. The overexposed SU-8 resist would remain almost un-etched in the
developer while the unexposed regions would be completely removed. In the numerical simulations with CA, both the single exposed regions and the double exposed regions were allocated with zero etching rates while the unexposed regions were still allocated with its normal etching rate. This has resulted forming of a two-cylinder structure as shown in Figure 3-16. We can see later in chapter 4 that this two-cylinder structure can also focus light.

![Figure 3-16 Simulation result of overexposed two intersected cylindrical structure of SU-8 after etching](image)

Figure 3-16 Simulation result of overexposed two intersected cylindrical structure of SU-8 after etching

![Figure 3-17 A faceted surface consisting of four pieces of cylindrical surfaces](image)

Figure 3-17 A faceted surface consisting of four pieces of cylindrical surfaces
The second case is that only the double-exposed regions are overexposed while the single exposed regions are underexposed and will be etched during the development. This will form a faceted structure consisting of four pieces of cylindrical surfaces as shown in Figure 3-17.

The third case is the both the single-exposed regions and double-exposed regions are underexposed. It should be emphasized that the double-exposed regions may also be etched away in the development process if they receive too low dosage. Thus in a practical fabrication process, the double exposed regions need to be slightly under full dosage to get the optimal surface profile. Figure 3-18 shows the simulation result of the microlens surface profile under an optimized exposure dosage. The single-exposed regions have a dosage of 3500mJ/cm\(^2\) while the double exposed regions have a dosage of 7000mJ/cm\(^2\). The simulation results show that the exposure dosages can be manipulated to get different surface profiles on the final structure.

![Simulation of microlens surface profile with an optimized exposure dosage](image)

Figure 3-18 Simulation of microlens surface profile with an optimized exposure dosage

3.7 Simulations of Microlens Surface Profiles under Different Etching Steps

In previous section the simulation results show that under an optimized exposure dosage, the surface profile of microlens after the development process can become a bi-convex microlens which is of our interest. To precisely control the final surface profile, the forming process of the
microlens surface needs to be studied. This can be accomplished by changing the development times, i.e. the iteration steps in the program.

The development process of the SU-8 photoresist should be understood in the following way: For the unexposed regions, they are dissolved under a much higher rate than that of the single exposed regions and double exposed regions. For the regions around the intersection, as soon as the single-exposed parts are developed, the etchant starts to attack the double-exposed regions. The intersection regions are smoothed and tend to become a spherical surface profile under well controlled parameters. In our simulation, the exposure dosage was fixed to be 3500 mJ/cm$^2$ while the development time changes from 150 iteration steps to 400 iteration steps. At this dosage, the development rate of the double-exposed regions is measured to be about 1/10 of the single exposed regions. Lithography beam diameter is set to be 60 grids.

Figure 3-19 shows the microlens surface profile from 150 to 400 iteration steps. The development process of the photoresist is visualized. The developer first etches away the unexposed regions. Then the single exposed layer on the intersection regions is etched. The intersection regions are smoothed during this process. The simulation result shows the transitional regions between the single exposed regions and double exposed regions become smoother as the development time increases. It also shows the diameter of single exposed cylinders decreases as the iteration steps increase.

Figure 3-20 shows the cross section of the surface profile under different etching steps. It can be seen that after 350 steps of iterations, the surface profile becomes much closer to a spherical lens which is of our interest. The next step is to establish the relationship between the etching step and the real etching time. More details on the forming mechanism will also be discussed in Chapter 5.
Figure 3-19 Microlens surface profile after different iteration steps
Figure 3-20 Cross sections of the surface profiles under different iteration steps
3.8 Conclusions on Modeling and Simulations

In this chapter a simplified 3D CA model was established for the numerical simulation of the surface profile forming process of SU-8 microlenses. The simulation was performed for different opening shapes on photomask, different exposure dosages, and different development times. The simulation results show that the different dosage in single-exposed regions and double-exposed regions lead to different etching rates and affect the final surface profile. The evolution of the surface profile was simulated using the established model.

In Chapter 4, the experimental results will be presented and compared with the numerical simulation results.
CHAPTER 4. EXPERIMENTAL RESULTS AND COMPARISON WITH THE SIMULATION RESULTS

In last chapter, a simulation and modeling tool using cellular automata (CA) was established to estimate the surface profile of microlens array fabricated under different parameters. In this chapter, a series of experiments corresponding to the modeling parameters were performed and compared with the simulation results in Chapter 3.

4.1 Microlens structure and fill factor

The fill factor of a microlens array is defined as the percentage of a lens area over one pixel area. The fill factor is affected by the pixel geometry and lens layout. A large fill factor is preferred for most microlens applications. The maximum fill factor for a circular microlens pixel in an orthogonal lens array is $\pi/4$ as shown in Figure 4-1(a). The maximum fill factor for a circular microlens in a hexagonally arranged array is $\sqrt{3}\pi/4$ as shown in Figure 4-1(b). For fabrication methods using reflow technique, it is very hard to improve the fill factor due to the peripheral gap between adjacent photoresist.

![Figure 4-1 Fill factor of a microlens pixel in (a) orthogonal array and (b) hexagonal array](image)

Figure 4-1 Fill factor of a microlens pixel in (a) orthogonal array and (b) hexagonal array
Figure 4-2 Fill factor of microlens array fabricated by cylinder beam lithography

Figure 4-2 shows the incident beam arrangement during the lithography step. D is the gap between two cylinder beams and d is the diameter of each cylinder beam. To get a maximum fill factor out of the beam arrangement, D should be zero. In this case, after exposure and the development, each pixel’s shape is a spherical surface cut on a square frame. This arrangement can help to achieve a fill factor close to 100%. To investigate the forming mechanism of the microlenses, lens array structures with gaps between two cylinder beams were also fabricated.

4.2 Microlens Surface Profiles Obtained Using Photomask of Different Opening Shapes

Figure 4-3 shows SEM images of a microfabricated bi-convex microlens array. The out-of-plane microlens array was fabricated on thick SU-8 resist.

Figure 4-4 shows SEM images of a plano-convex microlens array. Compared with the simulation results in Chapter 3.5, it can be seen that the assumption in our simulation is in accordance with the experimental results. That is, changing the geometric shapes on the photomask will result in different lens types.

While in laboratory experiment the structures on the photomask are limited due to the fabrication time and cost, in the simulation different opening shapes on the photomask can be
designed and ‘pre-tested’. Simulation in the photomask design step will provide guidance to the experiment. Other geometric shapes like parabola, circle, and hyperbola can also be used for the mask pattern depending on the requirements for the microlens’s surface profile. The user will have a better idea of which photomask structure is the optimum for a certain microlens surface profile.

Figure 4-3 SEM images of bi-convex microlens array with 350µm diameter lithography beam

Figure 4-4 SEM images of plano-convex microlens array with 350µm diameter lithography beam

4.3 Microlens Surface Profiles under Different Exposure Dosages

Figure 4-5 shows the SEM image of the overexposed intersecting cylindrical structure of cured SU-8 after development. The exposure dosage for single exposure regions was
8000mJ/cm². The unexposed regions were fully etched while the two cylinders remain almost un-etched. From the SEM images it also can be seen that the lower parts of the structure are not ideal cylinders. This effect is due to the insufficient exposure dosage at the bottom of the thick SU-8 resist layer and the light reflection from the substrate. It should be emphasized that since our model does not incorporate with exposure simulation, no diffraction effect or reflection from the substrate was considered. Thus the effect at the bottom of the cylinder in the SEM image was not demonstrated in the corresponding result in Figure 3-16.

Figure 4-6(a) shows a SEM image of overexposed microlens array. The beam arrangement here is D=2d according to the parameters in Figure 4-2. There is still non-uniformity near the bottom of photoresist due to the insufficient exposure. Figure 4-6(b) shows the microlens array image under a microscope. The light source of microscope was illuminated from the bottom of the observation stage. The image of the microlens array was captured by using a CCD camera. The bright spots at each intersection show the focusing effect of a two cylinder joint structure (Figure 4-7). This structure can also be used in coupling light.

![SEM image of overexposed two cylinder structure of SU-8 resist after development](image)

Figure 4-5 SEM images of overexposed two cylinder structure of SU-8 resist after development (250µm diameter lithography beam)
Figure 4-6 Overexposed microlens array under (a) SEM and (b) microscope (200µm diameter lithography beam)

Figure 4-7 Intersection of two cylinder joint

In our experiment, the thickness of SU-8 photoresist was around 1000µm. The diffraction and the absorption of light in the photoresist cause the light intensity distribution change in the cross-section of the cylinder as state before. Thus the exposure needs to be carefully controlled to provide enough dosage for the bottom part to get enough adhesion while the top part not over exposed. Figure 4-8 shows an example of the poor adhesion between the microlens structure and the substrate. The dosage for single-exposed regions used in the fabrication is about 1800 mJ/cm². In the figure, the microlens fell down on the substrate due to the poor adhesion caused
by low level of cross-linking. In our experiment, it was found that under 3000 mJ/cm$^2$ the single exposed regions could barely stand on the substrate.

As stated in Chapter 3, in a practical fabrication process, the double-exposed regions need to be slightly under the full dosage to obtain the optimal surface profile. An optimized dosage for single exposed region was found to be over 3000 mJ/cm$^2$ and lower than 4000 mJ/cm$^2$. Figure 4-9 shows SEM images of intersection formed by two intersected posts under different exposure dosages.

Figure 4-8 SEM images of microlens structures fall down on the substrate (200µm lithography beam diameter)

Figure 4-9(a) shows the surface profile of the final structure with a dosage of 6000mJ cm$^2$. The intersection regions of the two posts are supposed to be a “ball lens”, which is obviously not in the desired profile. This was caused by the excessive exposure dosage in the lithography. According to the relationship in Figure 3-8, the double-exposed regions were overexposed. Only the single exposed regions were developed at a very slow rate while the intersection remains un-etched.

Figure 4-9(b) shows the microlens surface profile with an exposure dosage of 3500mJ cm$^2$. In this case, the double-exposed regions were slighted under-exposed and were etched under a rate much lower than that of the single-exposed regions. The combination effect of the
etching of single-exposed regions and double-exposed regions made the final surface profile became a microlens as designed. From Figure 4-9(a) and Figure 4-9(b), it can be seen that the surface profile of the intersection became much closer to an ideal ball lens as the exposure dosage was manipulated.

![Microlens Surface Profiles Obtained with Different Development Times](image)

Figure 4-9 Microlens surface profile under different exposure dosages (a) 6000 mJ/cm² and (b) 3500 mJ/cm²

### 4.4 Microlens Surface Profiles Obtained with Different Development Times

According to the modeling results in Chapter 3, the surface evolution of microlens was as follows: first the unexposed regions were etched away very fast by the development solution. Then the cylinder structure was attacked. For the regions around the intersection, the single exposed layers cover the double exposed layers. As soon as the single exposed layer was developed, development solution started etching the double exposed layer. The final surface profile is a combined effect of the development of both the single exposed region and double exposed region at different etching rates.

Figure 4-10 shows the microlens surface profile with different development times. The SEM images in Figure 4-10(a), and Figure 4-10(b) show the surface profile after 60 and 120
minutes of development (etching), respectively. The diameter of the single-exposed region decreased and the surface was smoothed after enough etching time. The experimental trend of the surface profile change is in agreement with the simulation result.

![Surface profile after different development times (SEM picture with 150µm diameter lithography beam)](image)

**Figure 4-10** Surface profile after different development times (SEM picture with 150µm diameter lithography beam)

### 4.5 Experimental Results of Optical Properties of the Microlenses

Microlenses of different diameters were fabricated and tested under optimized parameters. The opening shape on the photomask is ellipse. The optimized exposure dosage is 3500 mJ/cm². The development time is 120 minutes. Under these experimental conditions, the surface profiles of the microlenses were observed to become extremely close to spherical surfaces. Figure 4-11 shows the surface profiles of microlenses with different lithography beam diameters. The lithography beam diameters change from 150µm to 300µm.
There are many methods to measure the focal length of a conventional lens. For example, if a thin lens was illuminated by collimated light source, a screen can be placed on the back of a lens to find the minimum focal pad. The distance between the lens and the screen can be approximately considered equal to the focal length. However, this method is not practical for the measurement of microlenses. Because the focal lengths of the fabrication microlenses are in the range of several hundred micrometers, it is very hard to precisely adjust a screen in such a short distance.

A test system based on microscope was used to measure the focal length, DOF, and minimum focal pad of the fabricated microlenses. The microlenses were carefully removed from the silicon substrate and put on the observation stage of microscope. A collimated light from the
back of the stage projected on the backside of the microlenses. The images of the focal pad were magnified by 10 times and a CCD camera was used to take the images. The focal lengths were measured with the help of a translational stage. In the measurement shown in Figure 4-12, the displacement of the translational stage between the minimum focal pad and image of a lens (with same size of the lens diameter) can be roughly considered to be the focal length.

![Figure 4-12 Microlens focal length measurement using microscope](image)

Figure 4-12 shows the focal pad images of the microlens array with different lithography beam diameters. The focal pads of pixels in the microlens array are uniform under the microscope measurement.

Table 4-1 shows the experimental results of microlens optical parameters with different lens diameters. Under the same experimental conditions, the focal length increases as the lens pixel size increases.
Figure 4-13 Microscope images of the minimum focal pads of microlens with different lithography beam diameters (10x magnification)

Table 4-1 Experimental results of microlens optical parameters with different lithography beam diameters

<table>
<thead>
<tr>
<th>Beam diameter (μm)</th>
<th>Focal length (μm)</th>
<th>Focal pad (μm)</th>
<th>Depth of Focus (DOF, μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>150 μm</td>
<td>103.5</td>
<td>31.2</td>
<td>44.3</td>
</tr>
<tr>
<td></td>
<td>101.3</td>
<td>29.0</td>
<td>42.0</td>
</tr>
<tr>
<td></td>
<td>110.0</td>
<td>32.2</td>
<td>45.0</td>
</tr>
<tr>
<td>Average:</td>
<td>104.9</td>
<td>30.8</td>
<td>43.8</td>
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(Table 4-1 Continued)

<table>
<thead>
<tr>
<th></th>
<th>Average:</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>200 μm</td>
<td>193.0</td>
<td>34.0</td>
<td>51.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>187.7</td>
<td>33.8</td>
<td>49.0</td>
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<td>188.6</td>
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<td></td>
<td>189.8</td>
<td>34.5</td>
<td>51.7</td>
<td></td>
</tr>
<tr>
<td>250 μm</td>
<td>250.5</td>
<td>58.0</td>
<td>53.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>243.5</td>
<td>59.6</td>
<td>52.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>244.0</td>
<td>64.0</td>
<td>50.9</td>
<td></td>
</tr>
<tr>
<td></td>
<td>246.0</td>
<td>60.5</td>
<td>52.1</td>
<td></td>
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<tr>
<td>300 μm</td>
<td>277.0</td>
<td>77.3</td>
<td>58.0</td>
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<tr>
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<td>259.6</td>
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</tr>
<tr>
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<td>263.9</td>
<td>72.0</td>
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<tr>
<td></td>
<td>266.8</td>
<td>73.6</td>
<td>55.9</td>
<td></td>
</tr>
</tbody>
</table>

4.6 Conclusions

In this chapter experiments under different parameters were performed and compared with the simulation results. Different geometric openings on photomask were designed and used to fabricate bi-convex and plano-convex microlenses. Different exposure dosages were also tested to study their influence on the surface profile. The evolution of the surface profile was demonstrated based on different development times.

These comparisons are basically qualitative to show that the established 3D CA model is a powerful tool for simulating the forming process of out-of-plane microlenses. A quantitative
comparison will be discussed in the next chapter. The CA model established here is also capable of simulating high aspect ratio photoresist etching process.

In our future work, the diffraction effect of light beam propagating in the photoresist will be considered and the light intensity distribution will be simulated. Some parameters like post bake temperature and time also need to be thoroughly studied for a complete photolithography simulator.
CHAPTER 5. USING THE THREE-DIMENSIONAL (3D) CELLULAR AUTOMATA (CA) MODEL AS A PROCESS DEVELOPMENT AND MANUFACTURING TOOL

The photolithography modeling can be used for the following purposes: 1) a research tool, 2) a development tool, 3) a manufacturing tool, and 4) a learning tool [47]. In the process of development and manufacturing of microlens arrays, it involves numerous experiments to determine the optimum process conditions which are time consuming and costly. It is therefore useful to develop a 3D CA model for numerical simulations as a process development tool and manufacturing tool to determine the optimum process settings in a practical experiment. This kind of computer-aided design (CAD) is essential to save time and money in experimental design. In this chapter the surface profile of two microlens arrays fabricated in previous chapter were measured. Then the design parameters were simulated using the modeling tool and compared with the experimentally measured microlens parameters.

5.1 Experimentally Measured Parameters of Microlenses

A laser scanning confocal microscope (Olympus LEXT OLS4000) was used to measure the surface profile of microlenses with diameter of 200µm. The exposure dosage was 3500 mJ/cm². The development time was 120 minutes. The lens array was broken off the substrate and scanned along the direction of the lithography beam. Figure 5-1(a) shows the SEM image of the fabricated microlens array. Figure 5-1(b) shows the surface profile scanned by a confocal microscope. Figure 5-1(c) the surface profile of the cross-section cut from the center of a microlens along the x direction. Our measurement result indicated that the uniformity of the lens array is well controlled thanks to the filtering of short wavelength. The average radius of curvature is about 125µm.
Figure 5-1 Surface profile of microlens array with beam diameter of 200µm measured by a confocal microscope. (a) SEM image of microlens array (b) Surface profile scanned by confocal microscope (c) Fitted curve using part of a sphere

A Tencor Alpha-Step 500 surface profiler was also used to measure the surface profile of microlenses with beam diameter of 300µm. The confocal microscope often needs the deposition of a reflection layer which will damage the sample. Compared with confocal microscope, mechanical surface profilometer using stylus are easy to operate and can also provide a high resolution measurement. The measured data was draw in a profiler curve and compared with the
ideal fitted sphere curve. The ideal sphere curve has a radius of curvature of 183µm, which is different from the radius of the lithography beam of 150µm.

![Profiler curve vs Sphere curve](image)

**Figure 5-2 Surface profile of microlens with 300µm lithography beam diameter**

### 5.2 Modeling and Simulation of the Designed Lens

The photoresist simulator requires the input of cylinder radius, exposure dosage, and the iteration steps. In the numerical simulation using CA model, the input parameters used are as follows: the cylinder diameter is 60 grids and the exposure dosage is 3500 mJ/cm². To establish a general simulator for microlens surface profile modeling, the relationship between the iteration steps in the simulation and the real etching times in the experiment need to be established. A test run using the simulator was performed. For a 100x100x100 unexposed photoresist cubic, complete removal of the unexposed photoresist cube needs 294 steps, which equivalent to 100 minutes of complete removal of 1000µm thick photoresist in a standard development process (the etching rate for unexposed SU-8 is around 10µm/min). So the relationship between the etching step in the simulation and the real etching time in the experiment is 1 minute = 2.94 steps. Thus 120 minutes of development corresponds to 352 steps in simulator.

The simulated surface profile is shown in Figure 5-3(a). A portion of the center curve was extracted and an ideal sphere curve was used to fit the simulation curve in Figure 5-3(b). In the simulation code the center of the cylinder was set at coordinator (51, 51, 51). Thus in the figure the x axis is from 30 grid to 72 grid. The radius of curvature of the sphere curve is 35 grids,
which is larger than the radius of cylinder that is 30 grids. This is in agreement with the experiment phenomenon that the development process will smooth the surface of the desired microlenses.

![Simulation curve vs Sphere curve](image)

Figure 5-3 (a) Cross section of microlens surface profile after 352 steps (b) fitted with a spherical curve

5.3 Forming Mechanism of the Microlenses based on Modeling Result

It is founded that the final radius of curvature of the surface is bigger than the beam diameter both in experiment and in simulation result. This can be explained by the forming mechanism of the microlenses. First, the unexposed regions were etched by the etchant. After the
etchant reach the single exposed regions, the cylinders and the intersections were attacked. The cylinders were etched at the development rate of single exposed photoresist. For the intersection, the double-exposed regions were covered by the single exposed layer. The central parts of the intersection (double exposed regions) were first attacked because the single exposed layer is the thinnest at the center. The etchant then gradually etched away the single exposed layers from the center to the edge of the intersection regions. At the same time, the double-exposed regions faced the etchant from the center to the edge gradually. Therefore, the central parts of the intersection were etched for a longer time than the edge parts. This is the reason that the etching process will smooth the lens surface and eventually form a surface profile with a larger radius of curvature than that of the designed cylinder beam.

This phenomenon can be seen clearly from Figure 5-3(b). The simulated points in the center part are more ‘flat’ than the edge points because these points have the longest etching time in the intersection. Those points around the edge have the least etching time and are more in accordance with the designed cylinder radius.

5.4 Comparison of results of numerical simulations and experiments

For a microlens array with 200µm diameter, 1 grid equal to 3.33µm, thus the simulated radius of curvature of the sphere curve should be 116µm. The measured radius of curvature was about 125µm. The simulated result is about 7% deviated from the measured result.

For a microlens array with 300µm diameter, 1 grid equal to 5µm, thus the simulated radius of curvature of the sphere curve should be 175µm. The measured radius of curvature was about 183µm. The simulated result is about 4% deviated from the measured result.

These two comparisons show that the theoretical value is smaller than the experiment value. There may be several reasons for this deviation. The first one is that the practical
development process is not a linear process due to the complicated geometrical shape and the non-uniformity of the developer density. For thick photoresists developing process, the local developer density changes as the etching wastes generated and the developer itself consumed during the etching. This can be added as a function of the developer density in future work. The second reason is that the cellular grid used in our simulation is 100x100x100, which limited the accuracy of the simulation result. This can be improved by added more grids in the future work.

While there is still room for further improvement for the CA model, this study has proved that it is feasible to use the model to simulate the fabrication process of the microlenses. Because testing large number of different photomask designs in laboratory is both time consuming and not cost effective, it would be much easier to simulate them numerically to find out what is the best design for a particular application. The CA modelling and simulation can therefore be used as a powerful tool in a computer-aid design and computer-aided fabrication process. It may help to reduce the product development time and obtain the optimal performances for the final product.

5.5 Comparison of the Optical Parameters

Unlike a thin lens, the thickness in the fabricated microlens cannot be ignored. Figure 5-4 shows the key parameters of a thick lens. b.f.l stands for back focal length. d is the thickness of the lens, and f is the equivalent focal length. If the two spherical surfaces has the same radii R. Then the thick equation can be expressed as

\[
\frac{1}{f} = \frac{(n-1)}{R} [2 - \frac{n-1}{n} \frac{d}{R}] 
\]

(5-1)

where n is the refractive index of the lens medium.
For 200\(\mu\)m diameter microlens, the thickness of microlens can be assumed to be 200\(\mu\)m although the surface was a little bit etched. The measured radius of curvature is 125\(\mu\)m. For 600nm wavelength light (about the average of the maximum transmission of SU-8 in visible light spectrum), the refractive index of SU-8 photoresist is about 1.61 [33]. The equivalent focal length \(f\) is 147.0\(\mu\)m, and b.f.l is 57.9\(\mu\)m. The measured focal length is 189.8\(\mu\)m. The equivalent focal length is about 22% smaller than the measured focal length. For 300\(\mu\)m diameter microlens, the thickness of microlens can be assumed to be 300\(\mu\)m, \(f\) is 217.6\(\mu\)m and b.f.l is 82.4\(\mu\)m. The measured focal length is 266.8\(\mu\)m. The equivalent focal length is about 18% smaller than the measured focal length. These differences may come from the aberration of the lens surface. The measurement method for the focal length also needs to be improved.

5.6 Conclusions

This chapter compared the surface profile simulated with the established CA model with the experiment data. The simulated results showed a deviation of 4%-7% from the measured ones. We analyzed several possible reasons that may cause the deviation. This method can be used to predict the microlens surface profile for computer-aided design in microfabrication.
Thick lens equation was used to calculate the focal length of the microlenses and compared with the measured results. The measurement method needs to be improved.

The ultimate goal of this work is to use the established model to predict the optimal processing conditions for the precision control of lithographically fabricated microlens profile.
CHAPTER 6. DESIGN AND FABRICATION OF A PRE-ALIGNED FREE-SPACE OPTICAL INTERCONNECTION DEVICE

6.1 Introduction

Traditional electrical interconnections for chip-to-chip transmission have been facing several critical challenges for years [62, 63]. First, the continuing scaling down of electronic device brings many problems to conventional metal interconnects, such as the degradation of the wire performance, the power dissipation, and the signal integrity. Second, for data transmissions between chips, the performance is dominated by the interconnection medium rather than the device at either end [62]. Because of the electrical resistance of interconnect wires and interferences, the distance between chips affects data transmission rate significantly, and the inter-chip and chip-to-board data transmission rate has become a bottleneck factor in computer industry. Optical chip-to-chip connection is a very attractive solution to maximize the data-transferring rate and permit longer inter-chip distance [64]. It also offers the advantages of lower signal loss and lower power consumption. Many different research efforts have been made in industry and academics [65-69]. These proposed optical approaches can be generally classified into guided wave and free space.

Those approaches based on guided wave technology involve the use of waveguides to propagate the optical singles [68, 70]. Free-space optical interconnect (FSOI) is another approach for chip-to-chip level interconnection.

In comparison with waveguide technology, it has the advantages of large interconnection density, lower power consumption, and better crosstalk performances [62, 66, 71]. The main remaining limitations are the fabrication cost and the tight alignment requirement during assembly [72].
Microlens array is dealing with alignment of microns over centimeters of a conventional single lens. Adaptive optical components are often used to compensate the misalignment [73, 74]. However, fabrication and control of the adaptive components are complicated and costly.

In this work we proposed the design and fabrication of a pre-aligned integrated FOSI for chip-to-chip connection application. We demonstrated that micro optic components like microlens array, micromirrors, and optical waveguides can be integrated on a single silicon substrate using direct lithography. All optical components are pre-aligned in mask design and fabrication stage and the resolution is only limited by the resolution of lithography. Our group has previously reported a fast replication out-of-plane microlens with polydimethylsiloxane (PDMS) and curable polymer [41]. Using this fast replication method, large amount of optical elements with excellent optical properties can be manufactured at very low cost. Several other alignment methods for micro-optical element integration were also discussed.

The principle of a free space optical interconnection for chip-to-chip data transmission is shown in Figure 6-1. On one end, the optoelectronic chip will transform data from electronic signal from the chip to optical signal and this optical signal is transmitted by microlens array. At the other end, the optical signal received by the other optoelectronic chip will be transformed to electronic signal to another chip. In this setup, the high resolution is only required at the light source and the detectors [65]. Although the field dependent aberration contributions are negligible, the spherical aberration of each microlens must be controlled. Three dimensional parallel data processing can be achieved using such ‘optical beam relay’ systems.

Our current work is mainly focused on the design and fabrication of the free space optical system that carries the data between optoelectronic devices.
6.2 Design of Free-space optical interconnection device

6.2.1 Maximum beam propagation design

The schematic diagram of one of our FSOI design is shown in Figure 6-2. A symmetric design is used to simplify the analysis and fabrication process. On one end of the FSOI system, vertical-cavity surface-emitting lasers (VCSEL) can be attached to emit the light signals while on the other end detectors may be attached to receive the signals. The design concept is to use as few microlenses as possible to achieve the maximum light propagation distance between the VCSEL and the detector.

A typical VCSEL output beam, as used by Wang et al. [68], has output optical aperture of 12µm, real divergence half-angle of 6°, and a wavelength of 850nm. Based on Gaussian beam
theory, this output beam can be characterized as a Gaussian beam with an M factor greater than 1 since it contains high order mode intensity distribution [75]. Gaussian beam propagation can be expressed in the following equation:

\[
w(z) = w_0 \sqrt{1 + \left(\frac{z}{z_R}\right)^2}, \tag{6-1}
\]

where \(w(z)\) is the beam radius at location \(z\), \(w_0\) is the input beam waist, and \(z_R\) is the Rayleigh range, \(z_R = \frac{\pi w_0^2}{\lambda}\) and for paraxial approximation the beam divergence half angle is \(\theta = \arctan(\lambda / \pi w_0) = \tan(\theta) = \lambda / \pi w_0\).

To investigate beams with higher order modes, M factor is introduced, which is defined as \(M = \frac{w_{M0}}{w_0}\). Beams with higher orders can be investigated in the same way as Gaussian beam, where only M needs to be multiplied to the beam radius calculated using Eq. (6-1). Thus, for a beam with higher order modes, the divergence half angle can be calculated as:

\[
\theta = M \times \theta = M \times (M \lambda / \pi W_{M0}) = M^2 \lambda / \pi W_{M0}. \tag{6-2}
\]

Substituting the previous aperture size \((w_{M0} = 12\mu m)\), wavelength \((\lambda = 850 nm)\) and divergence half angle \((\theta = 6^\circ)\) in the formula, the M factor for a typical VCSEL can be obtained as about 2.16. It can then be found that \(w_0 = 12\mu m / 2.16 = 5.56\mu m\) and \(z_R = 114.17\mu m\).

The first constraint in our design is the distance from the VCSEL to the first microlens array (L1), which is at least 1mm. The beam radius needs to be calculated when it first reaches the microlens array (MLA) plane. Assuming the reflection mirror does not introduce any phase difference and only change the beam propagation direction and taking \(z_1 = 1\)mm, \(w(z_1)\) is then computed as 49.00\mu m. The real beam radius at \(z_1\) is therefore 49.00\mu m \times 2.16 = 105.84\mu m. To keep its Gaussian profile, a clipping factor greater than 2 is normally required, it means that the design of the first microlens array requires radius greater than 200\mu m (\(D_{\text{max}} \geq 400\mu m\)). However,
there are two other factors need to be considered in choosing the lens diameter. The first is the limit of the fabrication technology. In the fabrication process based on UV lithography of SU8, the maximum thickness of the SU-8 photoresist layer is usually no more than 2mm, anything more than that would require other exposure sources such as x-ray. This maximum thickness of resist limits the pixel number of the microlens array. Another practical consideration is that to support a large number of connections in a single area, the microlens diameter is usually less than 500 µm [65].

The second design consideration is that in a free space optical interconnection system, a maximum propagation distance is usually desirable [69], which can be expressed as $z_{\text{max}} = f + f^2 / 2z_R$. As shown in Figure 6-2, in order to achieve the maximum propagation distance $z_{\text{max}}$, the distance from the initial beam waist $w_0$ to the first microlens (L1) should be $f_i + z_R$. A simple calculation can be carried out here. Since the distance between the VCSEL and L1 is $z_i=1000\mu$m, focal length of L1 need to be about $885\mu$m ($f_i = z_i - z_R$). The waist position after L1 will be at $z_{2\text{max}} = f + f^2 / 2z_R = 4322\mu$m and the distance between L1 and L2 is twice of that (8644µm). Due to the symmetric nature of the system, L2 is the same as L1, the beam waist after L2 is therefore 1000µm away from L2 and ideally has the same characteristics as the original beam from the VCSEL. In this case, L2 replicates the VSCEL array and another group of lens (L3 and L4) prorogate the beam even further. The propagation distance from the VCSEL to the other end is about 20mm.

With the two foregoing considerations, the final FOSI device was designed with microlens diameter about 450µm and focal length about 885µm. The entire device is about 20mm in length.
6.2.2 Fabrication of the Free Space Optical Interconnection Device

A direct lithography process, which can simultaneously fabricate different micro-optical elements on a single silicon substrate, was adopted. For the fabrication of microlenses, the opening shape on the photomask is ellipse (with long axis equal to \( \sqrt{2} \) times of the short axis) to get bi-convex microlens. The exposure dosage and the development time were adjusted to get microlens with a spherical surface. After the exposure of microlens array, the clutch was rotated 90° to expose the micromirror structure. The opening shape on the photomask for the micromirror is a rectangle. The whole structure of the micromirror was fully exposed as shown in Figure 6-3. During the development process, unexposed regions were dissolved and the exposed region formed the micromirror.

![Figure 6-3 Fabrication of 45° micromirror](image)

After the optical components of FSOI were fabricated using cured SU-8 polymer as the structural material, we used PDMS based molding process and a UV curable glue, NOA 73 (Norland Products Inc., Cranbury, NJ) to replicate the entire FSOI structure out of the SU-8 mold. The NOA73 polymer has excellent optical properties in comparison with SU-8 [36].

Figure 6-4 shows the replication process in details. First, all the optical components including the microlens array and micromirrors were fabricated with tilted lithography of SU-8 on a silicon substrate (Figure 6-4(a)).
The distance between the microlens array and the reflection mirrors was carefully calculated to reach the optimal performance of Gaussian beam propagated propagation in FSOI as stated before. Second, a negative PDMS mold was then created using the fabricated SU-8 master (Figure 6-4 (b)). Third, UV curable polymer such as NOA 73 was drop-dispensed on the PDMS mold and a transparent glass substrate was pressed onto the coated UV curable polymer (Figure 6-4(c)). Subsequently, it was exposed to UV light ($\lambda$=300-400nm) for several minutes through the glass substrate. After the UV curing, the fabricated optical structure was peeled off the PDMS negative mold (Figure 6-4(d)). In the last step, using E-beam evaporation method, a thin metal film (such as gold or aluminum) was deposited onto the micromirror to form the reflection coating (Figure 6-4(e)). It is need to be emphasized here that a PDMS ‘life off’ method
was used to make selectively deposition on the micromirror regions. This method is very similar to a traditional lithography lift off. The microlens regions were protected by PDMS while PDMS were peeled off from the micromirror regions. After the deposition process PDMS was peeled off from the microlens regions to achieve the selective deposition. No shadow mask was needed.

6.2.3 SEM images and Test Results

Figure 6-5 shows the SEM images of the fabricated FSOI. The upper-left image shows the microlens array L2 and L3 as illustrated in Figure 6-2. The upper-right image is a close view of the fabricated microlenses. The lower-left picture shows the mirror and the microlens array L1. The lower-right picture is a close view of the micromirror with gold coating.

Figure 6-5 SEM images of fabricated FSOI
The diameter and focal length of our designed microlenses was designed to be 450µm and 885µm, respectively. However, the fabricated microlenses only have focal lengths of 400µm, which is much smaller than the designed value. This will severely degrade the performance of the optical interconnection system. Although the aim for maximum propagation distance of Gaussian beam was not achieved in this work, future improvement on changing the mask patterns can be made to fabricate designed microlenses with longer focal length.

6.2.4 Beam Relay Design and Test

To get the optical transmission performance of free space interconnection made by SU-8 photoresist microlenses, another approach using optical beam relay was fabricated and tested. Thanks to the pre-alignment and direct lithography techniques, a large number of identical microlens arrays can be fabricated on a single silicon substrate simultaneously. The schematic diagram of beam relay using microlens arrays is shown in Figure 6-6. A set of identical lenses with focal length f separated by distance d was fabricated on a silicon substrate. This system may be used to relay light between two locations if \( d \leq 4f \) is satisfied [76]. The fabricated microlenses with lens diameter of 200µm have a focal length of 190µm. The distance between two adjacent lens arrays is 480µm.

Figure 6-6 Beam relay for optical interconnection
A simple experiment was performed to test the optical performance of the beam relay. An optical fiber (diameter of 200µm) connected to a light source was placed on the focus of a single microlens as shown in Figure 6-7. Another optical fiber was placed on the other end to receive the light. The optical loss or coupling efficiency was measured by a spectrometer.

![Microlens and an optical fiber connected to light source](image)

Figure 6-7 Microlens and an optical fiber connected to light source

The test of the optical performance the beam relay will include using a LED light source (Wavelength of 460µm) and spectrometer (Ocean Optics, Inc.). The light loss after beam relay will be measured by the spectrometer. The input signal is assumed to be the signal received by another optical fiber using direct coupling method. The measured intensity is $5 \times 10^4$ photon counts (integration time is 100µs) as shown in Figure 6-8. The light signal after eight identical lens arrays was measured to be $6 \times 10^4$ photon counts (integration time is 100ms) as shown in Figure 6-9. Thus the optical loss after the whole microlens beam relay is $6 \times 10^4 / (5 \times 10^4 \times 1000) = 0.12\%$ (about 30dB). The light loss after each microlens is about 43% (about 3.6dB).
Figure 6-8 Measured optical signal using direct coupling of two fibers

Figure 6-9 Measured optical signal after microlens beam relay
Both the strong aberration of the microlenses and the loose alignment in our experiment contributed to such high optical loss. Aspherical microlens array will be fabricated in the future work to reduce the lens aberration. In the current experiment setup, the alignment of microlenses with the optical fiber is a critical issue for the test. The relative position change between the optical fiber and the microlenses will severely affect the test result. Thus direct fabrication of pre-aligned optical waveguides or using silicon etched V-groove for alignment should be provided in the future work.

6.3 Future work on integrated micro-optical systems

For some applications like laser diode to optical fiber coupling, the spacing between the lenses and the optical fibers, laser diode should be maintained during the fabrication. Otherwise it may never be possible for a precise alignment. In our previous work, micro channels acting as optical fiber holder were fabricated together with microlens array using tilted lithography as shown in Figure 6-10. However, due to the swelling of SU-8 photoresist, the relative position between the fiber channels and microlenses may change after development. It is also very difficult to insert an optical fiber into the deformed channel.

![Figure 6-10 Integration of fiber channel and microlens array using tilted lithography](image)

Figure 6-10 Integration of fiber channel and microlens array using tilted lithography
There have been some research on silicon micromachined V-groove fiber couplers [77, 78]. The V-shape grooves fabricated by isotropic etching of silicon substrate not only provide precise alignment for optical fibers, but also can be directly integrated with other optical elements. The future work will be the integration of the lithographically fabricated microlenson onto the silicon bench. Photodiode and CCD array will be integrated on the other side of the lens array to measure the light signal.

![Figure 6-11 Integration of lithographically fabricated lens array on silicon bench](image)

6.4 **Conclusions and future work**

A free space optical interconnection device for maximum beam propagation was designed using Gaussian optics and the layout of the device was calculated based on the Gaussian beam propagation equation. An optical interconnection device with out-of-plane microlens array and 45° micromirror was successfully fabricated. The out-of-plane microlens array and the micromirror were pre-aligned during photomask fabrication stage. The optical components were fabricated by UV tilted lithography of SU-8 and fast replication of UV curable polymer (NOA 73). The NOA73 polymer has excellent optical properties compared with SU-8.
It was found that the surface qualities of the micromirrors and microlenses are good enough for the applications targeted. The rapid replication using PDMS molding method will help reduce the batch production cost. This technique of micro-optical elements can be used for alignment of a large number of optical elements at the same time. Due to the current fabrication limitation of microlenses, this optimization design cannot be realized. Instead, a simple beam relay system consisting of identical microlens arrays was tested. The optical loss for the beam relay system is around 90%. The high loss was caused by the loose alignment in experiment setup as well as the aberrations of the microlenses. For the alignment of optical fibers, one approach is to use silicon etched V-grooves as the fiber holder which will be included in our future work.
CHAPTER 7. SUMMARY AND FUTURE WORK

7.1 Summary

Microlens is a key element in micro-optical systems. Fabrication of out-of-plane microlens array is desirable for a lot of applications like on-chip detection, laser diode to optical fiber coupling, free space optical interconnection, and etc. Our group has been working on fabricating out-of-plane microlens arrays using titled lithography on SU-8 photoresist, which can significantly reduce the time and cost of manufacturing process. The major challenge in this technology is the precise control of the surface profile of microlens. This dissertation presented the fabrication process of SU-8 photoresist, analyzed the influences of different parameters on the final surface profile.

A simplified cellular automata model was established to simulate the forming mechanism of lithographically fabricated microlenses. The simulation algorithm was tested under different opening shapes on the photomask, different development dosages, and different development times. The simulation was performed in MATLAB and the surface points were exported to Pro/E to get the surface profile. The forming process and surface evolution of the microlens were explained using the established model. The simulation results are in agreement with the actual forming process of the microlenses.

A series of experiments were performed and compared with the simulation results. From this work, it is shown that the established 3D CA model is a powerful tool for simulating the forming process of the out-of-plane microlenses fabricated on thick SU-8 resist. This model can be used to predict the surface profile of the microlenses fabricated under different processing parameters.

The fabricated out-of-plane microlenses and micromirrors were used in a free-space optical interconnection device. The device was designed using Gaussian optics and the layout of
the device was calculated based on the Gaussian beam propagation equation. A simple beam relay using a sequence of identical microlens arrays was fabricated and tested. This work shows the direct lithography technique and the pre-alignment design can manufacture large number of out-of-plane microlens arrays simultaneously with low cost and tight tolerance. A fast replication method using PDMS mold and UV polymer was also realized. A selective deposition method of micro-optical elements using PDMS ‘lift-off’ technique was realized. No shadow mask was needed during deposition process.

7.2 Future Work

The future work includes two major subjects: the first one is to continue the modeling and simulation on the forming process of lithographically fabricated microlenses, the second one is to build an integration micro-optical system with microlens array, optical fibers, waveguides, and optoelectronic component.

The research on modeling and simulation will include the simulation of diffraction effect of the light beam propagating in the photoresist. Because the absorption rate of the resist is affected by the wavelengths of the light source used in lithography, the actual absorbed dosage is a function of both the nominal dosage as well as the spectrum of the light source. The actual absorbed dosage then determines the actual development rate that plays a vital role in the formation of surface profile. In order to achieve accurate control of the final lens profile and the focal lengths, we need to conduct a comprehensive study of these relations.

The other work is the fabrication of free space micro-optical system, which consists of microlenses, micromirrors and optical waveguides on a single substrate to form a laser diode optical fiber coupler. This is a challenge because this requires the direct lithography of optical waveguides, which is one of our current research interests. An integration of V-groove fiber
optical with the lithographically fabricated microlenses will be used for the fiber to lens coupling and will be tested in the future work.
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