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Design and fabrication of electromagnetic micro-relays using the UV-LIGA technique

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DESIGN AND FABRICATION OF ELECTROMAGNETIC MICRO-RELAYS USING THE UV-LIGA TECHNIQUE

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 Interdepartmental Program in Engineering Science

by
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May, 2004
For Denise and Kira,
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ABSTRACT

This dissertation reports a research effort to microfabricate an electromagnetic relay for power applications using a multilayer UV-LIGA process. A mechanically wrapped coil was used and very simple design for the magnetic circuit was adopted to increase the design flexibility and performances. The broad material selection and the capability of making high aspect ratio microstructures of the UV-LIGA make the technology best suited for fabricating microelectromechanical power relays.

Fabrication of the device required significant advances in the optical lithography of SU-8 negative photoresist. Research proved that aspect-ratios up to 40:1 in isolated open field structures of thickness between 1 and 1.5 mm can be obtained a standard broadband UV source. The principal factor in this achievement is the reduction of internal stress during the post-exposure bake process that eliminates large plastic deformations present during standard bake procedures.

Another challenging issue associated with producing high aspect ratio microstructures is the development narrow groves and deep holes in SU-8 lithography. To overcome this obstacle, megasonic agitation was applied to the developer bath, which resulted in faster development rates, more uniform development, and the ability to produce structures with higher aspect ratios. To date, this process has been used to achieve 100:1 aspect ratio open field features and 45:1 intact cylinder arrays.

A multi-layer SU-8 optical lithography and metal electrodeposition process was developed to fabricate the relay. The design required implementation of high aspect ratio lithographic processing techniques to produce a tall nickel magnetic core and insulated magnetic cup in which a pre-wrapped solenoid would be placed for electromagnetic
driving. After insertion of the solenoid a Ni-Fe actuator was bonded to the relay base to complete the device.

To better understand the fatigue life of electroplated microstructures, a theoretical model was developed determine the possible fracture mechanics properties and fatigue life of LIGA fabricated nickel and nickel-iron alloys for use in Microsystems applications.

The prototype micro-relays were tested for the dynamic characteristics and power capacity. The experimental results have confirmed that reasonably large current capacity and fast response speed can be achieved using electromagnetic actuation and the multi-layer UV-LIGA fabrication process developed.
CHAPTER 1: INTRODUCTION*

1.1. Electromagnetic Micro-relays

Relays are used industrially in a wide variety of applications. Traditional mechanical relays are large, slow, noisy devices, but are still widely used in various machines and processes for control purposes. Solid-state switches, which have much longer lifetimes, faster response, and smaller sizes when compared with conventional mechanical relays, have been available in different forms for many years. However, solid-state switches have low off-resistance and high on-resistance, which result in high power consumption and poor electrical isolation (typically no better than -30 dB). Design trade-offs for reducing the "on-resistance" of solid-state relays tend to increase output capacitance, which introduces additional problems in applications requiring the switching of high frequency signals.

The fast developing technology of microelectromechanical systems (MEMS) has opened up opportunities for developing new types of micro-relays.¹⁻² Like the revolution started by the miniaturization of electronic circuits, the industrial impact of micromechanical systems will be substantial. The principal technology for fabricating micro-mechanical elements has been silicon-based, which is relatively mature due to years of microelectronics research and development. Most commercially available micro-mechanical components and systems are made of silicon.

Compared with solid-state switches, electromechanical micro-relays have the same advantages as normal mechanical relays: lower on-resistance, higher off-resistance,

* Some material in this chapter will be printed in Microsystem Technologies under the title “Microfabrication of an Electromagnetic Power Micro-Relay Using SU-8 Based UV-LIGA Technology.”
higher dielectric strength, lower power consumption, and lower cost. By using MEMS technology, the size, cost, and switching time of mechanical relays are greatly improved. Furthermore, micro-relays can be combined with other electronic components. These advantages are even greater with multi-contact relays, such as matrix switches.

There have been several different prototypes of micro-relays reported, most of which were electrostatically actuated. Gretillat et al.\textsuperscript{3} created an electrostatic polysilicon micro-relay integrated with MOSFETs. Drake et al.\textsuperscript{4} developed an electrostatically actuated micro-relay for use in automatic test equipment (ATE). Guckel et al.\textsuperscript{5} reported an electromagnetic microactuator with inductive sensing capability. Guckel’s device uses a LIGA-fabricated (German acronym for lithography, electrodeposition and plastic molding) magnetic core with a mechanically wrapped coil. The electromagnetic actuator has a planar design and relatively large size (in the millimeter range). Other groups have also reported work on electromagnetically driven micro-relays. In 1994, Hosaka et al.\textsuperscript{6} reported some fundamental work on electromagnetically actuated micro-relays. In their research, a miniature (inch-size) electromagnetic relay was constructed using a microfabricated spring and a large external coil assembled together.

Rogge et al.\textsuperscript{7} published the first LIGA fabrication process for micro-relays. In their study, an integrated magnetic core wrapped with a microfabricated planar coil was made using the LIGA process. Many planar electromagnetic coils have also been developed for electromagnetic actuation from silicon-based technologies.\textsuperscript{8,9,10,11} These devices use solenoids that yield unconfined magnetic fields perpendicular to the plane of the wafer. These electromagnets can then be placed in close proximity, above or below a microactuator to induce a mechanical motion. Typical coils produced by this technology
are comprised of very thin wires that cannot carry high currents. They typically have less than 20 turns, yielding a low magnetic flux.

Recently, Kim and Allen\textsuperscript{12} produced a multilayer UV-LIGA fabricated electromagnetic solenoid. Kim’s work was extended to relay devices by Park and Allen.\textsuperscript{13} The solenoid was made using multiple resist patterning and electrodeposition steps to create a copper coil around a permalloy material. Improved relay designs have since been developed\textsuperscript{14,15} using the same fabrication techniques. They all used thick UV resist processing to produce a coil pattern that is electroplated to produce a solenoid parallel to the surface of the wafer. This process requires long distances to wrap a high number of turns and provides no magnetic confinement.

The practical utilization of electromagnetic actuators in MEMS systems is still very limited. The most common actuation principle is still the electrostatic one. This is mainly due to the difficulties in fabrication of micro-sized electromagnetic actuators. Another complication is that the electromagnetic actuation typically requires a sizable current, contributing more to on-board power consumption and heat generation.

1.2. Advantages of Electromagnetic Actuation

The limited number of electromagnetic actuators in MEMS is partially due to the difficulties in fabrication of micro-sized electromagnetic actuators with silicon-based MEMS technology, and partially because of some misconceptions about electromagnetic actuation. Busch-Vishniac\textsuperscript{16} provided a detailed discussion and strong arguments for electromagnetic micro-actuators by direct comparison of a magnetic with an electrostatic microfabricated actuator. It was concluded that the case for magnetic actuation is compelling in most of the scales of interest.
If the efficiencies of electrostatic and electromagnetic actuators are compared: the smaller the actuator, the more advantageous the electrostatic type, with the transition point around 1 mm. From a practical point of view, this size, which is two to four orders of magnitude smaller than conventional relays, is sufficiently small because, even if it were further reduced, total system size would not change much since the peripheral circuit would be the dominant feature.

Two key factors in selecting an actuation mechanism are reliability and cost. In terms of reliability, closing and opening of the mechanical contacts are dust-making processes. The actuator for the micro-relays must be unaffected by particulate. Electromagnetic actuators are superior to electrostatic actuators in this aspect, since the latter are affected by contaminant adhesion. When considering the overall cost of micro-relays, both the relays and the peripheral circuit costs must be taken into account. Electromagnetic actuators can be controlled with low-cost electronics, but electrostatic actuators typically need high voltage (>30 volts) to operate. Specially designed control devices and isolation wiring are required to handle these voltages, resulting in a higher overall cost.

1.3. Advantages in Using UV-LIGA to Fabricate Power Micro-Relays

To achieve higher power capacity, a micro-relay based on MEMS technology should have the following characteristics: (1) materials of high electric conductivity, for example, metals or alloys such as copper should be used as electrodes; (2) a relatively thick wire pattern to carry larger current is required, unlike the thin films as in silicon-based surface fabrication technology; (3) high aspect-ratio structures used in the design of the actuator to boost the driving force and to maximize moving range, permitting smaller
driving signals; (4) and finally, a simple design which will allow MEMS relays to be commercially competitive with solid state devices.

Flexibility in materials selection and the capability to make high aspect ratio microstructures with the LIGA process make it the best technology for microfabricating high power micro-relays and relay arrays. Compared with the more conventional MEMS processes based on silicon technology, the LIGA process has some unique advantages: (1) it allows the fabrication of high aspect ratio microstructures with structural heights from tens to one thousand micrometers; and (2) different materials such as plastics, metals, alloys, ceramics, or a combination of these materials can be used with the LIGA process. This second advantage makes it very suitable for microfabrication of the power micro-relay. For example; nickel-iron can be used for making a magnetic micro-spring. Thick metal structures can be used as electrodes to carry larger currents. Materials with excellent electrical conductivity such copper or gold can be electroplated as electrodes for better contacting conditions and reduced spark corrosion.

1.4. Designs for the Electromagnetic Power Micro-Relay

Figure 1-1 (a) shows a schematic diagram of the electromagnetic micro-relay, and Figures 1-1 (b) and (c) show the operation principle of the relay. The relay is comprised of the following components: a microfabricated spring, two electrodes - one for input and another for output, an electromagnetic actuator, and the magnetic core for the coil and magnetic flux circuit. The magnetic core (the circular post in the center) and magnetic flux circuit will be used as one of the electrodes, and the spring, which is electrically isolated from the remaining part of the relay, will be used as the other electrode. An electromagnetic coil is inserted on the central post shown in the diagram. This arrangement helps to reduce the number of components and simplifies the overall design.
The design presented in this dissertation is truly three-dimensional, unlike previous prototypes reported.

A typical operation sequence for the device is shown schematically in Figures 1:

(1) If there is no control current supplied to the coil, the spring remains in the neutral position and the relay is off (electrodes do not make contact), as shown in Fig. 1(a).

(2) If a current is supplied to the coil, the electromagnetic force generated by the electromagnet pulls the spring downward until contact is made between the two electrodes (the spring and the magnetic core), as shown in Fig. 1(b).

(3) If the control current is turned off, the elastic force restores the flat spring to the horizontal position, contact is broken and the relay is off, as shown in Fig. 1(c).

Figure 1-1 Schematic diagrams for the design and operation of the micro-relay
Most previous micro-relay designs have attempted to microfabricate coils, and thus significantly increased the complexity of the fabrication process. The LIGA technology and silicon-based MEMS technology alike should only be used for the work for which they are best suited for. A hybrid approach may be taken for fabrication of the electromagnetic components of the micro-relay. Using the UV-LIGA process for fabrication of a magnetic core and magnetic flux circuit has overwhelming advantages over silicon-based MEMS technology because of the unique advantages of LIGA in making microstructures with high aspect ratios and the flexibility in materials selection. However, making micro-coils with either silicon-based MEMS technology or the LIGA process is not a job that can be easily and efficiently done. Insulated copper wires with diameters as small as 25 µm are commercially available and coils can be custom-ordered. A micro-sized electromagnetic actuator with the magnetic core, flux circuit, and springs made with the UV-LIGA process, assembled with a mechanically-wrapped coil, would have much lower overall cost than a monolithic microfabricated system.

A mechanically wrapped micro-coil was used in the electromagnetic actuator. A nickel magnetic core and magnetic flux circuit was fabricated using the UV-LIGA process. The micro-coil was then inserted vertically onto the magnetic core. The spring was made with nickel-iron using the LIGA process. If the spring is made of a magnetic material, then a closed circuit for magnetic flux can be made and a permanent magnet for self-latching may not be necessary. The magnetic circuit is designed in such a way that the magnetic flux is well confined.

The flat spring in the design is mounted on separate supporting structures to have it electrically isolated from the magnetic core and flux circuit. This arrangement is necessary because both the magnetic core and the spring are used as electrodes, and the
signal wires will be connected to them for design simplicity. Another design option is to use the flux circuit as the supporting structure and directly bond the spring to it. In that case, an insulating layer between them will be required. To lower the contact resistance between the electrodes, a thin film of gold may also be deposited on the electrode surfaces.

This dissertation documents the design, fabrication, and tests performed on a prototype relay fabricated using the method briefly described above. Chapter 2 presents detailed design specifications required to generate the device. The following few chapters will present various aspects of the UV LIGA technique used in this project. Two notable improvements in resist processing required to implement this design will be demonstrated. A brief discussion on the electrodeposition of nickel-iron for use as a magnetic plunger will be followed by a model for predicting the fatigue life of such materials. Chapter 6 illustrates a detailed layout of the process scheme used to complete the device. A short presentation of the performance characteristics of prototype relays is included in Chapter 7. The dissertation will conclude with a short account of future research made possible by this study.
CHAPTER 2: DEVICE DESIGN

2.1. Introduction

Designing the relay required the creation of a working model for both the elastic properties of the spring and the attractive force generated by the electromagnet during operation. Comparison of the energies associated with both the spring displacement and the magnetic attraction provided the design limits for each component with respect to the other. The solution of two coupled non-linear ordinary differential equations governing the system compared well with the static model and accurately simulated the dynamic response characteristics of the device. Dynamic tests were later performed on a working relay to demonstrate the effectiveness of the dynamic model. Test results are presented in Chapter 7. This chapter documents the numerical model used to simulate device operation.

2.2. Computation of the Electromagnetic Force

The mechanical attractive force generated by passing current through a solenoid can be determined using Ampere and Faraday’s laws of magnetism. Ampere’s law stipulates that the integration of magnetic field intensity, $H$, around a closed contour of length $l$ is equal to the net current crossing the surface of the closed contour:

$$\int_{C} H \cdot d\ell = Ni,$$

Eqn. 2-1

where $i$ is the applied current and $N$ is the number of times the current encircles the contour. The integral of the field intensity in the contour is equal to the total magnetic flux, $\phi$, divided by the cross sectional area, $A$, and the magnetic permeability, $\mu$, of the material:
\[ H = \frac{\phi}{\mu A} \, , \quad \text{Eqn. 2-2} \]

Using the definition of magnetic flux, Ampere’s law can be restated as:

\[ \int \frac{\phi}{\mu A} \, dl = Ni \, , \quad \text{Eqn. 2-3} \]

where the flux can be separated from the integral by defining a term for the magnetic resistance called the reluctance, \( \mathcal{R} \). Ampere’s law can then be rewritten in terms of the magnetic flux and resistance through a material as:

\[ \mathcal{R} \phi = Ni \, . \quad \text{Eqn. 2-4} \]

The reluctance of the magnetic core post, the magnetic plunger, and air gap must all be considered to develop a complete working model of the electromagnetic relay. The total reluctance of the magnetic circuit is sum of these resistance terms in series

\[ \mathcal{R} = \frac{h_p}{\mu_p A_p} + \frac{h_s}{\mu_s A_s} + \frac{x_{\text{gap}} - x}{\mu_0 A} \, . \quad \text{Eqn. 2-5} \]

In the equation above, \( h \) represents the height of the material, \( p \) represents the core post of the relay, and \( s \) represents the moving member. The reluctance of the air gap with permeability, \( \mu_0 \), is defined by the displacement of the spring, \( x \), from its initial gap distance, \( x_{\text{gap}} \). Ampere’s law was developed for time invariant fields. Thus when considering only Ampere’s law, \( x = 0 \) and the reluctance remains constant. However, operation of the relay requires motion of the plunger over time. This causes a change in the reluctance that in turn changes the ratio of the total applied current over the magnetic flux within the circuit.

The physicist, Michael Faraday, was the first to solve this problem. Faraday stipulated that change in a magnetic field over time induces an electric field. The electrostatic potential induced by a moving magnet is equal to the derivative of the flux
linkage over time. The flux linkage is defined as the number of turns in the coil multiplied by the magnetic flux passing through the cross-sectional area of the coil. The voltage may then be derived as:

\[ V = \frac{d(N\phi)}{dt} = \frac{\partial(N\phi)}{di} \frac{di}{dt} + \frac{\partial(N\phi)}{dx} \frac{dx}{dt}. \]

Eqn. 2-6

Equation 2.6 can be rewritten using the inductance, L, of the circuit times the current, and the speedance, K\textsubscript{s}, of the circuit times the velocity of the plunger:

\[ V = L(x, i) \frac{di}{dt} + K_s(x, i) \frac{dx}{dt}. \]

Eqn. 2-7

The speedance is the coefficient of motional EMF across the coil\textsuperscript{17} and can be derived as:

\[ K_s(x, i) = N \frac{d\phi(x, i)}{dx} = N \frac{d}{dx} \left( \frac{Ni}{\mathcal{R}_p + \mathcal{R}_s + \mathcal{R}_g} \right). \]

Eqn. 2-8

The magnetic flux is based on two time-dependant variables: the current applied and the physical displacement of a magnetic material as it affects the potential in the coil. Assuming no electrical power loss in the coil, the change in work done as the total flux changes is:

\[ W = \int id(N\phi) = \int \mathcal{R}\phi \cdot d\phi = \frac{1}{2} iN\phi. \]

Eqn. 2-9

The force acting on the second magnetic element is:

\[ F = -\frac{dW}{dx} = -\frac{Ni}{2} \frac{d\phi}{dx}. \]

Eqn. 2-10

Substituting for the reluctance in the solution of the magnetic flux, the force provided by the electromagnet on the magnetic plunger can be written as:

\[ F_{mag} = \frac{(Ni)^2}{2\mu_s A} \cdot \frac{1}{\left[ \frac{h_p}{\mu_t A_p} + \frac{h_s}{\mu_s A_s} + \frac{x_{gap} - x}{\mu_0 A} \right]^2}. \]

Eqn. 2-11
The relay was designed using the parameters shown in Table 2-1. These constants provided the required information needed to solve for the electromagnetic force acting on the plunger at different gap distances as shown in Figure 2-1 when current was supplied to the coil. The plunger reluctance term for a 20 µm thick spring with comparable permeability and cross sectional area to that of the core post contributes less than 1% of the overall minimum magnetic attraction force and can be neglected in the numerical model.

**Table 2-1**  Physical constants associated with electromagnet design

<table>
<thead>
<tr>
<th>Applied Current (i)</th>
<th>70 mA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Turns (N)</td>
<td>50</td>
</tr>
<tr>
<td>Permeability of Free Space ($\mu_o$)</td>
<td>$4\pi * 10^{-7}$ N/A²</td>
</tr>
<tr>
<td>Permeability of Nickel ($\mu$)</td>
<td>$800 * \mu_o$</td>
</tr>
<tr>
<td>Radius of the Coil (r)</td>
<td>500 µm</td>
</tr>
<tr>
<td>Height of the Core Post (h)</td>
<td>1000 µm</td>
</tr>
<tr>
<td>Initial Gap Spacing</td>
<td>35 µm</td>
</tr>
</tbody>
</table>

![Figure 2-1](image.png)  Electromagnetic force vs. gap distance of the magnetic plunger
2.3. Computation of the Plunger Force

Several spring designs were considered to ensure the gap between the plunger and the core post could be closed when the electromagnetic force was applied. Early designs called for an over-constrained spring to provide uniform vertical displacement. However, the over-constrained spring designs produced large spring constants and required an initial gap size of less than 15 µm for device operation. Compressive stress observed in electroplated springs often produced a minimum gap of 35 µm. Therefore single and unconstrained dual spring plungers were developed.

For the following discussion, the term spring force refers to the force required to deflect a single spring. The plunger force is the force required to deflect the plunger. If a single spring is used for a particular plunger design, then the numerical value of the two forces is equivalent. However, plungers designed with two or more springs must be considered when discussing relay design.

The total deflection of the spring was then determined by summing the deflection of each member due to the applied load, P, torque T, and moment, M:

\[ \Delta X_{pi} = \frac{PL_i^3}{3EI}, \]  
\[ \Delta X_{Ti} = \frac{TL_i r}{JG}, \]  
\[ \Delta X_{Mi} = \frac{ML_i^2}{2EI}, \]

where \( E \) is the elastic modulus of nickel, \( G \) is the shear modulus, \( L_i \) is the length of the \( i^{th} \) beam, \( r \) is the torque length, and \( J \) and \( I \) are the rotational and bending moments of inertia of the beam along the z axis.\(^{18} \) The superposition the displacement due to tension,
vertical loading, \( P \), and torques, and moments were required to accurately predict the
deflection of the plunger. However, the deflection due to the applied tension accounted
for only a small change in the total displacement of the plunger. Beam deflections due to
shear was negligible. Figure 2-2 illustrates the loading conditions present in a flat S-
spring loaded downward out of the plane. The load on the end of each beam is described
by the cross patterns. Moments and torques are described with arrows on each beam.
Various other spring shapes were used, including flat and curved in-plane S-springs,
coiled beams and spiraled springs. All springs with rectangular shaped members can be
described using the method presented. The deflection of spiral shaped springs is most
often performed using Winkler’s theorem.\(^{18}\) A complete description of the deflection of
curved shapes is beyond the scope of this discussion, however curved springs were
observed to be among the most flexible produced.

**Figure 2-2**  Deflections on each beam of a S-spring displaced out of the plane

Table 2-2 lists the specific dimensions used for flat S-spring design. Using the
design constants provided, the total deflection of 15 member S-spring was simulated
using the following set of equations presented in Table 3-3. Dividing the force by the
displacement provides the spring constant, $k$, for an individual spring. The total deflection of the plunger was determined using the spring constants for each spring in the plunger design and the known electromagnetic driving force.

Figure 2-3 shows the deflection of the plunger versus the force applied for three plunger configurations. Two are single S-springs. The third is a two S-spring plunger design. The first spring constant determined, $k_1 = 15 \text{ N/m}$, was for a 15 $\mu$m thick spring deflected vertically out of the plane. The second, a 41 $\mu$m thick S-spring with a 78 N/m spring constant. The two spring S-spring system using 41 $\mu$m thick S-springs represents a very stiff plunger design with a spring constant of $k_3 = 156 \text{ N/m}$. A Young’s modulus of 210 GPa was used to evaluate the Ni-Fe springs presented. Results were compared to the finite element model presented in the next section.

![Figure 2-3](image_url)  

**Figure 2-3**  
Applied force on plunger versus plunger displacement
Table 2-2  S-Spring design constants

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Length (a)</td>
<td>150 µm</td>
</tr>
<tr>
<td>Beam Length (b)</td>
<td>175 µm</td>
</tr>
<tr>
<td>Beam Length (c)</td>
<td>450 µm</td>
</tr>
<tr>
<td>Beam Width (w)</td>
<td>50 µm</td>
</tr>
<tr>
<td>Beam Thickness (height=h)</td>
<td>10 – 40 µm</td>
</tr>
<tr>
<td>Young’s Modulus of Ni-Fe (E)</td>
<td>210 GPa</td>
</tr>
<tr>
<td>Poison ratio (v)</td>
<td>0.03</td>
</tr>
<tr>
<td>Shear Modulus (G)</td>
<td>$\frac{E}{2(1+v)}$</td>
</tr>
<tr>
<td>Moments of Inertia (Iz, J)</td>
<td>$\frac{wh^3}{12}$, $0.23wh^3$</td>
</tr>
</tbody>
</table>

Table 2-3  Governing equations for the deflection each beam in an S-spring

<table>
<thead>
<tr>
<th>Beam Deflection</th>
<th>Applied Load</th>
<th>Torsion</th>
<th>Moment</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta X_1$</td>
<td>$Pa^3 / 3EI_z$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Delta X_2$</td>
<td>$Pc^3 / 3EI_z$</td>
<td>$Pa^2 c / JG$</td>
<td></td>
</tr>
<tr>
<td>$\Delta X_3$</td>
<td>$Pa^3 / 3EI_z$</td>
<td>$Pc^2 a / JG$</td>
<td>$-Pa^3 / 2EI_z$</td>
</tr>
<tr>
<td>$\Delta X_4$</td>
<td>$Pb^3 / 3EI_z$</td>
<td>$P(2a)^2 c / JG$</td>
<td>$-Pcb^2 / 2EI_z$</td>
</tr>
<tr>
<td>$\Delta X_5$</td>
<td>$Pa^3 / 3EI_z$</td>
<td>$P(b-c)^2 a / JG$</td>
<td>$-Pa^3 / EI_z$</td>
</tr>
<tr>
<td>$\Delta X_6$</td>
<td>$Pb^3 / 3EI_z$</td>
<td>$P(3a)^2 c / JG$</td>
<td>$-P(b-c)b^2 / 2EI_z$</td>
</tr>
<tr>
<td>$\Delta X_7$</td>
<td>$Pa^3 / 3EI_z$</td>
<td>$Pc^2 a / JG$</td>
<td>$-3Pa^3 / 2EI_z$</td>
</tr>
<tr>
<td>$\Delta X_8$</td>
<td>$Pb^3 / 3EI_z$</td>
<td>$P(4a)^2 c / JG$</td>
<td>$-Pcb^2 / 2EI_z$</td>
</tr>
<tr>
<td>$\Delta X_9$</td>
<td>$Pa^3 / 3EI_z$</td>
<td>$P(b-c)^2 a / JG$</td>
<td>$-4Pa^3 / 2EI_z$</td>
</tr>
<tr>
<td>$\Delta X_{10}$</td>
<td>$Pb^3 / 3EI_z$</td>
<td>$P(5a)^2 c / JG$</td>
<td>$-P(b-c)b^2 / 2EI_z$</td>
</tr>
<tr>
<td>$\Delta X_{11}$</td>
<td>$Pa^3 / 3EI_z$</td>
<td>$Pc^2 a / JG$</td>
<td>$-5Pa^3 / 2EI_z$</td>
</tr>
<tr>
<td>$\Delta X_{12}$</td>
<td>$Pb^3 / 3EI_z$</td>
<td>$P(6a)^2 c / JG$</td>
<td>$-Pcb^2 / 2EI_z$</td>
</tr>
<tr>
<td>$\Delta X_{13}$</td>
<td>$Pa^3 / 3EI_z$</td>
<td>$P(b-c)^2 a / JG$</td>
<td>$-6Pa^3 / 2EI_z$</td>
</tr>
<tr>
<td>$\Delta X_{14}$</td>
<td>$Pc^3 / 3EI_z$</td>
<td>$P(7a)^2 c / JG$</td>
<td>$-P(b-c)c^2 / 2EI_z$</td>
</tr>
<tr>
<td>$\Delta X_{15}$</td>
<td>$Pa^3 / 3EI_z$</td>
<td>$Pb^2 a / JG$</td>
<td>$-7Pa^3 / 2EI_z$</td>
</tr>
</tbody>
</table>
2.4. Finite Element Analysis of the Spring Model

The ANSYS Multiphysics analysis package was used to validate the governing equations for spring deflection presented in Section 2.3. A force of 100 µN was applied to the free end of a 15 µm thick Ni-Fe spring with a Young’s modulus of 210 GPa shown in Figure 2-4. Displacement of the cross section of the fixed beam was held to zero. A solid tetrahedral ten node (no. 187) mesh type was used in the calculation. Convergence was demonstrated by increasing the number of elements used in the calculation by four and eight times. The following calculation was performed to insure convergence:

\[
\left| X^C - X^M \right| > \left| X^M - X^F \right|
\]

where X is the maximum displacement, C represents the coarse, M the medium, and F the fine mesh size. The predicted finite element calculation error, e, was determined as:

\[
e = \left| \frac{X^F - X^M}{X^F} \right|
\]

Table 2-4 list the results of the FEA simulation. The significance of this spring thickness is that the spring constant is small enough to accommodate the possibility of a much larger Young’s modulus often observed in electroplated Ni-Fe structures. Evidence of this modulus and the reasons for its existence will be discussed in Chapter 5.

<table>
<thead>
<tr>
<th>Table 2-4</th>
<th>S-Spring design constants</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coarse mesh size</td>
<td>40 µm</td>
</tr>
<tr>
<td>Medium mesh size</td>
<td>20 µm</td>
</tr>
<tr>
<td>Fine mesh size</td>
<td>10 µm</td>
</tr>
<tr>
<td>X^C</td>
<td>22.533 µm</td>
</tr>
<tr>
<td>X^M</td>
<td>23.731 µm</td>
</tr>
<tr>
<td>X^F</td>
<td>24.532 µm</td>
</tr>
<tr>
<td>e</td>
<td>0.033 µm</td>
</tr>
</tbody>
</table>
2.5. Comparison of the Electromagnetic and Mechanical Spring Forces

Figure 2-5 (a) plots the applied electromagnetic and elastic forces for a plausible relay over gap displacement. The spring contact force increases at a constant slope from the initial gap displacement of zero until the plunger comes into contact with the relay base after a displacement of 35 μm. For large gaps the spring force and the magnetic attractive force in Figure 2-5 (a) appear to overlap, while the magnetic attraction increases dramatically as the gap size decreases. The contact force is defined as excess force acted on the plunger by the magnetic attraction upon closing the gap. The contact force is often much larger than the force required to move the plunger the required distance. This excess force provides good electrical contact and a low electrical resistance across the switch.

The static force calculation in the overlapping region is plotted and integrated in Figure 2-5 (b) to evaluate the energy difference between the magnetic driving force and
the restoring force of the spring. In order for the relay to close, the area representing the energy difference in region 1 must be greater than the area represented in region 2. If the area in region 2 exceeds that of region 1, then the velocity of the relay becomes negative and the relay does not close. Furthermore, as region 2 grows larger, the displacement of the plunger becomes smaller and smaller leading to higher frequency harmonic oscillations. This particular mode of operation would typically be used for electromagnetic sensing or for use as an accelerometer.

Neglecting all other forces, relay actuation will occur for a device in which the area of region 1 is greater than or equal to that of region 2. As region 2 becomes smaller and smaller, the deceleration of the plunger over that particular special range decreases. For a spring constant of 136 N/m, a tangent exists between the spring force and magnetic attraction force functions; there is no deceleration, and the velocity term remains constant for a short instant before increasing again until the plunger comes into contact with the core post. For spring constants less than 136 N/m, there is no overlap. The acceleration increases continuously until the plunger comes into contact with the core post.

2.6. Viscous Air Damping

Mechanical damping of the spring-mass during operation can be derived from a linearized form of the compressible Reynolds gas-film equation:  

$$b = \frac{3 \cdot \nu \cdot A^2}{2 \cdot \pi \cdot (x_{gap} - x)^3},$$  

Eqn. 2-17

where \( A = 9.6 \times 10^{-8} \text{ m}^2 \) is the area of the plunger, and \( \nu = 1.583 \times 10^{-5} \text{ kg/(m*s)} \) is the air viscosity which can be computed using known relations of vacuum science. Use of this dampening coefficient in the relay model provides a method to simulate the effects of the increased air pressure generated as two surfaces come into contact. In order to minimize
Figure 2-5  Applied force versus plunger displacement:
   a) over a 35 µm gap distance
   b) over the initial displacement of 20 µm
the effects of air dampening, large contact surfaces are typically patterned with holes that allow the air to be pushed out through the top of the moving member as it comes into contact with another flat surface. Bergqvist\textsuperscript{22} was the first to model the damping coefficient for porous plates in which circular holes etched into them improve the performance of a micromechanical actuator. In Bergqvist’s model,

$$b = \left( \frac{12 \cdot \nu \cdot A^2}{n \cdot \pi \cdot (x_{gap} - x)^2} \right) \left( p - \frac{p^2}{8} - \frac{\ln(p)}{4} - \frac{3}{8} \right)$$

Eqn. 2-18

where \( n \) is the total number of holes etched into the moving plate, and \( p \) is the hole fraction of open area in the plate defined by the number and size of the holes divided by the area of the plate without any etched holes. Figure 2-6 plots the damping coefficient as a function of hole-fraction of open area for a plunger with 50 holes. For this experiment, a hole-fraction of 1.8 was chosen because it allows for moderate increases in the damping coefficient as the gap decreases below 0.7 \( \mu \text{m} \) without producing a large enough damping force to significantly alter the switching speed of the device.

![Figure 2-6](image-url)  
Viscous Air damping coefficient versus volume fraction of open area

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2.7. Dynamic Equations

Using the relations previously described, the following coupled set of first order nonlinear differential equations can be developed to completely model the device:

\[
\begin{align*}
\frac{dx}{dt} &= v \\
\frac{dv}{dt} &= F_g - K \cdot x - b(x,i) \cdot v + K_s(x,i) \cdot i + \frac{d}{dt}(x(i)x) \\
L(x,i) \frac{di}{dt} &= V_a - K_s(x,i) \cdot v - R \cdot i
\end{align*}
\]

where

\[v\] = velocity of the moving coil
\[x\] = coil displacement (with initial value of \(x_{\text{gap}}\))
\[i\] = coil current
\[m\] = mass of the plunger
\[F_g\] = gravitational force on the plunger
\[K\] = mechanical spring constant
\[b\] = viscous damping coefficient
\[K_s\] = speedance
\[L\] = inductance of the coil
\[V_a\] = voltage applied to the electronic circuit
\[R\] = electrical resistance of the coil

The equations above were solved using the MATLAB ODE 45 solver. ODE 45 is an explicit one-step 4\(^{th}\) order Runge Kutta solver typically used to solve problems with moderate accuracy. The solution typically produced 30,000 points per variable and failed to solve only when the change in values became negligible.

One dynamic solution for the relay model is shown in Figure 2-7. In this case the initial gap was set at 35 \(\mu\)m. The spring constant was varied between 25 and 200 N/m.
The height of the core post was set at 1000 µm with a radius of 200 µm and a 50-turn coil. An applied voltage of 10 V and a 143 Ohm resistance were used to model the electronic circuit. The steady state response time for the inductor was calculated to be on the order of 10 µs, which is significantly faster than the response time of the relay. The dynamic response curve for the displacement of the plunger predicted a range of switching times between 5 and 10 KHz using plungers with spring constants ranging from 162 N/m to 25 N/m. The dynamic simulation results match well with the static model predicting a constant velocity for the 136 N/m spring. Similarly, spring constants between 136 and 162 N/m also closed with decreasing acceleration between the displacement distance of 12 and 18 µm. Spring constants greater than 162 N/m required too much energy. Plungers using these springs are predicted to become oscillators. Deflection of the spring with a 163 N/m spring constant was predicted to travel no more than 17 µm. All results were consistent with the predictions of the static force model. It should be noted that energy difference associated with the force of gravity was $1.1 \times 10^{-11}$ J. The dynamic model predicted failure at a total energy difference of actuating forces of less than $3 \times 10^{-11}$ J.

Figure 2-8 shows a velocity simulated during operation of the relay. Current induced in the coil by the motion of the magnetic plunger is plotted in Figure 2-9. The simulated driving current was reduced by 24 mA as the plunger came into contact with the relay. After contact, the current rose sharply again to 50 mA. Furthermore, prediction of the velocity profile agreed well with the response characteristics described in Section 1.5. The velocity of plunger using a spring constant less than 136 N/m continuously increased as the plunger moved toward the relay base. For a mechanical member with a spring constant of 136 N/m, the velocity remained
constant for a short period in the displacement range predicted by the tangent between both magnetic attractive and mechanical spring forces. Systems with spring constants greater than 136 N/m decelerate in region 2 of Figure 2-5b. If the velocity of the plunger simulated in Figure 2-8 becomes negative, then the energy associated with the magnetic driving force is insufficient to overcome the energy of the spring’s restoring force and the relay will not close.

Air damping also appeared to play a finite role in the operational performance of the relay. The sharp decrease in velocity just prior to closing the circuit followed by a slow contact of the plunger and the magnetic core shown in Figure 2-8 are direct consequences of air damping in the model. According to the simulation, a large viscous damping force is generated as the plunger closes to within 1µm of the core post at high speeds. The damping force is overcome when the relay slows enough to push the remaining air out of the gap.
Figure 2-8  Driving current versus time

Figure 2-9  Plunger velocity versus time
2.8. Magnetic Circuit Design for Prevention of Magnetic Flux Leakage

The model developed in this chapter assumes a uniform magnetic field throughout the magnetic circuit. However, a magnetic field emerging from a solenoid is known to diverge as the distance from the solenoid increases to a comparable diameter of the coil. While divergence effects should not affect the first order performance characteristics of a relay plunger actuating within 50 µm of the core post, they may have parasitic effects on other nearby LRC circuits. Therefore, a magnetic cup was implemented in the relay design to obtain a closed magnetic circuit. The magnetic circuit consists of four nickel arcs evenly distributed around the coil that act to confine the magnetic field above the base of the relay. The geometries required for the device (including the magnetic springs) make the exact solution of the electromagnetic ordinary differential equations (ODE’s) quite difficult. Implementation of this precautionary procedure confinement scheme should not change the design requirements for the device in any way. It was therefore used in the design scheme to help insure performance. Figure 2-10 shows the effects of a magnetic cup (or shield) on a magnetic circuit. 

![Figure 2-10](image)

**Figure 2-10** Effects of a magnetic cup on the relay circuit
CHAPTER 3: FABRICATION TECHNIQUES

3.1. Introduction to Photolithography

Photolithography is the process by which light is used to alter a photosensitive plastic to produce distinct patterns. The photosensitivity of the polymer is the measure of the chemical change that occurs when particular frequencies of light are absorbed. Polymers with high photosensitivity can be patterned by selective exposure to light followed by immersion in a chemical that develops away only the low molecular weight material present. Immersion of the polymer in the dissolving medium is traditionally termed ‘development’. After the development process, only the regions where the polymer has a significantly high molecular weight remains, yielding a sharp pattern in the plastic.

Two types of photosensitive polymers exist. Positive photosensitive polymers undergo scission in which molecular weight of the polymer chains is dramatically reduced when light is absorbed. Negative photosensitive polymers cross-link and increase their molecular weight during exposure.

A few other requirements must be met before the photosensitive polymer can be used for a photolithography process. Traditionally, photolithography has been used to produce a masking pattern on a substrate in order either to transfer the exposed pattern into the substrate via etching or to add a hard material onto the substrate using various deposition techniques. Both processes often require the exposed polymer to be resistant to temperature variations, acids, bases, and vacuum. Polymers that show such resistances and can be patterned by exposure to light are called resists.
Resists are often produced in liquid form and are typically cast onto the substrate by spin coating. This technique uses centrifugal force to spread the liquid evenly across a smooth substrate while allowing for rapid evaporation of the solvent. Once the resist is spun on, the substrate is baked to remove the remainder of the solvent. The product is a uniform solid resist coating on the substrate. Direct casting can also be used for highly viscous resist, or for coating complex geometries. For solid resists, such as PMMA used in deep X-ray lithography, direct bonding of the plastic to the substrate is often performed.

3.2. Introduction to LIGA

The LIGA process was developed to produce high-aspect-ratio metallic devices with critical dimensions of a few microns. The traditional process requires the exposure of resist to X-ray radiation using a highly collimated X-ray source called a synchrotron. The technique requires exposure and development of the resist on a conductive substrate. Metal is then electroplated into the pattern. Following this, the remainder of the resist is chemically stripped to reveal a metallic micro-part. The metal pattern is used as a master for the injection molding or hot embossing of many plastic parts. The plastic molds can be used as final products or as electroplating molds for further metallic devices as needed.23

The use of X-rays to produce lithographic patterns has tremendous advantages over many MEMS technologies. The LIGA technique allows for the production of bulk metallic microdevices. It has also yielded the highest height to width aspect ratios to date. Structures up to 3 mm tall with aspect ratios of 100:1 can be produced in either plastic or metallic form with very smooth sidewalls using this technology. Multi-layer
and angled patterns have been demonstrated allowing for a direct exposure and electroplating of 3-D microdevices.

Unfortunately the cost involved in producing micro-parts directly using synchrotron radiation is considerable. In the United States, there are currently 5 synchrotrons with operational beamlines used for deep X-ray lithography of thick resist. All of these sources are funded by the state or federal government and are used for the development of science and technology in the United States. Although there are commercial companies such as International MEZZO Technologies and AXSUN that are making a limited number of LIGA-based devices for sale on the open market, most of the larger companies have yet to invest heavily in a technology requiring synchrotron radiation. The large initial investment and relative immaturity of molding processes capable of mass producing plastic parts from a single electroplated master with micron resolution and aspect ratios up to 100:1 has prevented the LIGA process from becoming a mainstream industrial technology in the MEMS market.

3.3. UV-LIGA

Recent advances in resist chemistry have allowed for the development of a UV-LIGA process. The UV-LIGA technique uses either a positive or negative photoresist sensitive to ultraviolet light. Although UV lithography cannot be used to obtain the same quality structures produced using X-rays, it can provide a viable alternative for many MEMS applications. The diffraction of UV light causes significant pattern distortion as the thickness of the resist is increased. Certain benefits, including resist thickness, aspect ratio and sidewall quality, are sacrificed, but the process is inexpensive and therefore can be used to mass-produce both polymer and metal microstructures industrially without the need for injection molding. Although injection molding of UV-LIGA fabricated
microstructures is a viable option, the UV-LIGA technique does not require injection molding. The lithography process is relatively inexpensive and can be used directly to mass-produce devices. Direct molding of SU-8 structures for ceramic or other polymeric devices has proven a useful tool for MEMS technology. Figure 3-1 shows the basic steps involved in UV-LIGA processing.

![UV-LIGA process using SU-8 negative resist](image)

**Figure 3-1** UV-LIGA process using SU-8 negative resist

### 3.4. **SU-8 Resist for UV-LIGA**

In the past few years, SU-8 has received a lot attention in MEMS field and is quickly becoming the preferred resist for high aspect-ratio micromachining. Although the process required to produce SU-8 structures remains challenging, it is the only resist that can be exposed 20 to 1500 µm deep with aspect-ratios greater than 10:1 using either

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*Some material in sections 3.4 and 3.5 will be printed in *Journal of Microlithography, Microfabrication, & Microsystems* under the title “Study on the Stress Reduction During the Postbaking Process and the Effects on Lithography of Ultra-Thick High Aspect Ratio SU-8 Microstructures.”*
optical\textsuperscript{24} or deep X-ray\textsuperscript{25,26} lithography. Until recently, SU-8’s major competitor for optical lithography was AZ 4562. The AZ resist can be coated using multiple spins to produce structures more than 100 \( \mu \text{m} \) thick.\textsuperscript{27} Within the past year, structures as thick as 1.4 mm has been lithographed with JSR THB-430N, but the aspect ratios are at about 5:1 with relatively poor sidewall quality.\textsuperscript{28} In comparison, microstructures with higher aspect ratios can be easily achieved using UV lithography of SU-8. Recent publications show the ability to expose 1 mm tall isolated SU-8 structures with aspect ratios exceeding 10:1\textsuperscript{5,29} and 1.5 mm structures with 15:1 aspect ratios.\textsuperscript{30}

The aspect-ratio and sidewall quality of microstructures obtained using UV lithography of SU-8 have been limited by many factors as reported by many researchers. The reported results are often difficult to duplicate because the properties of the resist have made consistent processing a challenge for research labs. The published research results suggest that there are two major factors that limited the aspect ratio and sidewall quality in UV lithography of SU-8: 1) use of a light source with suitable wavelengths; and 2) significant diffraction problems due to low uniformity caused by the difficulty in spin-coating uniform and thick resist on a substrate.

Exposing the resist with the proper light spectrum is one of the key requirements to achieve the best lithography results of SU-8.\textsuperscript{31,32} The UV absorption of SU-8 resist is dominated by that of the photo initiator content added in the SU-8. The SU-8 resist has a very high absorption rate for wavelengths less than 350 nm. Shorter wavelengths tend to be absorbed at the surface of the resist while the longer wavelengths have a much lower absorption rate, and tend to be able to penetrate deeper and can be used for exposure of thick resist. If the light source used for the exposure has a wide spectrum, high frequency
light will be absorbed at the surface layer of the resist and only the lower frequency (longer wavelength) light source will be able to penetrate deep into the resist. Over-exposure at the surface layer by high frequency UV light produces a skin effect on the resist, a layer of highly cross-linked polymer with a thickness ranging from two to a few tens of microns. This effect greatly distorts the pattern near the surface and yields low quality microstructures. Optical filters are therefore often used to eliminate unwanted wavelengths and to overcome the skin effect in SU-8 structures.\textsuperscript{31,32} Dentinger\textsuperscript{31} has recently shown that complex patterned structures with high aspect-ratios up to 700 \textmu m thick can be achieved by using a combined approach of an optical filter for wavelength selection and modification of the chemical properties of SU-8.

The second critical factor for lithography of thick SU-8 resist is, as in any other optical lithography processes, the diffraction effect. This problem is made much worse in comparison to optical lithography of integrated circuits because the increased resist thickness results in higher non-uniformity of the resist. Direct casts of the resist\textsuperscript{30,33} are currently required to obtain layers greater than 1 mm on a substrate. The second challenge is to overcome the residual stress in baked SU-8 films. Often, thick layers of SU-8 retain so much residual stress under the suggested bake parameters\textsuperscript{34} that large exposed resist fields either de-bond from the substrate, bow or even lead to cracks in silicon substrates after exposure.\textsuperscript{35,36} Most thick SU-8 films have 5-10\% error in the resist thickness across a 4” substrate due to extended contact with a non-level surface prior to exposure. The error in resist thickness causes gaps between the masks and the substrate during exposure which are arguably present in almost all thick SU-8 lithography results presented to date. In a recent paper, Chuang, Tseng, and Lin\textsuperscript{37} filled these gaps with glycerin during the exposure. Glycerin has nearly the same refractive index as SU-
Their results showed a significant drop in diffraction during the exposure. Structures produced using glycerin showed significant improvement in the pattern quality of 100 µm SU-8 exposures.

Very little of the literature has focused on the post-baking conditions and the effects on the lithography of very thick resist. Typical SU-8 procedures call for the resist to be cooled rapidly from 96 °C to 65 °C, held for a few minutes and then removed from the heat source and cooled to room temperature. This procedure does not fully remove the internal stress built up in thick resist films. To reduce the stress observed in thin SU-8 films under 100 µm in height, Chang and Kim suggested a decrease in temperature at constant rate from 96 °C to room temperature. However, no study focused on the residual stress effects of the temperature reduction during post-baking and optimization of the temperature reduction process has been reported in open literature.

This chapter reports a study on the stress reduction during the postbaking process and the effects on lithography of ultra-thick high aspect ratio SU-8 microstructures. It is well known that internal stress is always induced in the SU-8 layer during the resist baking processes, and that the stress affects the overall pattern quality of the structures. However, the significance of this effect has not been well appreciated and carefully studied. The experiments described in this dissertation were designed to study this important issue. A complete discussion of resist coating, baking, and exposure parameters will be presented. The related residual stress reductions and effects on lithography quality during the bake cycle will be examined in detail. This research work shows how to obtain high aspect ratio structures through optimization of the bake process and exposure dose. The process described uses standard Micro-Chem SU-8 100 with no
additional additives and attempts to follow the protocol of traditional optical lithographic processing with as little human involvement in application of the resist as possible. In addition, a multi-layer spin-coating process was also developed to coat uniform SU-8 resist for a thickness up to 1.5 mm. Our research proved that aspect-ratios up to 40:1 in isolated open field structures of thickness between 1 and 1.5 mm can be obtained without any modifications of the resist chemistry or changes in the light spectrum applied from a standard broad-band UV source.

3.5. Standardized SU-8 Resist Processing

3.5.1. Substrate Selection

SU-8 has poor adhesion to most commonly used metals, though it adheres well to silicon, SiO₂, aluminum, Al₂O₃, and gold films very well. It does not adhere to copper, titanium, nickel, or iron. This limitation has often been overcome by patterning the metal layer, or by increasing the surface roughness so that the substrate has a better mechanical hold on the resist. In our experiment, a 1 mm thick, 4-inch diameter machineable alumina substrate was used to develop this process. This substrate was chosen for two reasons: the mechanical strength and the surface roughness. The substrate shows excellent mechanical strength and no significant deflection of the substrate was observed due to residual stress in the SU-8 film during process development. In addition, the increase in adhesion due to substrate surface roughness lead to less de-bonding of high aspect ratios structures during development.

3.5.2. Spin Coating

The experiments were performed using MicroChem SU-8 100 with no chemical modifications. To obtain 1100 µm of SU-8 on the substrate, 10 ml of SU-8 was applied to the center of the substrate and spun at 400 rpm for 25 seconds. SU-8 layers thicker than
1200 μm were obtained using two spin coats. To obtain a 1500 μm thick SU-8 film, a second layer of SU-8 100 was spun on a prebaked 1100 μm thick film. The second spin coat required 6 ml of SU-8 100 at 400 rpm on top of previously baked film. The resist was spun for 25 seconds and care was taken to remove any excess resist from the edge of the substrate.

For all thicknesses greater than 900 μm, excess resist was removed from the edges of the substrate prior to baking to prevent resist over-flowing off of the substrate during the pre-exposure bake (PB) process. In order to maintain uniform resist thickness, the substrate had to remain on a level surface until after exposure. Pre-exposure baking on a surface with a slope of only 1° can cause significant error in the uniformity of the resist, and in extreme cases, leads to over-flow of the resist off of the substrate.

3.5.3. Prebake

All samples were prebaked in a temperature-controlled oven. The oven was ramped from room temperature to 96 °C over a 30-minute time interval, and held for a specific period of time depending on the thickness of the resist. Our experiments have shown that each 100 μm of resist thickness of SU-8 requires a 50 minute bake time at 96 °C. At the end of the bake process, the resist was cooled at a constant ramp rate. When necessary, an additional coating was made to achieve the desired resist thickness.

Multiple coatings required extended pre-baking time for each additional layer. For example, two layers of resist were spin-coated to obtain a 1500 μm thick resist as used in our experiments. The second bake time was extended to 13 hours at 96 °C even though the second layer was only several hundred micrometers thick. The substrates were then cooled at constant rate for 8 hours to room temperature.
A hotplate may also be used to bake the resist. A temperature of 96 °C may still be used to bake SU-8 films up to 1.5 mm thick on a silicon substrate. However, if a thick substrate with poor thermal conductivity or a very thick SU-8 layer is used, a hot plate temperature of 100 to 105 degrees Celsius may be required to obtain 96 °C on the top surface of the resist based on a very simple calculation using ANSYS.

After evaluating several different temperature reduction schemes, it was found that the reduction of temperature at slow rates after the prebake process did not significantly contribute to the overall pattern quality in open field exposures. The data suggest instead that a prebaked substrate can be removed from the hotplate or oven and cooled quickly to room temperature. A short relaxation period should be used prior to exposure to reduce any residual stress.

3.5.4. Exposure

The resist was exposed using a Quintel UL7000-OBS Aligner with a 1000 W Hg lamp. Table 1 shows the power output of the major peaks in the spectrum emitted from the lamp for most exposures performed during the experiment. No additional filters were used to optimize it for SU-8 exposures, leaving minor skin effects on the surface of the resist due to the presence of a low but measurable power density from wavelengths below 350 nm. Further improvement of the lithography quality can be achieved by application of a SU-8 resist filter to eliminate wavelengths other than 350-400 nm.32

Exposures were performed under hard contact conditions. Excess contact force often resulted in minor adhesion between the SU-8 film and the mask. Lowering the contact force applied by the exposure station reduces adhesion risk between the mask and the substrate but may result in more diffraction of the pattern due to increased air gaps between the mask and the substrate in non-contact regions.
It was noted that nearly all samples in our experiments had some degree of nonuniformity in the resist layer thickness. Measured deviations averaged around 5% of the resist thickness across the whole area for those wafers baked and rested on a properly leveled surface. Even this slight deviation can lead to a 50 µm gap between the mask and wafer under simple contact conditions. Although Glycerin was not used to reduce the diffraction in this experiment, it has been demonstrated to greatly increase exposure quality in exposure of thick SU-8 resist\[37\].

Exposure doses for film less than 500 µm thick were established at CAMD and verified by numerous experiments. The CAMD work provided a thorough inspection of the absorption characteristics of the SU-8 resist. The experiments showed that broadband UV light between the wavelengths of 350 and 550nm would provide the best exposures for SU-8 resist. Figure 3-1 shows the expected bake time of SU-8 negative resist as a function of thickness in a convection oven. Table 3-1 shows the exposure dose for different thicknesses of resist using the broad-band UV exposure station at CAMD.

Test exposures for ultra-thick films were completed at varying applied doses. As expected with all UV resists, the dosage required to expose different patterns in the resist on the same substrate was significantly different. Open field structures, such as crosses and squares, required significantly higher dosages, than close field holes in the resist. Similarly, cylindrical structures required different dosages and development parameters than standard open field structures. Table 3-2 shows the different dosages observed for a few commonly used feature types in resist of 1-1.2 mm and 1500 mm. Aspect ratios for these features are also presented.
Table 3-1  Standardized CAMD exposure doses for SU-8 resist vs. thickness

<table>
<thead>
<tr>
<th>Thickness (µm)</th>
<th>Dose (mJ/cm²)</th>
<th>Thickness (µm)</th>
<th>Dose (mJ/cm²)</th>
<th>Thickness (µm)</th>
<th>Dose (mJ/cm²)</th>
</tr>
</thead>
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<td>210</td>
<td>240</td>
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<td>840</td>
<td>500</td>
<td>1680</td>
<td>800</td>
<td>2580</td>
</tr>
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</table>

Table 3-2  Optimum applied dose conditions for test structures

<table>
<thead>
<tr>
<th>Structure</th>
<th>Resist Thickness</th>
<th>Optimum Dose</th>
<th>Aspect ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cross</td>
<td>1150/1500 µm</td>
<td>3000/7000 mJ</td>
<td>45/40</td>
</tr>
<tr>
<td>Cylinders (Id &lt; 250 µm)</td>
<td>1100 µm</td>
<td>2000 mJ</td>
<td>&gt;24</td>
</tr>
<tr>
<td>Square Cylinder</td>
<td>1100 µm</td>
<td>2000 mJ</td>
<td>28</td>
</tr>
<tr>
<td>Round Hole</td>
<td>1100 µm</td>
<td>2000 mJ</td>
<td>&lt;10</td>
</tr>
<tr>
<td>Line</td>
<td>1150/1500 µm</td>
<td>3000/7000 mJ</td>
<td>18</td>
</tr>
</tbody>
</table>
3.5.5. Postbake

Experiments were designed and conducted to evaluate and optimize the temperature cooling conditions required after post-exposure bake (PEB) processes. Figure 3-2 shows details of the temperature reduction rates evaluated. All of the samples were ramped from room temperature to 96 °C over a 30-minute period and baked for 25 minutes prior to cooling. For condition A, the substrate was removed from the oven at 96 °C and cooled to room temperature using a cold plate. The substrate was then placed on a level surface and allowed to relax internal stress for 2 hours prior to exposure. Condition B required cooling the substrate to 50 °C at a constant rate of 23 °C/hour. The substrate was then removed from the oven, cooled to room temperature on a cold plate, and allowed to relax for 2 hours. Samples using conditions C, D, and E were cooled at a constant rate to room temperature at the rate of 17.5, 11.8, and 8.8 °C/hour, respectively.

Reduction in the cooling rate showed significant improvement in the overall quality of the printed resist pattern. Experimental bias due to increased bake times associated with slow cooling rates was compared to samples with longer bake times and ramp cycles. The data showed that there was no significant bias of the experimental results due to the increased bake time required for slow cooling of the resist.

3.5.6. Development

Development was performed using standard SU-8 Developer and isopropyl alcohol at room temperature with no agitation. The test mask used in this experiment was designed to expose only 40% of the total substrate surface area. To improve development of large dissolvable volumes, the developer was refreshed 5 hours into development. Post in 1.2 mm thick films were completely developed after 7 hours. It took 10 hours to develop the same posts in 1.5 mm thick films. Hollow cylinders could
not be developed completely within this time; however, proper changes in the dose and development time showed that cylinders could be overdeveloped as deep as 1.1 mm in 12 hours. Holes were also developed in 1.1 mm closed field patterns after 12 hours in the developer.

For experimental purposes, a test mask was made with several common shapes such as crosses, line spaces, hollow cylinders, hexagons, posts, and closed field holes. Multiple exposures were performed on each substrate to and with one dose often repeated

![Figure 3-2](image)

**Figure 3-2**  Experimental procedure for ramp conditions after baking

### 3.5.7. Experimental Results

on other substrates to reduce the probability of erroneous data. The data presented were observed for the same dose on at least 2 different substrates for process verification. Figure 3-3 shows four SEM images of some typical microstructures obtained with a UV lithograph of a 1 mm thick SU-8 layer under the four different cooling conditions. Except for changes in the postbake cooling rate, the same processing conditions such as pre-bake, exposure dose, and development conditions were used to pattern each substrate.
Figure 3-3 (a) shows a SEM image of structures cooled using a cold plate. Significant deformations of structures and low sidewall quality can be observed. This is caused primarily by the significant difference between the thermal expansion coefficients of exposed SU-8 and the ceramic substrate. The residual stress concentrations cause large plastic deformations of the microstructures and sometimes debonding of fine features from the substrate. The smallest obtainable cross patterns, 35 µm wide, were twisted and distorted near their bases.

Figure 3-3 (b) shows the same group of microstructures obtained using a constant cooling rate over a 4-hour period immediately following exposure. The quality of microstructures was improved significantly. However, there were still structural deformations caused by residual shear stress. In addition, the finest features in the design were all debonded from the substrate, as in the case using the cold plate. Likewise, the smallest obtainable cross pattern was 35 µm in width.

Figure 3-3 (c) shows results obtained using a constant cooling rate over 6 hours. These 25 µm wide microstructures represent the finest cross patterns remaining on the substrate after development. However, they were twisted and debonded from the surface due to the residual stress caused by mismatch in the rate of thermal contraction between the substrate and the resist. Larger patterns remained very similar to those produced using a 4-hour cooling cycle.

Figure 3-3 (d) shows an image of the same group of 25 µm wide microstructures obtained using a cooling rate of 8 hours. The structures in this particular image are 1200 µm tall. No debonding or significant deformation was observed. From these results, it
Figure 3-3  1 mm tall microstructures obtained using different cooling rates. The same pre-baking, exposure dose, and development conditions were used. Postbake cooling rates were varied. Crosses in a) and b) are 35 µm in width. The small crosses in c) are 25 µm wide. The crosses in d) are 35 and 25 µm in width and 1200 µm tall.  

a) Cooled in minutes using a cold plate  
b) Cooled to 25 °C over 4 hour period  
c) Cooled to 25 °C over 6 hour period  
d) Cooled to 25 °C over 8 hour period
can be seen that extremely fine features with the highest aspect ratios are very sensitive to the post baking conditions and the resulting residual stress. As the feature sizes increase and aspect ratios reduce, the final results become less sensitive to variations of cooling rates.

Further experimentation revealed little improvement in sidewall quality by cooling at rates lower than 8.5 °C per hour.

Figures 3-4 and 3-5 show SEM pictures of some microstructures fabricated using the optimal post-exposure processing. Figure 3-4 shows a set of open-field crosses of SU-8 (1500 µm tall) produced by a single exposure. The optimal dosage for this structure was found to be 7000 mJ/cm². Figure 3-5 shows 1150 µm tall completely developed cylinders. The inner diameter of the smaller cylinders was less than 85 µm at the top and approximately 100 µm at the base. The observed aspect ratio based on measurements from the top of the pattern is approximately 24:1. The exposure doses required were 2000 mJ/cm² for the cylinder and holes.

From the SEM images of these microstructures, significant distortions at corners and sidewall profiles can still be observed. Variations in thicknesses of the structures are also notable. These distortions are caused primarily by diffraction effects due to weak contact between mask and substrate and the shorter wavelength components (below 365 nm) in the light source used in lithography.

To further study the effects of using glycerin for diffraction reduction and filtered light source, experiments were conducted using a filtered light source with an I-line filter and glycerin respectively. In both cases, the same postbake cooling conditions were used (8.5 °C/hour). Figure 3-6 (a) shows the SEM image of a group of microstructures
fabricated using a broad-band light source. Figure 3-6 (b) shows a SEM image of the same cross patterns made using a filtered light source (I-line filter), and Figure 3-6c shows a SEM image of the same cross structures made using a glycerin coating between the mask and resist layer. The designed thickness of the cross is 40 µm. The thickness of the structures in Figure 3-6 (a) shows the largest error from 53.6 µm to 23.4 µm. The thickness of the structures in Figure 3-6 (b) varies from 41 µm at the surface to 32.3 µm at the bottom. The thickness of the structures shown in Figure 3-6 (c) changed from 41 µm at the surface to 23.4 µm at the bottom. Several observations can be made from these results: 1) using a filtered light source mainly contributes to the improvement in the surface layer; 2) using glycerin to reduce the diffraction seems to improve the precision in sidewall thickness significantly; and 3) further improvement in lithography quality can be made by using a combined approach with a filtered light source, glycerin for diffraction reduction, and optimal postbake cooling conditions as suggested in this study. The experimental results reported here have shown that the aspect ratio and sidewall quality of the microstructures obtainable through the SU-8 photolithography process are closely related to the cooling rate after the post-exposure bake. This is principally due to the internal stresses induced in exposed microstructures during the cooling process. To produce fine feature sizes with high aspect ratios, the cooling rate during the postbake process has to be controlled carefully to allow for proper stress reduction. Our experiments show that patterns more than 1000 micrometers tall with aspect ratios exceeding 40:1 can be obtained by effectively reducing the residual stress with extended cooling time. Although cooling at slower rates may indeed allow for further reduction residual stress, experiments show that a plateau is reached at roughly 8.5 °C/hour and
Figure 3-4  
1500 µm tall field of crosses
Small crosses on the right have width of 35 µm at top of the structure. The recorded aspect ratio is greater than 42:1.

(a)  (b)

Figure 3-5  
1150 µm tall cylinders
a) SEM of cylinder walls; b) Optical image showing complete development. Cylinders from left to right in Figure 3-5b are presented top to bottom in Figure 3-5a
Figure 3-6  Identical structures produced under different exposure conditions
a) Structures made with broad-band exposure; b) Structures made using broad-band with
glycerin for diffraction reduction; c) Structures made using an I-line UV light source
(filtered light, no glycerin used)
further reduction of cooling rate seems no longer to affect the structure quality. The results have also shown that the best results can be obtained by using an optimal lithography process that includes a filtered light source, glycerin for diffraction reduction, and optimal cooling rate during the post-exposure bake procedure. This process may be used for the fabrication of ultra-thick high aspect-ratio microstructures that, to date, have only been obtainable using the X-ray lithography based LIGA process.

3.6. Advanced Processing Techniques: Megasonic Development*

It is extremely difficult to fully develop horizontally orientated closed channels, microstructures with extremely narrow gaps, and micro tubes. The development solution cannot effectively work in ultra deep and narrow structures with simple stirring. The development may take many hours, damage fine features, and still not be fully developed. This has been a very challenging problem in SU-8 processing. A new development process is presented here. The process adopted a megasonic agitation process for development of SU-8 microstructures with aspect ratios up to 100:1, the best results reported to date for the optical lithography process of SU-8.

Dip development, or stagnant development, can be used to produce patterns up to the limits defined by the exposure process; however, the time required to produce high aspect ratio closed structures or closely packed deep groves is significantly greater than the time required to produce open structures. For the closed channels in the plane of the substrate, the situation may become much worse. It can lead to degradation and debonding of the open field structures during the development of a widely varying pattern. This type of development can last from 3 to 14 hours depending on the thickness

*To be printed in Microsystem Technologies under “Using Megasonic Development of SU-8 to Yield Ultra-High Aspect Ratio Microstructures with UV Lithography.”
of the resist, the type of pattern being developed, and the aspect ratio of closed field structures. The process can often be enhanced by raising the temperature. Nevertheless, since development is limited by diffusion, rates are generally slower than those using some form of agitation.

Dip development with stirring enhances diffusion, which increases the development rate. However, strong stirring can cause small high aspect ratio patterns to deflect in the solution. This leads to pattern deformation, debonding, and adhesion between nearby structures and structure loss. Currently, stir development is the standard for producing low to medium aspect ratio structures. This is because structures with aspect ratios below 15 are structurally sound and do not deflect in the pressure gradient associated with stirring.

Furthermore, placement of the substrate in the stir bath has an effect. Resists often maintain an intermediate layer of saturated developer fluid near the liquid-solid interface. To enhance techniques for the removal of this layer, Cheng placed the wafer upside down facing the magnetic stir bar in the development bath. Placing the wafer upside down allows gravitational forces to aid in the removal of resist as it is dissolved in the developer. This enhanced development produced higher quality structures in less time. However, small open field structures were subject to high stress fields generated by the motion of the developer fluid.

Sonic development can be applied to solve the problems associated with both stagnate and stir development. Sonic development can be broken into two categories: ultrasonic and megasonic. Ultrasonic development uses frequencies in the kilohertz range to agitate the developer and increase the pressure at the resist surface. The increase in pressure leads to higher diffusion rates and faster development. However, ultrasonic
waves cause vibrations in the pattern structures, which lead to cracks and debonding over time. For this reason ultrasonics are rarely used in SU-8 development due to the stress often adherent in SU-8 processing. To overcome this effect one can use higher frequencies, well above the vibrational modes of the resist structures, to produce a pressure gradient without damaging the pattern. These frequencies between 1-10 MHz are generally referred to as megasonic agitation.

Zanghellini\textsuperscript{40} was the first to present a megasonic development process for resist development of high aspect ratio PMMA microstructures for deep X-ray lithography. This work showed that 1 MHz frequency agitation could be used to develop PMMA microstructures. Furthermore, Zanghellini showed how small increases in the power density of the megasonic actuator could increase the development rate to as much as 10 times that of a stagnant fluid. Zanghellini’s results agree well with a theoretical study by Nilson and Griffiths\textsuperscript{41}, who modeled the development conditions using fluid dynamic models with acoustic streaming.

Khelif et al.\textsuperscript{42} have recently modeled the megasonic agitation of low-aspect-ratio patterns for semiconductor devices. Their work showed the generation of high-pressure fields inside trenches and around vertical structures. These pressures increase with both the amplitude of the incoming wave and the angle of incidence. However, at 90° incidence angles, the pressure gradients are non-uniform and may cause pattern loss at very high power densities. These pressure fields are the driving force for the enhanced development.

A comprehensive study by Meyer\textsuperscript{43} compared stagnant, stirred, and megasonic development for PMMA showed that megasonic development was the superior technique for producing evenly developed high aspect ratio structures in widely varying patterns in
short periods of time. However, the use of megasonics has not carried over to produce high-aspect-ratio microstructures in SU-8. Until recently, SU-8 microstructures were limited in aspect ratio to approximately 30:1. The recent push to produce ultrahigh-aspect-ratios in both UV and deep X-ray lithography has driven SU-8 processing to aspect ratios up to 50:1 in optical and well over 100:1 by X-ray lithography. Features with these aspect ratios have similar limitations in development to that of the traditional PMMA processing with deep X-ray lithography. SU-8 has only played a significant role in deep X-ray lithography for the past four years. In that time, many processing issues regarding stress, exposure, and multiple layer exposure have all been resolved.

3.6.1. Experimental Method

Alumina substrates were spin-coated with SU-8 100 negative photoresist and baked for 50 min per 100 microns at 96 °C then cooled to room temperature over an 8 h time interval. Exposure was completed on a Quintell 7000 contact aligner with a 1000 W power supply. Exposure doses were calculated using power density measurements taken at 365 nm; however the source emitted a broad-band of the UV spectrum between 310 and 410 nm. Doses were 3 J/cm² for open field structures and 2 J/cm² for cylinders. After exposure, the substrates were postbaked at 96 °C for 25 min. and cooled to room temperature again over an interval of 8 hours.

Development was performed using a SONOSYS megasonic actuator driven with a 250 W power supply. The megasonic transducer was placed in a water bath supporting a quartz tank that contained the developer and the substrate. Wafers were developed parallel to the standing wave in order to produce the uniform pressure fields calculated by Khelif. Figure 3-7 is a diagram showing the exact experimental placement of the
substrate with respect to the megasonic transducer. Experimental studies of angle variation as well as increase in the power density of the wave are still ongoing.

3.6.2. Experimental Results

The experiments were conducted to compare megasonic development to traditional development schemes such as dip development and dip development with stirring. The results indicate the possibility to obtain aspect ratios up to 50:1 in open field structures using a power density of 0.75 W/cm² for no more than 3 hours, with some structures of even higher aspect ratio broken off from the base of the ceramic substrate.

A quick test was made to test limit in the aspect ratio obtainable with the megasonic agitated development process. A thin layer of SU-8 resist was spin-coated on the ceramic substrate and flood exposed prior to coating of the thick resist layer. A 600 µm layer of resist was then coated over the exposed SU-8 and patterned using broad-band optical lithography. Figure 3-8 (a) shows a series of crosses exposed and developed

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**Figure 3-7**  Graphic representation of the developer bath

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51
using megasonic development. The cross on the far left is 6 µm wide and 630 µm tall. The aspect ratio for this cross is 100:1.

One immediately notices the poor sidewall quality of the 100:1 aspect ratio structure. It appears that the broad-band source has exposed significantly more of the upper half of the pattern than the lower half. This is due to uneven absorption of different wavelengths emitted by the contact aligner. Choosing a particular photon wavelength or a narrow band of wavelengths more suited towards the exposure of thick SU-8 resist material will eliminate this problem as reported by some other researchers. An adjustment of the dose may also be made to compensate for the absorption of the wavelength desired. Use of glycerin or another high index media should also be used to reduce the effects of diffraction that cause higher sidewall angles in the exposure. Finally, one might choose to use a chemically altered SU-8 resist to improve the pattern quality and achieve better sidewall quality. Sidewall quality has been a topic of numerous research works reported and is not specifically related to the megasonic aided development process. Therefore, it is not the focus of this dissertation.

Another feature of interest is the gap between the 30 and 35 µm wide crosses. A 7 µm trench is observed from the top of the structure. It is possible that resist swelling may have caused part of the pattern to close near the top, but there is a distinct gap observed between the crosses with a maximum width of 14 µm. Figures 3-8 (b) and (c) are enlargements of these two areas. The height of these patterns was confirmed by optical microscopy, physical measurement, and optical interferometry.

Another important observation from this test was the production of very high aspect ratio cylinders. Figure 3-9 shows the current limit of megasonic development for SU-8 cylinder production using a thin SU-8 under-layer. Cylinders shown in the figure
Figure 3-8  Megasonic development of ultra high aspect ratio structures
630 µm tall open field structures exposed with broad-band UV lithography and
developed using megasonics on a thin exposed SU-8 underlayer.  (a) Width of the crosses
observed roughly corresponds to the number above it in microns.  Some swelling of the
resist has distorted the actual values slightly.  For example, the 5 µm wide cross is
actually 6 µm.  The 10 µm cross is actually 12 µm wide.  (b) Close up of the 6 and 12 µm
wide 630 µm tall cross structures.  (c) Close-up of the slot developed between the 32 and
38 µm wide crosses.  The slot has a width of 7 µm at the top and 14 µm near the base.
are 600 µm tall with wall thicknesses of 10 and 15 µm. Severe buckling is observed in the 10 µm cylinder after development to the resist under-layer. The 15 µm cylinder walls are intact, but not perfect. The dimensions of the features shown in Figures 3-8 and 3-9 seem to represent the limit of the development process reported here.

3.6.3. Discussions and Conclusions

SU-8 microstructures with aspect ratios up to 100:1 have been successfully developed. This is by far the highest aspect ratio reported with any resist using optical lithography. Although the pattern quality is poor due to the use of a broad-band contact aligner, the development of features with these aspect ratios could not be obtained using conventional methods. The use of megasonics to provide adequate agitation sonically without mechanical damaging of the features during development provided a significant advantage in the development of high-aspect-ratio features. Further study is needed to better understand the process. Parameters such as damping effect, the agitation power density, the orientation of the sonic wave relative to the features and substrate all need to be carefully studied. A megasonic development process can be especially useful for the development of horizontally orientated closed channels, microstructures with extremely narrow gaps, micro tubes, and other hard-to-develop microstructures.
Figure 3-9  
600 µm tall Cylinders developed with wall thickness of 10 and 15 µm. Cylinders with 10 µm walls are buckled at the base once developed. 15 µm cylinders remain standing with slight deformations.
CHAPTER 4: METAL ELECTRODEPOSITION

4.1. Introduction

A basic understanding of the metal electrodeposition was required to produce both the nickel and nickel-iron components in the device. Electrodeposition is the process by which solid metal surfaces are grown on a conductive cathode when a potential is applied between the anode and cathode inserted into a bath of metal salts.\textsuperscript{45} The process requires strict control of several parameters, including the salt and buffer concentrations, pH, and temperature of the bath, to deposit the metal and surface finish. Other conditions, such as the applied potential, bath current, pattern geometry, and rate of mixing in the bath, affect the uniformity of the deposition. The large number of parameters and various physical conditions in which the metal should be deposited require the engineer to develop an expertise in the specific process.

4.2. Nickel Electrodeposition Process

In this experiment, nickel was electrodeposited into patterned SU-8 using the nickel sulfamate bath listed in Table 4-1. The incorporation of sulfur increases the reactivity of [100] nickel over [111] nickel and enhances corrosion resistance. The size of the sulfide molecule is also larger than a single nickel atom, producing an intrinsic compressive stress in the plated material.\textsuperscript{46} The IV curve for sulfamate baths typically shows a slower increase in the current as the overpotential is increased in the current ranges most often used for the deposition of high aspect ratio microstructures. Each constituent in the plating bath has a specific role in the electrodeposition process. Nickel sulfamate is the primary metal salt. Boric acid is used to stabilize the pH at the cathode during the plating process. Lauryl sulfate is a wetting agent which activates the surface
during the plating process. Other chemicals are commonly used to brighten the plated nickel surface, though they typically introduce excess stress into high aspect ratio devices and were removed from the baths used by the Microsystems Engineering Team at LSU.\textsuperscript{47} Courmarin is sometimes added to maintain a level deposit. Saccharin, another additive often used in nickel electroplating baths, reacts with hydrogen to produce sulfur anions that are codeposited at currents less than 250 mA/cm\textsuperscript{2}.\textsuperscript{46} As stated above, the codeposition of sulfides can increase the compressive stress in the material.

**Table 4-1** Nickel electroplating bath (Molar Concentrations)

<table>
<thead>
<tr>
<th>Component</th>
<th>Concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nickel Sulfamate</td>
<td>1.8 M</td>
</tr>
<tr>
<td>Boric Acid</td>
<td>0.6 M</td>
</tr>
<tr>
<td>Lauryl Sulfate</td>
<td>0.01 M</td>
</tr>
<tr>
<td>Temperature</td>
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</tr>
<tr>
<td>pH</td>
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</tbody>
</table>

High aspect ratio nickel microstructures were produced using the nickel sulfamate bath prepared at a pH of 4.5 and a temperature of 50 ºC. Nickel was electrodeposited into the patterns using controlled potentials and a saturated calomel electrode (SCE). The transfer potential was often varied between -0.9 and -1.1 V depending on the thickness and uniformity of the plating process required. Substrates requiring electrodeposition of nickel uniformly over many patterns up to thicknesses of 100 µm, were electroplated slowly at -0.9 V with a measured current density of 7.4 mA/cm\textsuperscript{2}. This reduced the need for chemical mechanical polishing (CMP) of the electroplated surface of thin nickel microstructures. Tall structures, for which polishing could be performed, were often electroplated at a -1.1 V with a current density of 21 mA/cm\textsuperscript{2}. 
4.3. Galvanostatic Nickel Plating

Galvanostatic plating is the process in which a constant current is supplied across the bath with no direct control of the bath potential. This technique is commonly used for electrodeposition processes with established relationships between the current and overpotential. The advantage of this method is that it does not require complex electronics such as an electrochemical potentiostat or a reference electrode. It is typically carried out using a heated bath, standard cathode, and a constant current power supply. The use of a previously established IV curve for the electrochemistry of the bath used provides enough information to determine if plating is in the kinetic or diffusive rate limiting regime. The deposition rate, \( r \), of plated nickel structures in the kinetic regime can be predicted using

\[
 r = \frac{m \cdot n}{\varphi} j , \quad \text{Eqn. 4-1}
\]

where \( m \) is the atomic mass (109.5 g/mol), \( n = 2 \) is the number of electrons required for the reaction, and \( \varphi \) is the density of the metal (8.907 g/cm\(^3\)). The thickness of potentiostatically electrodeposited nickel structures can also be determined using Eqn. 4-1, provided that the current is properly monitored over time throughout the deposition process.

4.4. Electrodeposition of Ni-Fe

Unlike nickel, the deposition of a Ni-Fe alloy is not straightforward. Preferential iron deposition in nickel-iron baths has been repeatedly noted in the literature. This is thought to occur because iron in the salt bath increases the overpotential for nickel electrodeposition. This phenomenon was first called anomalous codeposition (ACD) by Brenner,\textsuperscript{48} who along with many others, attempted to understand how and why this
reaction occurs. Dahrms and Croll\textsuperscript{49} offered the first explanation for this behavior. They proposed that the high iron content in their deposits was due to the formation of ferrous hydroxide on the surface of the cathode. It was proposed that the hydroxide formation generated a large pH near 7.2 that reduced the iron hydroxide to iron that then preferentially deposited on the surface. Hessami and Tobias\textsuperscript{50} developed and tested a model that compared the hydrolysis of both nickel and iron during the reaction. They cited previous work by Matulis \textit{et al.}\textsuperscript{51} which suggested that NiOH\textsuperscript{+} appeared to play a role in the electrodeposition of nickel films. Hessami and Tobias’s model\textsuperscript{50} predicted a higher concentration of NiOH\textsuperscript{+} that reduced at a pH of only 4.3. This suggested that NiOH\textsuperscript{+} was the primary hydroxide present in the bath; however, researchers could not rule out the FeOH\textsuperscript{+} mechanism previously proposed. Later, Deligianni and Romankiw\textsuperscript{52} demonstrated experimentally that the increase in pH at the cathode surface during deposition was not high enough to promote the reduction of FeOH\textsuperscript{+}, suggesting that the formation of nickel hydroxide at low pH values (typically between 2 and 4) was responsible for the high concentration of Fe in the ACD of Ni-Fe.

Other considerations such as the effects of additives were also considered. The primary additive to nickel and nickel iron baths, is boric acid. Gangasingh and Talbot\textsuperscript{53} studied the effects of boric acid on Ni-Fe electrochemistry and found no significant effect on the current density of the deposited alloy or the composition. Their work was found to be in complete disagreement with Gadad and Harris\textsuperscript{54} who documented an increase in the efficiency of Ni-Fe electrodeposition in chloride baths. Horkans\textsuperscript{55} also showed decreases in the sulfate bath current and improved efficiencies in the presence of Boric acid. Other materials and plating parameters were also shown to affect the composition and partial current densities of the two metals. Popov \textit{et al.}\textsuperscript{56} showed that the addition of small
amounts of organic additives, such as saccharin and even boric acid, change the fractional coverage of the electrode surface. This effect polarizes the surface without depleting the concentration of nearby metal ions. The result is an increase in the local pH near the cathode surface which enhances the reduction rate of NiOH⁺ and reduces the percentage of iron in the plated material.

Harris et al.\textsuperscript{57} investigated the effects of adding organic amines to a Ni-Fe bath. The proper use of amine chemistry was shown to reduce the iron content in ACD Ni-Fe deposits from about 50\% to 25\% in a controlled fashion. These experiments were performed at a pH of 5.0, which increased the likelihood of FeOH⁺ reduction, as well the concentration of Fe in the bath. Amine groups limited Fe partial current density uniformly for both chloride and sulfate baths between 7 and 25 mA/cm². These results are significant to this project because they provide a method for controlled deposition of low iron content alloy at current densities desired to the production of microfabricated structures.

Other work by Harris and St. Clair\textsuperscript{58} showed opposite effects in the Fe content on the ACD of Ni-Fe using tartaric acid. The addition of tartaric acid to Ni-Fe a bath at pH =5 prevented the precipitation of iron from the reduction of FeOH⁺ by limiting the rise in pH on the cathode surface. It was further hypothesized that the formation of bitartrate near the cathode surface limits the formation of NiOH⁺ and thus the nickel deposition rate. Limiting both reactions reduces the anomalous codeposition effect present in most Ni-Fe baths, allowing for a deposition model more consistent with the initial concentration of the individual ionic species.

Menon and Harris\textsuperscript{59} reported the bath chemistry used by Kanigicherla,\textsuperscript{60} a graduate student in the Microsystems Engineering Team at LSU. Kanigicherla used the
Ni-Fe bath with tartaric acid as the additive to reduce the effects of ACD and electroplate microparts with Ni-20%Fe permalloy. This bath, comprised of both NiSO₄ and FeCl₂ and tabulated in Table 4-2, was used to produce most of the soft magnetic permalloy magnets used for the design of the spring-mass in this research work.

<table>
<thead>
<tr>
<th>Nickel Sulfamate</th>
<th>0.87 M</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iron Chloride</td>
<td>0.06 M</td>
</tr>
<tr>
<td>Boric Acid</td>
<td>0.6 M</td>
</tr>
<tr>
<td>Sodium Chloride</td>
<td>0.17 M</td>
</tr>
<tr>
<td>Lauryl Sulfate</td>
<td>0.001 M</td>
</tr>
<tr>
<td>Saccharin</td>
<td>0.005 M</td>
</tr>
<tr>
<td>Coumarin</td>
<td>0.002 M</td>
</tr>
<tr>
<td>Tartaric Acid</td>
<td>0.025 M</td>
</tr>
<tr>
<td>Temperature</td>
<td>30 ºC</td>
</tr>
<tr>
<td>pH</td>
<td>2.8</td>
</tr>
</tbody>
</table>

### 4.5. Experimental Results on Electroplated Ni-Fe

Nickel-iron alloys were deposited using the bath presented in Table 3-2. As expected, alloy composition varied at different temperatures, pH values, and applied potentials. Another unexpected factor also affected to alloy composition. The Ni/Fe ratio deposited increased significantly over the span of 10 days. During that time, Fe(OH)₂ precipitated out of the solution, changing the iron concentration within the bath. Alloys plated within 24 hours of creating the bath showed a 40% iron content. After 9 days, 16% iron content was recorded using X-ray energy dispersive spectroscopy (XEDS). The current hypothesis is as follows:

1. For high iron concentrations, there appears to be ACD of Ni-Fe.
2. Over time, the concentration of FeOH⁻ in the bath increases, though the pH in the bath and on the electrodes never gets high enough (pH = 7.2 is required) to reduce
the FeOH\textsuperscript{−}, leading to the production of Fe(OH)\textsubscript{2(s)} that precipitates out of solution.

(3) The decreased concentration of iron in the bath competes less with nickel for the buffering effect of the tartaric acid.

(4) The effective increase in concentration of bitartrate at the cathode surface inhibits the formation of NiOH\textsuperscript{−}, leading to less ACD and more deposition from the ionic species themselves.

Another notable observation was the presence of Ni(OH)\textsubscript{2} in films electrodeposited at applied potentials less than -1.0 V. Springs produced with Ni(OH)\textsubscript{2} present in the alloy typically had larger grain sizes, and were therefore softer than permalloy springs, which had an average grain size of 100 nm or less. Electroplated springs were etched for 4 hours in concentrated NH\textsubscript{3}OH and H\textsubscript{2}O\textsubscript{2}. Small amounts of etched Fe(OH)\textsubscript{2} were observed during the etch process, but the springs looked almost identical before and after the etch. This result supported the case for formation of Ni(OH)\textsubscript{2}, rather than large deposits of Fe(OH)\textsubscript{2} predicted in the literature. The Ni/Ni(OH)\textsubscript{2}/Fe springs used in the experiment were analyzed using XEDS and found to contain 32% iron, 45.6% nickel, and 22% oxygen. The springs were easily magnetized and performed well during device testing.

The formation of springs with hydroxide groups was not, however, the focus of this experiment. Permalloy springs were deposited at potentials between -1.2 and -1.3 V. XEDS results showed that springs used for the final test consisted of 85% nickel and 15% iron. The bath used to deposit the samples was 10 days old. The deposition rate for the applied potential of -1.25V was 0.7 \textmu m per minute. Springs were plated to a thickness of
17 µm. The springs were shiny with a very fine grain structure and showed no signs of pitting or etching during the 4 hour NH₃OH/H₂O₂ etch process.

Intrinsic compressive stress present in electroplated Ni-Fe was another primary concern. Springs with iron contents greater than 40% often bowed as much as 75 µm after being released from the substrate. Springs with low iron showed a 35 µm out of plane deflection. These results compare well with experimental data on hardness and internal stress published by Sadakov et al.⁶¹ These deflections were used to set the initial gap distance between the plunger and the magnetic core of the relay.

Magnetic properties of Ni-20%Fe plated using the electroplating bath as used in this experiment were analyzed by Kanigicherla.⁶⁰ He observed a magnetic permeability of 800 times the permeability of free space ($\mu_0 = 4\pi \times 10^{-7}$ N/A²) and a saturation field of 0.8 Tesla. Myung and Nobe⁶² showed that magnetic saturation of electroplated nickel-iron alloys does increase from 0.75 to 1.4 Tesla as the iron content increases from 15 and 45% Fe. Coercivity remains relatively constant between 1 -10 Oe over the same range of Fe content, thus all Ni-Fe magnets produced during this experiment are soft magnets and are sensitive to changes in the local magnetic field over time. For this experiment, springs were magnetized using 1 Tesla rare earth permanent magnets for at least 30 seconds prior to device assembly. The field strength is thought to be high enough to saturate the Ni-Fe spring providing that the permeability is between 800 and 1400 $\mu_0$. 

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CHAPTER 5:  MECHANICS OF MATERIALS

5.1. Introduction

Electrodeposited nickel and nickel-iron alloys are the most commonly used metals in LIGA fabricated microdevices. These metals are produced using a wide variety of electroplating baths. Different plating techniques typically produce metals with different grain sizes, internal stresses, and elastic constants than their American Society of Mechanical Engineering (ASME) standardized bulk metal counterparts. This presents a great challenge to those attempting to determine the mechanical properties of these materials as a whole. Recent efforts by Mazza et al.\textsuperscript{63} and Dual et al.\textsuperscript{64} have attempted to determine the tensile properties of LIGA fabricated nickel and Ni-20\%Fe microstructures by destructive stress-strain analysis. Others such as Majjad et al.,\textsuperscript{65} Chung and Allen\textsuperscript{66} and Zhang\textsuperscript{67} have determined Young’s modulus for electroplated nickel microstructures measuring the nondestructive deflections of MEMS devices. Sharpe and McAleavey\textsuperscript{68} were the first to show a significant variation in the stress-strain curves of nickel and Ni-20\%Fe electroplated microstructures produced by different LIGA foundry services. Christenson and Buchheit et al.\textsuperscript{69,70} later produced stress-strain curves for Ni and Ni-20\%Fe using LIGA electroplated samples at Sandia National Laboratory. More recently, Cho et al.\textsuperscript{71} published nickel stress-strain curves and fatigue life for the current nickel electroplating process used by the LIGA group at the Center for Advanced Microstructures and Devices. The work by both Sharpe and McAleavey\textsuperscript{68} and Cho et al.\textsuperscript{71} showed different stress-strain curves and elastic constants for electroplated nickel and Ni-20\%Fe when compared to one another and to hardened bulk nickel. Changes in the elastic constants of a metal alter the fracture mechanics and fatigue life of the material.
under applied loads. This is the primary reason that LIGA fabricated metal microstructures do not show the same fracture and fatigue properties as the standardized bulk counterparts.

This research work discusses a fracture mechanics and fatigue life study on LIGA fabricated nickel and Ni-20%Fe and compares them to their conventionally produced bulk values. The model used can be extended to any metal that shows significantly different mechanical properties due to its small grain size in comparison to that of the standardize bulk material. The fatigue and fracture mechanics analyses performed in this study were made possible by the application of a recently developed theory for ultra-fine grain metals. The model requires an accurate stress-strain curve for the material in question and some knowledge of the bulk material properties to accurately determine the stress intensity factor, fracture damage zone, and fatigue life of the fine grain sized material. Although the model was developed for low cycle fatigue predictions, it was also demonstrated by high cycle fatigue life predictions by the original author. It was not originally intended for use with materials having grain sizes greater than a few hundred nanometers. The results demonstrated in this dissertation for electrodeposited nickel metals show similar fatigue predictions to that of hardened bulk nickel. The model also predicts a longer fatigue life for electroplated Ni-20%Fe materials than that published for bulk Ni-15%Fe. The increased fatigue life in LIGA Ni-20%Fe, relative to its bulk counterpart, is due to the increased yield strength and ultimate tensile strength associated with the decreased grain size of the electrodeposited metal.

5.2. Development of the Mathematical Model

The experimental stress-strain curves for LIGA fabricated nickel and Ni-20%Fe samples were taken from previously published results. Further studies on
electrodeposited Ni-20%Fe were performed at Sandia National Laboratories. All metals were electroplated into dog-bone shaped PMMA patterns made using Deep X-ray Lithography and tested for tensile failure. Further samples produced by Cho et al. were fatigue tested in an attempt to develop a fatigue curve for LIGA fabricated nickel microstructures. Nickel electrodeposition was performed using slight variations of the same nickel sulfamate solutions. The grain structure of the nickel materials was found to be approximately 2-4 µm. The bath chemistry of the Ni-20%Fe electrodeposition studied by Sharpe was not provided, but is thought to be a nickel sulfamate bath containing iron sulfate. The Ni-20%Fe deposition at Sandia National Laboratories was performed using a nickel sulfamate/iron sulfate solution and plated at 20 mA/cm² at 50°C. After deposition, the samples were mechanically polished to a thickness between 150 and 400 µm. Tensile tests were performed to determine the stress-strain curves of each sample. Estimates of the Young’s modulus, yield strength, and ultimate tensile strength of each group of samples were recorded and published.

In this work, data from the published stress-strain curves for nickel and Ni-20%Fe were fit to a power law function:

\[ \Delta \sigma = \xi (\Delta \varepsilon)^{\beta}, \]

where the extrapolated strain-hardening exponent, \( \beta \), and strength coefficient, \( \xi \), were recorded for each tested metal. Figures 5-1 and 5-2 show the extrapolated functions for published nickel and Ni-20%Fe data. The functions were used to fit the plastic region of the stress-strain curve in order to predict fracture mechanics properties of the crack tip during failure. Two curve fits were required to accurately model materials such as electroplated Ni-20%Fe, which do not exhibit much strain hardening. Table 5-1 lists the elastic and strain-hardening constants for each published stress-strain curve of nickel and
Ni-20%Fe respectively. Table 5-1 also lists the bulk mechanical properties for each material. 

5.3. Stress Intensity Factor for LIGA Fabricated Ni and Ni-20%Fe

Crack propagation through a material depends greatly on the stress intensity factor. Variations in the stress intensity factor near a defect cause significant changes in the physical properties of a specimen. Calculations of the stress intensity factor for various electroplated metals used in the LIGA process have not been published in the literature. One can, however, determine the effective stress intensity range, ∆K_{eff}, using the following relation:

\[
\Delta K_{eff} = Y \Delta \sigma \sqrt{a} = Y \zeta (\Delta e)^{\beta} \sqrt{a}.
\]

Eqn. 5-2

<table>
<thead>
<tr>
<th>Table 5-1</th>
<th>Elastic and hardening constants for electroplated nickel and Ni-20%Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Nickel Samples</strong></td>
<td><strong>Elastic Constant (E, (GPa))</strong></td>
</tr>
<tr>
<td>Bulk Nickel</td>
<td>177</td>
</tr>
<tr>
<td>Cho</td>
<td>163</td>
</tr>
<tr>
<td>LIGAMUMPS 3</td>
<td>181</td>
</tr>
<tr>
<td>LIGAMUMPS 4</td>
<td>158</td>
</tr>
<tr>
<td>Hi MEMS</td>
<td>182</td>
</tr>
</tbody>
</table>

| **Ni-20%Fe Samples** | **Elastic Constant (E, (GPa))** | **Yield strength (σ_y (MPA))** | **Ultimate Tensile strength (σ_ut (Mpa))** | **Strain hardening exponent (β)** | **Strength coefficient (ξ)** |
| Bulk Ni-22%Fe | 210 | 159 | 455 | | |
| Sharpe (Ni-22%Fe) | 1900 | 2410 | 0.4 | 0.0998 | 1550.0 |
| Sandia (Ni-20%Fe) | 810 | 1350 | 1850 | 0.8123 | 1186.3 |
| | | | | 0.2036 | 1457.8 |
Figure 5-1  Stress-strain curves of electroplated nickel microstructures

Figure 5-2  Stress-strain curves of electroplated Ni-20%Fe microstructures
Here, $\Delta \sigma$ is the change in applied stress calculated using equation (1), $\Delta \varepsilon$ is the change in applied strain, $a$ is the half crack length, and $Y$ is the geometric configuration factor and is often assigned a value of 1.12 if there are no geometric constraints on the problem. Using the power law formulation above, the effective stress concentration range can be equated to changes in strain. Using this formulation, one is able to relate measurable changes in the size of the material to known concepts in fracture mechanics.

Cho et al.\textsuperscript{71} observed a distinct mixed mode fracture with a critical crack length on the order of 300 $\mu$m. Mixed mode fracture is often associated with samples tested which are too thick to record a plain stress critical intensity factor, $K_C$, but not thick enough to record a value for the plain strain critical stress intensity factor, $K_{IC}$. One can estimate a critical stress intensity factor, $K_{max}$, for materials within a thickness range of 100 to at least 500 $\mu$m using the critical crack length observed in the sample, provided that there is some evidence of mixed-mode fracture.

Figure 5-3 shows a broken Ni-20%Fe sample from Sandia National Laboratories.\textsuperscript{80} A ductile shear fracture is observed throughout the sample. The only regions of mixed mode fracture present in the sample are due to defects in the electroplated metal. Therefore, critical fracture length could not be ascertained from the uniform fracture within the sample and is found to be greater than 150 $\mu$m. The clear evidence of a ductile break in this sample requires the calculation of a plain stress critical intensity factor, $K_C$, using the width of the sample as the value for the half crack length. Substituting these crack length values for the half crack lengths in Equation 5-2, the effective stress intensity factor can be evaluated for some of the published nickel stress-strain curves.
5.4. Crack-Tip Plastic Zone Calculations

Two geometric zones can be defined to describe crack propagation through a material. The first is the crack-tip plastic zone. This zone lies ahead of the crack tip, encompassing the entire region in which the localized stress at the crack tip exceeds the yield strength and causes the material to deform plastically. Within the plastic zone is a fracture-damaged zone in which severe shearing processes produce crack growth. The length of these zones is required to determine the average accumulated plastic strain occurring within the fracture-damaged zone at the crack tip.

The plastic zone deformation radius in a metal, \( r_c \), can be evaluated as:

\[
 r_c = \lambda \left( \frac{\Delta K}{2\sigma_y} \right)^2 ,
\]

Eqn. 5-3

where \( \lambda \) is the plastic zone correction factor. The commonly used value for an elastic material under plane strain conditions is \( \lambda = (1/3\pi) \). Under plane stress conditions the value for \( \lambda \) is \( 1/\pi \). Failure of LIGA plated microstructures typically results in ductile fracture as shown in Figure 5-3 or mixed mode fracture. Therefore, in this study the value for \( \lambda \) was taken as \( 1/2\pi \) to account for the mixed mode fracture of nickel and the effects of voids and particulates present in Ni-20\%Fe structures.

To determine the plastic zone deformation for ultra-fine grain size materials, Ding et al. defined two new numerical parameters. The first factor was defined as the ratio of yield stress of the fine grain sized material to yield stress of the bulk material. In this model, the grain boundary-strengthening factor is defined inversely as:

\[
 F = \sigma_y / \sigma_{3p} ,
\]

Eqn. 5-4
which is defined as the ratio of the yield stresses for the small grain size (or electroplated) material, $\sigma_{yp}$, and the bulk material, $\sigma_y$ respectively. The second parameter is the grain boundary constraint factor, $C$, which Ding et al. defined as one half the ratio of the stress amplitudes of the bulk to the fine grain sized material and was assigned a numerical value of 0.25 for uniaxial tensile loading. This parameter was neglected for the nickel samples used in this study because they maintain a micron scale grain structure. However, data in Figure 5-4, using dark field TEM, suggest that the Ni-20%Fe plated at Sandia National Laboratories has a grain size between 70 and 100 nm. In this case, the grain boundary-constraint factor should be taken into account. The following equations presented in this work contain a $C$ term representing where the multiplier is to be defined. The grain boundary-strengthening factor however, was assumed to be the primary factor contributing to changes in the fracture mechanics properties of LIGA fabricated materials with grain diameters larger than a few hundred nanometers.
The grain boundary-strengthening factor is used to establish the relationship between the bulk and electroplated metallic properties of nickel and Ni-20%Fe presented here. Combining equations (2), (3), and (4) allows one to obtain a value for the radius of the plastic zone in the plated material as:

$$ r_{cp} = \lambda \left( \frac{F \Delta K_{eff}}{2C \sigma_{yp}} \right)^2 = \frac{\lambda \pi a F^2}{4C^2} \left( \frac{Y \xi (\Delta \epsilon)^\beta}{\sigma_{yp}} \right)^2. $$  \text{Eqn. 5-5}

To determine the radius of the fracture-damaged zone, the stress distributions within the crack-tip plastic zone is taken into consideration. Assuming a singular function near the crack tip, the stress distribution is described as:

$$ \sigma_{atip}(r) = \Delta \sigma (r_{cp} / r)^{\beta / (B+1)}, $$  \text{Eqn. 5-6}

and

$$ \epsilon_{pl}(r) = \Delta \epsilon_{pl} (r_{cp} / r)^{\beta / (B+1)}. $$  \text{Eqn. 5-7}
where the maximum stress applied is assumed to be equal to the ultimate tensile stress of the electroplated material, \( \sigma_{utsp} \). Substituting equations 5-1 and 5-5 into equation 5-6 provides the solution for the radius of the fracture-damaged zone:

\[
r_{fdzp} = r_{cp} \left( \frac{\Delta \sigma}{\sigma_{utsp}} \right)^{1+\beta} \left( \frac{\lambda \pi u (YF)^2}{4C^2} \right) \left( \frac{\xi^{3+1/\beta}}{\sigma_{utsp}^{1+1/\beta} \sigma_{yp}^{2}} \right) (\Delta \epsilon)^{\beta+1}. \tag{Eqn. 5-8}
\]

Integrating equation 5-6 over the fracture-damaged zone, and normalizing, provides a measure of the accumulated plastic strain present at the crack tip during propagation:

\[
\epsilon_{pl} = \frac{1}{r_{fdzp}} \int_{0}^{r_{fdzp}} \epsilon_{pl}(r) dr = \left( \frac{\beta+1}{\beta} \right) \left( \frac{\sigma_{utsp}^{1/\beta}}{\xi} \right). \tag{Eqn. 5-9}
\]

### 5.5. J-Integrals and Theoretical Fatigue Life of LIGA Ni and Ni-20%Fe

After the accumulated plastic strain is obtained, it can be multiplied by the applied stress at the crack tip and integrated over the volume of the fracture-damaged zone to determine the interaction energy as the crack grows through the material. The derivative of the energy with respect to \( r_{fdz} \) provides the driving force for the crack to propagate. This force is often referred to as the J-integral\(^81\) in the literatures for fracture mechanics and can be written as:

\[
J = -\frac{\partial}{\partial r} \left( \int_{V_{fdz}} \sigma_{utsp} \epsilon_{pl} du \right) = \frac{\partial}{\partial r} \pi \left( \frac{r_{fdzp}}{2} \right)^2 \sigma_{utsp} \epsilon_{pl}. \tag{Eqn. 5-10}
\]

For a given change in applied strain, \( \Delta \epsilon \), the change in force applied as the crack propagates past a particular point can be reformulated as:

\[
\Delta J = \left( \frac{\lambda \pi^2 Y^2 F^2 a}{8C^2} \right) \left( \frac{\beta+1}{\beta} \right) \left( \frac{\xi^3}{\sigma_{yp}^2} \right) (\Delta \epsilon)^{\beta+1}. \tag{Eqn. 5-11}
\]
Under both linear elastic and plastic conditions, the change in force required to change the crack tip opening displacement (CTOD) is written as: \[ \Delta J = m \sigma_{yp} \Delta COTD, \] Eqn. 5-12

where \( m \) is a numerical constant between 1 for a non-hardening material and 2 for hardened materials. For this case, \( m \) is taken as 3/2. In linear elastic fracture mechanics (LEFM) the crack growth rate, \( \frac{da}{dN} \), directly relates to the driving force and therefore the change in the crack tip opening displacement. Tomkins\(^77\) suggested that under LEFM conditions, the crack growth rate was equal to half the crack tip opening displacement. Using equation 5-11, the crack growth rate is derived to be:

\[
\frac{da}{dN_f} = \left( \frac{\lambda \pi^2 Y^2 F^2 a}{24C^2} \right) \left( \frac{\beta + 1}{\beta} \right) \left( \frac{\xi}{\sigma_{yp}} \right)^3 (\Delta \varepsilon)^{3(\beta+1)},
\] Eqn. 5-13

where \( a \) is the half crack length and \( N_f \) is the number of tensile stress cycles undergone by the structure. Finally, the fatigue life, or the number of cycles that the plated metal will undergo prior to failure, can be evaluated as a function of the applied strain:

\[
N_f = \frac{24C^2}{\lambda(\pi F Y)^2} \left( \frac{\beta}{\beta+1} \right) \left( \frac{\sigma_{yp}}{\xi} \right)^3 \left( \ln(\alpha_f / \alpha_i) (\Delta \varepsilon) \right)^{(3(\beta+1))},
\] Eqn. 5-14

where \( \alpha_i \) and \( \alpha_f \) are the initial and critical crack lengths respectively. It is assumed that the smallest flaw size, or initial crack length, is on the order of a single grain diameter. The grain diameter of as-plated nickel has been documented at 2-4 \( \mu \)m.\(^69,71\) An initial crack length of 2 \( \mu \)m was used in the nickel calculations presented. Using the Ni-20%Fe TEM image presented in Figure 5-4, which shows grain size variations from 70 to 100 nm, the initial crack length of nickel-iron was assumed to be 80 nm.
5.6. Results and Discussions

Figure 5-5 plots the crack growth rates for both the LIGA fabricated Ni and Ni-20%Fe alloys analyzed as a function of the stress intensity factor. The constant rate of change in the nickel data illustrates the effect of strain hardening on crack propagation. For the Nickel samples, $K_{\text{max}}$, was determined to be approximately 12-20 MPa$^\text{m}^{1/2}$. The nickel-iron samples, however, show a critical fracture toughness of the material in plane stress, $K_c$. For Ni-20%Fe, $K_c$ was calculated to have an approximate value of 40 MPa$^\text{m}^{1/2}$ for the Sandia sample$^{69,80}$ and 60 MPa$^\text{m}^{1/2}$ for the Sharpe sample.$^{68}$

The slope of the functions plotted in Figure 5-5 is also important. The analysis predicts large increases in the crack propagation rate over small increases in the local stress intensity factor. This explains why previous tests using dog-bone shaped structures lead to fracture at the corners and not along the un-notched surface in the middle of the pattern. It is therefore suggested that structures with much longer straight sections than the dog-bone structures used by Shape$^{68}$ and Cho$^{71}$ should be tested in the future. Experimental work$^{70,83}$ has demonstrated that a large increase in the straight section of the dog-bone produced cracks in the center of the structure and reduced the local stress concentrations near the neck of the dog-bone, allowing for more accurate mechanical testing.

The fatigue life at different applied stresses for the electroplated metal can be calculated using the experimental value for the critical crack length, and by substitution of equation (2) into equation (12). This substitution yields the traditional plot for stress versus fatigue life, where the number of reversals is defined as $2N_f$. Figures 5-6 and 5-7 plot the predicted fatigue curves derived using the stress-strain curves for the electroplated nickel and Ni-20%Fe as reported by Sharpe$^{68}$ Cho$^{71}$ and Sandia National Laboratory.$^{69,80}$
Figure 5-5  Fatigue crack growth rates calculated for Ni and Ni-20%Fe data

Figure 5-6 shows the predicted fatigue curves using the presented model for each reported group of LIGA fabricated nickel microstructures as compared to that for bulk nickel. Although the elastic constants for each of the electroplated samples varied by 50-100 MPa from that of the bulk metal, the resulting fatigue curves are very similar. Cho et al.\textsuperscript{71} obtained an experimental fatigue curve for cracks propagating from the corner of the dog-bone in their samples. The predicted curve obtained in this dissertation matched closely to the data presented in their paper. Low cycle deviations present in the model with respect to the experimental measurements of Cho et al.\textsuperscript{71} show the experimental error associated with fracture at the corner of the dog-bone. Furthermore, it should be noted that the model does not accurately describe the nickel material for lifetimes above 1 million cycles. Many ferrous and some nonferrous metals such as nickel reach a
minimum failure stress often referred to as the high cycle fatigue limit. The model presented does not take the fatigue limit into account, thus predicting failure at lower values of stress for high cycle fatigue as observed experimentally by Cho. The model should however be able to predict high cycle fatigue failure in non-limiting metals such as copper.

The analytical fatigue curves for stress versus fatigue life of Ni-20%Fe are recorded in Figure 5-7. For permalloy, the ultimate tensile and yield strengths of the bulk metal were many times smaller than that of the electroplated material. The resulting fatigue curve shows a much longer lifetime and higher susceptibility to applied stress for the electroplated alloy. This is most likely due to the small grain size of the electroplated Ni-20%Fe alloy. The result adds validity to the assumption that dramatic decreases in the grain structure of a metal often result in higher elastic strengths and longer life cycles.

![Fatigue curves](image)

**Figure 5-6** Fatigue curves as predicted by the theoretical model presented for electroplated Ni microstructures in comparison with the fatigue data for bulk Ni as provided by Cho and the “Fatigue Data Handbook”.
Calculations of the plastic and fracture-damage zone radii allowed for the
determination of the accumulated plastic strain at the crack tip and the crack growth rate.
Using this formulation, the fatigue life was calculated for LIGA fabricated Ni and Ni-
20%Fe and compared to bulk metals and the experimental data presented in the literature.
Comparisons between analytical and experimental fatigue life curves show little
deviation. The comparative match between the numerical model and experimental data
suggests the model for ultra-fine grain sizes does indeed hold true for grains up to a few
microns in diameter.

There remains a significant difference between the fatigue life of the bulk Ni-
20%Fe metal and the electroplated alloys. This difference cannot be accounted for by
simply improving the stress-strain curve fit. There remains some influence of the grain
size present in the data that does provide longer fatigue life at higher applied stresses.

![Fatigue Curve](image)

**Figure 5-7** Fatigue curves as predicted by the theoretical model presented
for electroplated Ni-20%Fe microstructures compared to experimental fatigue data for
bulk Ni-20%Fe provided by the “Fatigue Data Handbook”\textsuperscript{78}
Finally, the authors see the need for further experimentation to compare the calculated stress concentration values and crack propagation lengths within the plastic zone to the measured values. Further testing of both LIGA Ni and Ni-20%Fe should also be performed in attempt to obtain complete shear and ductile breaks. This will provide experimental data for the critical crack lengths associated with both plain stress and plain strain intensity factors, and allow for a complete understanding of the fracture mechanics associated with Ni and Ni-20%Fe using this fabrication technique.

5.7. Conclusions

Research presented in this chapter was intended to evaluate the primary fracture mechanics characteristics and fatigue properties of electroplated Ni and Ni-20%Fe alloys whose elastic strain curves had been previously published in the literature. It is the first theoretical model used to determine the possible fracture mechanics properties and fatigue life for LIGA microfabricated materials in the literature. Although the focus of the work has been to derive the properties of nickel and nickel-iron systems, it is not limited to any particular type of metal and may be applied to a wide variety of micron-scale grain-sized materials produced by a wide variety of techniques. The model does not account for the high cycle fatigue limit observed in many nickel alloys. Future work should be performed to correct for the fatigue limits present in such systems.
CHAPTER 6: DEVICE FABRICATION*

6.1. Introduction

In this chapter, the fabrication procedure of the prototype electromagnetic actuated power relay is presented. The device was fabricated using a multi-layer UV-LIGA technique using the optimized SU-8 resist and metal electrodeposition processes described in previous chapters. A mechanically wrapped solenoid insert was used to provide the driving mechanism for the actuator. The solenoid can be wrapped up to 4 layers thick and as tall as 1500 µm. Because the relays are based on very thick metal pads for conducting current, they are expected to have high power capacity, high off-resistance, lower on-resistance, low power consumption and low heat generation. This provides sufficient flexibility to use the electromagnetic driver for a wide variety of switching applications as well as other devices such as sensors and magnetic positioning devices. The detailed fabrication process is presented in Table 6-1. Figures 6-1 through 6-11 show images of the prototype electromagnetic relay at different stages of the fabrication process.

6.2. Patterning the Relay Base

An alumina substrate was used in this process to reduce the probability of electrostatic breakdown while maintaining good resist adhesion. The UV lithography process of SU-8 on alumina substrates presented in Chapter 3 demonstrated aspect ratios over 40:1. However, fabrication of thick metal layers on a porous ceramic substrate proved difficult. To prevent under-etching of the metal layer, the liftoff process

* Some material in this chapter will be printed in Microsystem Technologies under the title “Microfabrication of an Electromagnetic Power Micro-Relay Using SU-8 Based UV-LIGA Technology.”
presented in Table 6-2 was used. AZ 4580 was used to create the pattern for the plating base, and a 1 µm thick copper layer was deposited into the pattern by physical vapor deposition. The resist was then removed to reveal the pattern shown in Figure 6-1. Copper leads extend from the pattern to larger electrical contacts used for electrodeposition.

**Table 6-1  Fabrication procedures**

<table>
<thead>
<tr>
<th>Step #1</th>
<th>Copper electroplating base patterned on 4” alumina substrate using a liftoff process. The result is shown in Figure 6-1.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Step #2</td>
<td>Nickel electroplated into patterned SU-8 layer to produce relay base capable of carrying large currents. The result is shown in Figure 6-2.</td>
</tr>
<tr>
<td>Step #3</td>
<td>Substrate is coated with 50 µm of SU-8 and exposed to reveal interconnect patterns shown in Figure 6-3.</td>
</tr>
<tr>
<td>Step #4</td>
<td>Another layer of 1000-1500 µm of SU-8 resist was spun, exposed, and developed to form the negative pattern of the bottom part of the relay. Figures 6-4 and 6-5 show SEMS of the exposed photo pattern obtained.</td>
</tr>
<tr>
<td>Step #5</td>
<td>Nickel is then electroplated selectively into the pattern to produce the magnetic cup, core post and electrical leads for the relay. Figures 6-6 and 6-7 show of the bottom parts of the relay that has been electroplated.</td>
</tr>
<tr>
<td>Step #6</td>
<td>The Solenoid was wrapped using 50 µm diameter copper wire and inserted onto the relay base. Figure 6-8 shows a micro-coil wrapped mechanically.</td>
</tr>
<tr>
<td>Step #7</td>
<td>Magnetic spring made of electroplated NiFe was made on a second substrate.</td>
</tr>
<tr>
<td>Step #8</td>
<td>Plunger is then released from its substrate and bonded on top of the base to yield a device. Figure 6-11 shows a photograph of the relay that has been assembled.</td>
</tr>
</tbody>
</table>
Table 6-2  Lift off process with AZ resist

<table>
<thead>
<tr>
<th>Step</th>
<th>Procedure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wafer Descumb</td>
<td>O₂ Plasma for 2min</td>
</tr>
<tr>
<td>Resist coat AZ 4620</td>
<td>2000 rpm for 30sec</td>
</tr>
<tr>
<td>Prebake</td>
<td>96 °C for 1 h in Oven</td>
</tr>
<tr>
<td>Exposure</td>
<td>69 mJ/cm²</td>
</tr>
<tr>
<td>Chlorobenzene</td>
<td>Immerse for 20 s, Rince in Running DI Water</td>
</tr>
<tr>
<td>Developer/ Rinse</td>
<td>AZ 40K 4:1 Developer:H₂O, Rince in DI Water</td>
</tr>
<tr>
<td>Deposit Metal</td>
<td>100 nm Cr or Ti, 500 nm Cu</td>
</tr>
<tr>
<td>Metal and Resist Strip</td>
<td>Scotch 301 Tape to Remove Metal, Strip Resist and Remove Metal with Acetone, Rince in IPA</td>
</tr>
</tbody>
</table>

Figure 6-1  Patterned copper plating base

A subsequent layer of SU-8 between 50 and 250 µm thick was then patterned over the plating base to reveal the initial layer of the relay. Substrates were cleaned prior to electrodeposition by immersion for five minutes in C-12 Activator. The C-12 chlorinated solvent etched both the organic material and the metal oxides on the surface of the plating base. As an extra precaution for samples with a visible amount of oxide, a 10 second dip in 3% HCl was used prior to the C-12 dip. Nickel was uniformly electrodeposited into the pattern, as shown in Figure 6-2, using the modified nickel sulfamate bath presented in Table 4-1.
Chemical mechanical polishing was performed, if needed, to provide a uniform nickel layer thickness. The substrate was then cleaned using a strong base and plasma ashed prior to coating a second SU-8 layer. The Intermediate SU-8 layer was then coated and patterned to reveal only the nickel areas that were to be plated to the top of the relay base. Figure 6-3 shows a photograph of the patterned intermediate layer. The white rings around the pattern are areas of debonded SU-8 due to the poor adhesive properties of nickel and SU-8 resist. The debonded areas shown did not underplate or affect the final product. After development, the substrate was dried, cleaned in O₂ plasma, and coated with the final SU-8 layer.

The third resist layer required a spin coat between 1000 and 1500 µm thick. Two spin coats were required to obtain layers thicker than 1200 µm in height. The pattern presented in Figure 6-4 is 1200 µm tall with a core cylinder wall that is 75 µm thick. The insulation layer between the magnetic cup and the solenoid is 50 µm wide, yielding an aspect ratio of 24:1.
Cured SU-8 is extremely difficult to strip. At the same time, it also has very good mechanical properties, a high dielectric constant, and is a very good electrical insulator. In our design, effort was made to avoid the unnecessary stripping procedures associated with cured SU-8. The resist was kept as part of the permanent structure for the relay. Cured SU-8 was used not only to serve as the electroplating mold for the magnetic core, but also as the insulator between the core and solenoid that was used to drive the device.
The relay base cross section spliced and imaged in Figure 6-5 shows a 1350 µm tall relay base with a maximum aspect ratio of 27:1. It can be seen that the micro-patterns for both the cylindrical magnetic flux path (to hold the coil) and the magnetic core were designed in such a way that the exposed SU-8 resist does not need to be stripped and is kept as part of the overall structure after the electroplating process is completed. The 50 µm SU-8 intermediate insulation layer patterned around the base of the relay’s core post is revealed in Figure 6-5. The flat pad with a circular tip in the lower left corner of the SEM image is the first electroplated nickel layer. This pattern was used to plate one of the four nickel cylinders surrounding the magnetic cup and used to support the Ni-Fe spring mass. Figures 6-6 and 6-7 are images of a plated relay base after the cylinders were polished down to a height of 1000 µm. The insulation layer prevented plating inside the magnetic cup and allowed for easy insertion of a wrapped solenoid for electromagnetic actuation. After polishing, a thin film of copper or gold was plated onto the nickel patterns to enhance the bonding process and improve the electrical contact resistance.

Figure 6-8 is a photograph of a 30 turn solenoid wrapped using 46 gauge insulated copper wire. A stickpin was placed next to the coil to demonstrate size. After wrapping, the solenoid was bound using adhesive and placed into the magnetic cup on the relay base. The wire leads of the coil were placed into the patterned slots on either side of the magnetic cup. They were then soldered to the square nickel post shown in Figure 6-7. This allows for larger interconnects between the relay and an external driving source. Placement of the solenoid represents the completion of the relay base. It can then be used to create local magnetic fields for electromagnetic actuation of any magnetic material.
Figure 6-5  SEM image of relay base cross section

Figure 6-6  Photograph of the relay base
Figure 6-7  SEM image of electroplated relay base

Figure 6-8  Micro-coil is wound around pin
6.3. Patterning of the Plunger

A second silicon wafer was deposited with 300 Å of titanium for adhesion to silicon followed by 5000 Å of copper. The substrate was coated and exposed to produce 20 µm thick patterns of SPR positive photoresist in a two spin process described in Table 6-3. The process can be repeated to make two-layer Ni-Fe patterns, if there is no exposure to white light during the electroplating process. The plunger substrate was cleaned by a 10 second rinse in 3% HCl followed by immersion in C-12 Activator for approximately 5 minutes prior to plating. A Ni-Fe alloy was then deposited into the plunger pattern at -1.25 V for 15 to 25 min using the electroplating bath described in Table 4-2. Ten to 17 microns of the alloy were deposited with less than a 1 µm deviation in all the patterns across 3 inches of the substrate.

After plating, the resist was stripped using acetone to reveal the copper-plating base across the wafer. Figure 6-10 shows a plated Ni-Fe plunger on a resist stripped substrate. The plungers were released in 4 hours using concentrated ammonium hydroxide and hydrogen peroxide.

<table>
<thead>
<tr>
<th>Table 6-3</th>
<th>20 µm SPR 220 resist process</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wafer Descumb</td>
<td>O₂ Plasma/ 2min</td>
</tr>
<tr>
<td>First SPR 220 Spin Coat</td>
<td>3000 rpm for 30sec</td>
</tr>
<tr>
<td>Prebake</td>
<td>96 °C in Oven for 90 sec</td>
</tr>
<tr>
<td>Second SPR 220 Spin Coat</td>
<td>2000 rpm for 30 s</td>
</tr>
<tr>
<td>Prebake</td>
<td>96 °C in Oven for 90 sec</td>
</tr>
<tr>
<td>Stress Relaxation</td>
<td>115 °C on Hotplate for 2 min</td>
</tr>
<tr>
<td>Exposure</td>
<td>550 mJ/cm² (600 mJ/cm² on Silicon)</td>
</tr>
<tr>
<td>Stress Relaxation</td>
<td>1 Hour at Room Temperature</td>
</tr>
<tr>
<td>Developer/ Rinse</td>
<td>OCG 365/ DI H₂O</td>
</tr>
</tbody>
</table>
The power relay design required the actuation of a thin magnetic spring mass. To make the spring mass, a flat Ni-Fe spring was also successfully fabricated using a single layer resist on a silicon substrate and then under-etching a thick plating base or stripping an exposed negative resist base. Iron content in the Ni-Fe alloy plated under different bath conditions has been tested with XEDS to contain between 15 and 40 \%.

**Figure 6-9**  Plunger pattern

**Figure 6-10**  Sidewall of electroplated Ni-Fe plunger with Ni-Fe supporting ring prior to release from the substrate
6.4. Device Assembly

The spring mass was then bonded to the top of the completed relay base. The bonding process can be performed using either a conductive paste or epoxy resin. The final gap distance between the plunger and the core post will have to be evaluated experimentally after bonding of the plunger to the outer post of the relay. The optimum gap distance, $x_{gap}$, will be determined both theoretically and experimentally.

Figure 6-11 shows a photograph of the relay that has been assembled. The prototype relay is currently being tested in our lab for response time and current capacity. Different spring geometries are being evaluated to produce a relay with the optimum desired response.

![Photograph of the assembled prototype electromagnetic relay](image)

**Figure 6-11** Photograph of the assembled prototype electromagnetic relay
CHAPTER 7: EXPERIMENTAL TEST AND RESULTS

7.1. Tests on the Electromagnetic Actuator

Ideally the relay would be assembled using the patterned base described in the previous chapter, a machine wrapped coil, and a magnetic spring that is attached using a flip-chip bonding process. The wafer would be diced with a diamond saw. Electrical leads would be attached using a wire bonder and the chip would be packaged in an 8-pin assembly similar to those used for operational amplifiers. However, none of this was required to test the prototype relay because the purpose of the test in this work to is to prove the feasibility of the prototype relays and fabrication technology.

A hand-wrapped coil was manually inserted into the magnetic cup of a prototype relay. Many high quality machine wrapped coils are commercially available. However, hand-wrapped coils were good enough for the preliminary testing of the electromagnetic relay. For the experiment, a 50 turn coil of 46 gauge copper wire was wrapped and inserted around the core post of the relay base. The total wire resistance of the coil was measured at 3.8 Ohms. Large copper leads were attached and the coil was connected to the circuit pictured in Figure 7-1. A 10 watt, 98 Ohm resistor was placed in series with the inductor coil to limit the maximum current when a controlled voltage was supplied. The leads were connected to a constant voltage source. Current was measured in series.

Test results presented showed that the coil was capable of carrying a 100 mA current for periods of more than 5 minutes without overheating. However, after passing currents greater than 80 mA for periods longer than a few seconds, the nickel core post began magnetizing.
Magnetic field measurements were performed using a Lakeshore 420 Gaussmeter. The sensor placed within approximately 100 µm of the surface of core post. The meter recorded values between 3 and 14 Gauss while passing 50 mA through the coil. The predicted value for the magnetic field generated in the magnetic core using the dynamic model was 20 Gauss. Error in the measurement is caused by divergence of the magnetic field as it leaves the surface of the nickel core.

Next, an AC driving circuit was developed and tested using a voltage-controlled current source (VCCS). Figure 7-2 shows the schematic diagram required to produce the VCCS inverse circuit for floating loads. The input voltage signal was generated using a Wavetek 10 MHz DDS Function Generator model 29. The VCCS circuit used an APEX PA02 wideband power amplifier capable of producing current signals of 5 A up to frequencies of 350 KHz. The circuit produced a -20/+70 mA AC driving current under a 10 V AC applied load with a 5 V DC bias. A square wave was used to produce a step-like response. Various driving frequencies were tested, ranging from 0.01 – 900 KHz. The circuit and coil both operated properly within the frequency range with little or no phase delay or significant changes of gain.

**Figure 7-1**  DC test circuit.
7.2. Assembly and Test for Maximum Switching Current

In order to determine the true response characteristics of the device, a second relay was constructed using nickel acetate to paste electrical leads onto the spring-mass and core post. A new solenoid was soldered to external wiring for device testing. Electrical leads between the nickel core and the external circuit were measured to have a resistance of 4.2 Ohms. Likewise, electrical leads to the plunger had a resistance of 4.6 Ohms. The minimum contact resistance recorded through these connections was 8.8 Ohms. For this test an 86Ni/14Fe spring was used. The spring consisted of a 17 μm thick 50 μm wide line bent at right angles and looped inwardly toward the plunger.

The relay was tested to determine the maximum allowable switching current. A DC constant current power supply was placed in series with a 10, Watt 98.1 Ohm resistor and the open relay connection. After closing the relay, the power supply was turned on

\[ i_0 = -\left(\frac{V_a}{R_s}\right)\left(\frac{R_f}{R_i}\right) \quad \text{For } R_s \ll R_f \text{ or } R_i \]

**Figure 7-2** VCCS for floating load; Inverting configuration
and ramped from 4.5 to 23.5 Volts in 0.5 V increments. The current driven through the relay was raised and lowered incrementally between 38 and 215 mA three times over several minutes. After careful measurement, the voltage was raised incrementally again in 1 Volt increments to 36.5 V at which time the current was measured to be 329 mA with good stability. Upon increasing the voltage to 37.5 V, the resistance dropped sharply and resistive heating annealed the Ni-Fe spring. The voltage was reduced to 8.3 Volts and a second burnout test was performed. In the second test, the preheated nickel acetate connection burned out at 18.5 V with a maximum stable switching current of 141 mA. Figures 7-3 and 7-4 show the IV curve for the two burnout tests and a picture of the spring-mass attached to the relay after testing was completed.

7.3. Dynamic Response Test

A prototype relay was assembled using a 17 µm thick curved spiral spring. A 50 turn coil was inserted into the magnetic cup and soldered to external leads to complete the driving circuit. Electrical leads were glued to the outer contacts of the relay base using nickel acetate. A 17 µm thick curved spiral spring was bonded to the top of the relay base. Compressive stress in the spring produced a 15 µm initial gap between the plunger and the core post. The prototype relay was actuated using both the DC and AC driving methods as previously described. The dynamic response test was carried out by increasing the frequency of the inductor circuit while monitoring an applied potential of 8.9 V across the switch. To reduce the switching current during the test, a 10 KΩ resistor was placed in series with the switch. Figures 7-5 a) and b) show the response of the relay driven at 50 and 500 Hz using the AC using presented in Figure 7-2.

From the response curves shown in Figures 7-5 a) and b), it can be observed that the front end of the waveforms is always much sharper than the tail-end. The main
Figure 7-3  IV curve for switching current capacity

Figure 7-4  Assembled relay with 86Ni/14Fe after burnout test
reason for this behavior is that the system is limited by the dynamics of the mechanical spring and not by the electrical circuit. When the spring suspended plunger was pulled down, the softer the spring is, the faster the response. However, the restoration of the plunger to the open-position is controlled by the sprung force which is the direct effect of the spring stiffness, therefore it is much slower than the pull-down motion. As soon as the relay starts to disconnect, an equivalent capacitance, \( C(x) \), is formed between the suspended plunger and top surface of the magnetic core. As this air gap increases, the equivalent capacitance, \( C(x) \), decreases. It is this capacitance that contributed to the tail-off curved as observed in Figures 7-5 (a) and (b).

The experimental results showed that after the relay was driven at frequency above 500 Hz, the relay could not operate reliably. Occasional switching was observed at frequencies above 2 KHz, but not continuously. The results are primarily determined by the natural frequency of the plunger.

7.4. Conclusions

Relays were assembled and basic tests were performed to demonstrate the device. The switch was capable of passing electromagnet driving currents over 100 mA and switching currents up to 325 mA for particular spring designs. Closed switches were demonstrated in 10 W electrical switching circuits. The dynamic response of the prototype relay demonstrated a stable operation bandwidth of 500 Hz with an 8.9 V DC bias across a spiral shaped flat spring plunger. The release of relay showed capacitive driving effects as can be observed from the response curves shown in Figure 7-5. This seems to be caused by the equivalent capacitance between the top plunger and the core post of the magnetic cup. It was also observed that the dynamic response of the spring-mass of the plunger that limited the maximum bandwidth of the relay.
Figure 7-5  Dynamic response for a micro-relay driven at:  a) 50 Hz b) 500Hz
CHAPTER 8: CONCLUSIONS AND FUTURE RESEARCH

8.1. Project Discussion

Most micro-sized switches (micro-relays) currently on the market or reported in the literature are solid-state devices made using semiconductor technology, with silicon the predominant material. Such devices typically have low current capacity, low off-resistance, significant on-resistance, significant power consumption, and low dielectric strength. In recent years, the fast-evolving technology of microelectromechanical systems (MEMS) has opened up new opportunities for microfabricating microelectromechanical switches. However, most of the MEMS relays based on silicon fabrication cannot be used for power applications. The objectives of the research work presented in this dissertation were to design, model, fabricate, and test an electromagnetic micro-relay for power applications. To achieve these objectives, the following research tasks were completed:

• Mathematical model was developed for the prototype design of the electromagnetic micro-relays. Various designs of the suspension springs were compared based on both numerical analysis of the equivalent spring stiffness. The spring was designed to achieve large current capacity and still to be soft enough to be pulled down with low electromagnetic force. The mathematical model of the relay was developed to simulate the performances of the prototype relays for optimal designs. Another design consideration of the prototype relays was to easy to be fabricated. The prototype devices were fabricated using multilayer UV-LIGA technology. The technology used multiple layers of SU-8 and electroplated metal. A mechanically wrapped solenoid insert was used to provide the driving mechanism for the actuator. The solenoid can be wrapped up to 4 layers thick and as tall as 1500 mm. Because the relays are based on very thick metal
pads for conducting current, they expected to have the high power capacity, high off-
resistance, lower on-resistance, low power consumption and low heat generation. This
provides sufficient flexibility to use the electromagnetic driver for a wide variety of
switching applications as well as other devices such as sensors and magnetic positioning
devices.

- The LIGA technology based on X-ray lithography of PMMA has the
disadvantages of higher cost and longer exposure time. Although molding processes can
be adopted to overcome these disadvantages, the technology is not very suitable for the
multi-layer fabrication process required for this particular design of electromagnetic
relays. In recent years, a relatively new type of negative photoresist, EPON SU-8,
received a lot attention in MEMS field because of its excellent lithography properties.
Significant research efforts have been made to obtain high aspect ratio SU-8
microstructures with good sidewall quality. Currently, selection of optimal wavelengths
of the UV light for lithography and reduction of the diffraction effects are believed to be
the two most important factors for achieving high quality lithography of SU-8 as reported
in literature. Other reported efforts also include modifications of the chemical properties
of SU-8 for better lithography quality. Research proved that aspect-ratios up to 40:1 in
isolated open field structures of thickness between 1 and 1.5 mm can be obtained without
any modifications of the resist chemistry or changes in light spectrum applied from a
standard broadband UV source. The principal factor in this achievement is the reduction
of internal stress during the post-exposure bake process, which eliminates large plastic
deformations present during standard bake procedures. This process may be used for the
fabrication of ultra-thick high aspect-ratio microstructures that to date, have only been
obtainable using X-ray lithography based LIGA process.
One of the challenging issues in SU-8 lithography is to fully develop narrow grooves and deep micro-sized holes. Megasonic agitation to the developer bath used for SU-8 has been shown to greatly improve the quality and aspect ratio of structures produced by optical lithography. This technique has produced some of the highest aspect ratio structures ever documented in optical lithography. It has also yielded faster and more uniform development of complex patterns that would otherwise be extremely difficult to produce.

The combined use of baking, and megasonic development procedures presented in this dissertation as well as the proper use exposure wavelength and diffraction control may indeed allow for the production of 1 mm tall 100:1 aspect ratio microstructures with good sidewall quality in the very near future. Production of such structures with standard optical lithography equipment would allow companies and researchers that may not wish to invest in synchrotron radiation to invest heavily in the LIGA technique.

Cross-linked SU-8 polymer is well known to be extremely difficult to remove in the microfabrication community. In the multi-layer processing technique developed for the fabrication of the prototype relay, a unique design approach was taken to utilize cross-linked SU-8 as part of the final structures in the prototype devices. Incorporating cross-linked SU-8 polymer into the relay design offered three significant advantages. First, polymerized SU-8 made a good insulator for the metal leads in the device. Second, multiple layers of exposed SU-8 were used to selectively electroplate nickel into certain lithographically patterned structures without electroplating onto insulated metal structures. Finally, making use of exposed SU-8 in the design removed the need stripping the resist.
• Though the main focus in this dissertation is material science, some study on the fatigue property of the electroplated Ni/Fe alloy was also conducted because Ni/Fe is the primary material used in the prototype relay and fatigue is expected to be one of the main reasons of relay failure. A model was developed to evaluate the primary fracture mechanics characteristics and fatigue properties of electroplated Ni and Ni-20%Fe alloys whose elastic strain curves had been previously published in the literature. The model uses a few material dependent constants and the ratio of the yield strength of bulk metal to that of electroplated metal to predict the failure of electroplated metal microstructures. Although the focus of the work has been to derive the properties of nickel and nickel-iron systems, the approach is not limited to any particular type of metal and may be applied to a wide variety of materials with grain sizes up to a couple of microns produced by a wide variety of techniques. The model does not account for the high cycle fatigue limit observed in many nickel alloys.

• A very simple experimental set-up was built to check the functionality and dynamic behavior of the prototype relays. The particular prototype relay tested was found to have at operating frequencies up to 500 Hz using a spiral flat spring design. The contact resistance, as expected, was nominal. The current limit of the prototype relay was measured to be approximately 330 mA at an applied voltage of 36.5 V. The relay is therefore capable of operating in a 10 Watt power circuit with a power loss no greater than 8% across the switch. The current capacity of the relay can be modified by increasing the thickness of the suspension spring. Of course, a compromise always needs to be made because increased thickness of the suspension spring may also require increased driving current or an increase in the number of turns in the driving coil.
8.2. Future Areas of Research

The research presented has introduced five new topics for study:

- Further development of the optical lithography process should be performed to improve the pattern quality for the production of viable plastic and metallic micro-parts with aspect ratios up to and above 100:1. Continued research in this effort may produce a rival to traditional X-ray based LIGA processing in industrial laboratories for most of the applications in the MEMS field.

- More research into the use of megasonic actuation to enhance mixing in both the developer and electroplating baths will help to overcome current device patterning and plating limitations. Unlike ultrasonic agitation which often causes mechanical failure of micro-patterned resist structures, the proper use of megasonic actuation does not lead to pattern deterioration. Further optimization of megasonic actuation will improve developed pattern quality, increase the ability to electroplate metals into ultra-high aspect ratio patterns, and possibly allow for directional development of microstructures exposed at multiple angles. Research in this subject would always require better understanding and a valid mathematical model for the agitation process in micro-groves and holes.

- Fracture toughness and fatigue tests for electroplated LIGA microstructures should be developed and performed to validate the numerical model presented in this dissertation. Provided that the model holds, both the model and the tests should be expanded to assemble data on all of the electroplated metal systems produced using this technology. This will provide an invaluable source of information to design engineers looking to develop future LIGA based MEMS.
• Further study can be performed to modify the performance of the micro-relay presented in this dissertation using control theory. Proper control of the driving and switching signals may improve device performance and lead to more advanced studies in the contact performance or spark erosion in microsystem technologies. Recently NSF initiated a special forum to focus on the micro and nano-control issues in MEMS and nanosystems. Research in this control of micro- and nanosystems may have a significant impact on the performance of existing and future devices.

• The device can also be analyzed to determine the appropriate sensing parameters and compare them to the numerical simulations derived in Chapter 2. Using the device as a sensor or high frequency capacitive varactor may offer as many product applications as the relay mode of operation.
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VITA

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