Copyright

by

Anh Quoc Nguyen

2001
Asymmetric Fluid-Structure Dynamics in Nanoscale Imprint Lithography

by

Anh Quoc Nguyen, B.S.

Thesis

Presented to the Faculty of the Graduate School of The University of Texas at Austin in Partial Fulfillment of the Requirements for the Degree of

Master of Science in Engineering

The University of Texas at Austin
August 2001
Asymmetric Fluid-Structure

Dynamics in Nanoscale Imprint Lithography

Approved by

Supervising Committee:

____________________________________

S. V. Sreenivasan

____________________________________

Ofodike A. Ezekoye
Dedication

To God,

my parents,
Ban Van Nguyen (deceased) & Mai Thi Dinh,

and my fiancée,

Mengjing Huan,

who has enriched my life.
Acknowledgements

First of all, I would to thank my research supervisor, Associate Professor S. V. Sreenivasan, for his guidance and support throughout the course of my graduate research career. Without his help, much of this work would not be possible. I would also like to thank Associate Professor Ofodike Ezekoye for taking on the challenge of advising a student outside of the Thermal-Fluids area and sharing his knowledge of the fluid mechanics discipline. I appreciate help from Professor Roger Bonnecaze who helped to enlighten me on issues in analytical modeling of the Reynolds equation. I owe a debt of gratitude to Professor Scott Collis at Rice University, who convinced me to attend graduate school. Special appreciation goes to Dr. Byung Jin Choi, from whom I learned many new and magical tricks in programming, theoretical analysis, mechanical design, and experimentation. Dr. Choi was always willing to lend his experience and advice, while being patient as I climbed the learning curves. From questions regarding LabVIEW™, to designing a part for my experiments, to debugging hardware issues, he was there to struggle with me when tasks seemed impossible and helped to make them trivial. In addition, I would like to express my appreciation for Matt Colburn who was integral in developing a gap-sensing tool for use in my experiments. My gratitude goes to ‘Super’ Mario Meissl, who helped me learn Pro/ENGINEER® and gave me insight into my design issues. Finally, I am grateful to DARPA for their financial support during this past year.

August 2001
Asymmetric Fluid-Structure Dynamics in Nanoscale Imprint Lithography

by

Anh Quoc Nguyen, M.S.E.
The University of Texas at Austin, 2001

Supervisor: S.V. Sreenivasan

This thesis investigates the effect of the fluid mechanics of a low viscosity, UV curable liquid film on the system dynamics of an imprinting system used in a patterning process known as Step and Flash Imprint Lithography (SFIL). SFIL is a novel, low-cost, high-throughput alternative approach to patterning nanoscale features for semiconductor applications. This research is essential to the practical development of the SFIL process and is applicable to the development of a real-time control scheme for SFIL.

The thesis starts with an introduction to optical lithography, established next generation lithography (NGL) research efforts, and SFIL. A theoretical analysis of the template-fluid-wafer (TFW) system shows that the imprinting pressures are proportional to the approach velocity of the template towards the wafer and the inverse of the cube of the film thickness, \( h^3 \). Analytic solutions to the pressure distribution due to the etch barrier fluid are applied to numerical simulations, which are benchmarked by experiments using an active stage prototype. The development of an active stage prototype is detailed and a real-time gap sensing system for sub-micron films based on the FFT of spectral reflectivity is discussed. The experiments and simulation show that the TFW system is overdamped. An asymmetric squeeze film pressure distribution provides a corrective torque in the presence of orientation misalignments.
Table of Contents

List of Tables ........................................................................................................... x
List of Figures ......................................................................................................... xi

Chapter 1: Background and Motivation ............................................................... 1
  1.1 INTRODUCTION ........................................................................................ 1
  1.2 OPTICAL LITHOGRAPHY ........................................................................ 3
    1.2.1 Optical Lithography Process Overview ........................................... 4
    1.2.2 Limitations of Optical Lithography ............................................... 5
  1.3 STEP AND FLASH IMPRINT LITHOGRAPHY .......................................... 8
    1.3.1 Step and Flash Imprint Lithography Process Overview ............... 8
    1.3.2 Challenges to Step and Flash Imprint Lithography .................. 11
  1.4 THESIS ................................................................................................... 15

Chapter 2: Theoretical Analysis ......................................................................... 17
  2.1 INTRODUCTION ...................................................................................... 17
  2.2 THE INCOMPRESSIBLE REYNOLDS EQUATION .................................... 20
  2.3 THE TWO-DIMENSIONAL REYNOLDS EQUATION ............................... 26
    2.3.1 Derivation of the Two-Dimensional Reynolds Equation .......... 26
    2.3.2 Squeeze Film Due to a Parallel Surface of Infinite Width .......... 28
    2.3.3 Squeeze Film Due to an Inclined Surface of Infinite Width ........ 29
  2.4 THREE-DIMENSIONAL PROBLEM ......................................................... 35
    2.4.1 3D Pressure Distribution for Parallel, Rectangular Plates .......... 35
    2.4.2 3D Pressure Distribution for Parallel, Circular Plates ............... 38
  2.5 TOPOGRAPHY EFFECTS ......................................................................... 39

Chapter 3: Active Stage Design ....................................................................... 41
  3.1 OPTIMIZING BASE LAYER THICKNESS, ORIENTATION ALIGNMENT, AND
       THROUGHPUT ............................................................................................ 41
3.2 ACTIVE STAGE COMPONENTS ................................................................. 42

3.2.1 Wafer Stage Assembly ................................................................. 43

3.2.2 Template Orientation Stages ......................................................... 44

3.2.3 High-Resolution Actuation System .............................................. 46

3.2.4 Force Sensing System ................................................................. 49

3.3 IMPLEMENTED DESIGN ..................................................................... 49

Chapter 4: Real-Time Gap Sensing Via Fast Fourier Transforms of Spectral
Reflectivity .......................................................................................... 52

4.1 INTRODUCTION .................................................................................. 52

4.2 ANALYSIS OF SPECTRAL REFLECTIVITY ........................................... 53

Chapter 5: Numerical Simulations .......................................................... 59

5.1 DYNAMIC SYSTEM MODEL ............................................................. 59

5.2 SYSTEM PARAMETERS FOR NUMERICAL SIMULATION ................. 61

5.2.1 Etch Barrier Fluid Properties ..................................................... 61

5.2.2 Composite Stiffness and Damping Coefficients ......................... 62

5.3 NUMERICAL METHOD ..................................................................... 66

5.3.1 Fourth Order Accurate Runge-Kutta with Adaptive Time Step ... 66

5.3.2 Modeling the Initial Conditions for an Imprint............................ 68

5.4 SQUEEZE FILM DYNAMICS OF INCLINED SURFACE OF INFINITE WIDTH 70

5.4.1 Single S-Curve Motion Profile .................................................. 70

5.4.2 Double S-Curve Motion Profile .................................................. 72

5.5 SQUEEZE FILM DYNAMICS OF PARALLEL, CIRCULAR PLATES ....... 75

Chapter 6: Experimental Results ............................................................ 77

6.1 INTRODUCTION .................................................................................. 77

6.2 EXPERIMENTAL SETUP .................................................................... 77

6.2.1 Experimental Adaptations of the Active Stage Test Bed ............ 77

6.2.2 Data Acquisition Hardware ......................................................... 79
Chapter 7: Closing Remarks

7.1 SUMMARY OF RESEARCH

7.2 FUTURE WORK

7.2.1 Numerical Solution to the Generalized Reynolds Equation

7.2.2 Distributed parameter model of the mechanical system

7.2.3 Measurements with Patterned Templates

Appendix A: Axisymmetric Problem

Appendix B: Design of Semi-Circular Notched Flexures

References

Vita
List of Tables

Table 2.1 Time required to reach desired base layer thickness with constant force application for the case of a flat, square template ........................................38
Table 5.1 Mechanical system stiffness values ......................................................65
Table 5.2 Simulation Parameters Reflecting Experimental Setup .......................69
Table 6.1 PIDL parameters, recommended and actual settings for the C-842.....83
Table 6.2 Parameters passed to the C-842 onboard s-curve profile generator .....83
List of Figures

Figure 1.1 Optical microlithography process .......................................................... 5
Figure 1.2 Step and flash imprint lithography process ........................................ 10
Figure 1.3 Ratio of line height to base layer thickness ..................................... 12
Figure 1.4 Base layer types .............................................................................. 13
Figure 2.1 Continuity of flow in an infinitesimal fluid element ...................... 22
Figure 2.2 Force equilibrium of an infinitesimal fluid element .................... 24
Figure 2.3 Two flats showing orientation alignments ...................................... 27
Figure 2.4 Parallel-surface squeeze film flow ................................................. 28
Figure 2.5 Inclined-surface squeeze film flow ................................................. 30
Figure 2.6 Two-dimensional pressure distribution ......................................... 34
Figure 2.7 Gap height as a function of time for a flat, square template .......... 37
Figure 2.8 Idealized template topography ..................................................... 40
Figure 3.1 Wafer stage assembly .................................................................. 44
Figure 3.2 Motion requirement for template orientation .................................. 44
Figure 3.3 Multi-imprint α-β template orientation stages ............................. 45
Figure 3.4 One degree-of-freedom template orientation stage ...................... 45
Figure 3.5 Actuation leg .............................................................................. 47
Figure 3.6 Distributed flexure ring ................................................................. 47
Figure 3.7 Initial and final desired orientation with three-point control .......... 48
Figure 3.8 Active stage prototype, side view ............................................... 50
Figure 4.1 Interference effect ....................................................................... 55
Figure 4.2 Normalized intensity of a 500 nm film as a function of wavelength.. 56
Figure 4.3 Normalized intensity of a 500 nm film as a function of wavenumber 57
Figure 4.4 PSD of theoretical reflectivity signal with a 500 nm thickness ....... 58
Figure 5.1 Lumped Parameter Model ............................................................. 60
Figure 5.2 Stiffness in the $z$ direction of the active stage system.........................62
Figure 5.3 Model of actuator for stiffness computation........................................63
Figure 5.4 Fixed-fixed beam..................................................................................63
Figure 5.5 Ideal s-curve (solid line) and actual encoder data (squares)..............66
Figure 5.6 Simulated single s-curve actuator motion profile...............................70
Figure 5.7 Base layer thickness corresponding to single s-curve actuation........71
Figure 5.8 Force corresponding to single s-curve actuation ................................72
Figure 5.9 Simulated double s-curve actuator motion profile...............................73
Figure 5.10 Base layer thickness corresponding to double s-curve actuation ....74
Figure 5.11 Force corresponding to double s-curve actuation ..............................74
Figure 5.12 Base layer thickness corresponding to the case of finite, parallel
circular plates ..................................................................................................75
Figure 5.13 Force corresponding to the case of finite, parallel circular plates ... 76
Figure 6.1 Chromium-Plated Quartz Substrate Fixture .......................................78
Figure 6.2 Physical layout of the experimental setup.............................................80
Figure 6.3 Screenshot of control software to perform experiments.....................82
Figure 6.4 Average film thicknesses from simulation results (solid line) and
experimental results (circles).  Calibration set...............................................86
Figure 6.5 Angle of inclination from simulation results (solid line) and
experimental results (circles).  Calibration set...............................................87
Figure 6.6 Force due to fluid pressure from simulation results (solid line) and
experimental results (circles).  Calibration set...............................................87
Figure 6.7 Average film thicknesses from simulation results (solid line) and
experimental results (circles).  Correlation set..............................................88
Figure 6.8 Angle of inclination from simulation results (solid line) and
experimental results (circles).  Correlation set..............................................89
Figure 6.9 Force due to fluid pressure from simulation results (solid line) and experimental results (circles). Correlation set.......................................................... 89

Figure 6.10 Film thickness during squeezing with *six* microns of downward actuation. Spectrometer probe 1 (circles) and probe 2 (squares)....................... 91

Figure 6.11 Film thickness during squeezing with *five* micron of downward actuation. Spectrometer probe 1 (circles) and probe 2 (squares)............... 92

Figure 6.12 Film thickness during squeezing with *five* microns of downward actuation. Spectrometer probe 1 (circles) and probe 2 (squares)............... 93

Figure 6.13 Force due to fluid pressure from experimental results for varying values of average approach velocity............................................................. 93

Figure 6.14 FFT of the intensity of the reflectivity data (a) $2^{13}$-point FFT (b) $2^{14}$-point FFT ........................................................................................................ 97

Figure 6.15 False signal masking the true signal in FFT ........................................... 98

Figure 7.1 Recessed depth to aide in gap sensing with pattern templates ....... 101

Figure B.1 Semi-circular notch flexure hinge............................................................. 105
Chapter 1: Background and Motivation

Semiconductor materials such as silicon, GaAs, and SiGe are the fundamental building blocks for microelectronic chips, which make possible the Internet and electronic commerce, telecommunications, computers, consumer electronics, industrial automation and control systems, and analytical and defense systems. A critical unit process associated with the manufacture of semiconductor chips is patterning using photolithography. This research addresses a low-cost, high-throughput alternative to photolithography in the sub-100 nm regime.

1.1 Introduction

The recent decades have experienced an inundation of technological innovations in the fields of computing and microelectronics. This progress has been brought about by the ability to replicate increasingly higher resolution circuit patterns on semiconductor wafers. Smaller patterns allow semiconductor manufacturers to produce more densely packed circuits that operate at faster speeds, and to place more circuits onto a single wafer, thus decreasing manufacturing costs. The industry standard process for pattern generation has historically been optical microlithography (or simply optical lithography). Advances in optical lithography have made it possible to allow high-throughput manufacture of circuits with feature sizes as small as 130 nm. However, it is believed that the current progression in optical methods is approaching limits, which will lead to prohibitive costs in capital equipment for marginal improvements in technology for microelectronics manufacturers.
The exponential escalation in the cost of the optical lithography equipment has been the driving force behind research efforts to develop next generation lithography technologies.1 Traditional NGL techniques include extreme ultraviolet (EUV) lithography [Stulen and Sweeney 1999] and 157nm lithography [Miller et al. 2000]. Among some of the non-traditional alternative approaches to optical lithography currently being researched is a class of pattern transfer technologies known as imprint lithography. These processes can be thought of as micro-molding processes because the topographical features of a template or mold are generally used to mechanically transfer defined patterns onto a substrate material.

This chapter will develop the motivation for the exploration of new pattern generation technologies by providing a background of the optical lithography process and enumerating some of its limitations. Then a description of Step and Flash Imprint Lithography, a technology currently being developed by researchers at The University of Texas at Austin in a collaborative effort between the Departments of Mechanical Engineering (Principal Investigator: Dr. S. V. Sreenivasan) and Chemical Engineering (Principal Investigators: Dr. C. G. Willson and Dr. J. E. Ekerdt), will be given. The researchers developing the SFIL process face several important challenges in order to make SFIL a manufacturing technology. The last part of this chapter will introduce one of these challenges: the fluid mechanics of the etch barrier layer – a low viscosity, UV curable liquid film – and its effect in achieving parallel alignment of the template and wafer substrate with a minimum base layer thickness. A clearer

1 See Figure 4 page 77 of Lithography Cost of Ownership Analysis Revision Number 4.0 at www.sematech.org/public/resources/coo/index.htm
understanding of the interaction between the fluid-solid interface will be essential for the practical development of the SFIL process.

1.2 Optical Lithography

Historically, the manufacture of microelectronic devices has utilized optical lithography. The processing technologies have evolved over the past four decades, moving from 20 μm to 130 nm minimum feature sizes, and are well established in the semiconductor industry. Thus far, the progress in optical lithography has been made primarily through the exploitation of shorter wavelength exposing sources. These have included lines from the emission spectrum of different light sources: the g-line (mercury-xenon arc lamp, $\lambda \approx 436$ nm), the i-line (mercury-xenon, $\lambda \approx 365$ nm), and deep ultraviolet (krypton-fluoride excimer laser, DUV, $\lambda \approx 248$ nm), etc. Electron beam exposure systems have been successfully used in specialized applications to pattern micro and nanoscale features while x-ray ($\lambda \sim 1$ nm) and ion beam exposure systems have demonstrated fine feature capability. However, each of these approaches have proved inferior to optical lithography since they have either lower throughput, higher mask complexity and costs, higher tools costs, etc.

The basic scheme of optical lithography is to replicate two-dimensional patterns from a master pattern on a durable photomask, typically made of a thin patterned layer of chromium on a quartz plate [Sheats and Smith 1998]. The patterns are developed on semiconductor wafer substrates using photosensitive resist material, complex projection optics systems, and chemical etch/deposition processes. The next section gives a brief summary of the optical lithography process. Then, some of the limitations of optical lithography are discussed.
1.2.1 Optical Lithography Process Overview

The initial step is to have a semiconductor wafer spin-coated and baked with an imaging layer of photoresist. The photoresist acts as a layer of photosensitive organic polymers that is selectively exposed through an aerial image of the photomask. The solubility of the photoresist is increased (positive resist) or decreased (negative resist) upon exposure to the illumination source. Rinsing the wafer in a developer solution selectively dissolves the photoresist while the circuit pattern remains on the semiconductor wafer.

Central to the image transfer process in optical lithography is the exposure system comprised of a lithographic lens, an illumination source, and a wafer positioning system. The lithographic lens is a large compound lens comprised of 10 to 20 simple lens elements. The lens systems of today are designed to produce a typical demagnification factor of 4×. The illumination source is typically a high-pressure mercury-xenon arc lamp with undesired wavelengths removed with multi-layer dielectric filters. The remaining narrow-band light, with less than 0.003 nm spectral width, is sent through a series of relay optics and uniformizing optics and is then projected through the photomask and lithographic lens [Sheats and Smith 1998]. Figure 1.1 illustrates the optical lithography process.

The circuit pattern on the quartz plate, written by electron beam lithography, contains the master pattern at four times the size of the imaged pattern. The imaged is reduced in size through the lithographic lens and the imaging layer is exposed. The solubility of the photoresist is altered by this radiation. The wafer is then rinsed in a developing solution to remove the high-contrast soluble resist. The remaining resist pattern will serve as a mask for processes such as metal deposition, epitaxial growth, and ion implantation [Choi, Johnson, and Sreenivasan 1999].
Step 1: Spin-coat wafer with photoresist

Step 2: Expose imaging layer through photomask and projection optics

Step 3: Develop photoresist

Figure 1.1 Optical microlithography process

1.2.2 Limitations of Optical Lithography

The International Technology Roadmap for Semiconductors forecasts the volume manufacture of integrated circuits at the sub-100 nm level within seven to eight years. Since today’s optical lithography steppers are fundamentally diffraction limited, however, there has been a lot of effort in designing systems that minimize the effect of wave diffraction. In order to produce the circuit
patterns to the desired specifications, the design of the lens system has very tight tolerances, which can cause the equipment costs to quickly escalate.

The resolution limit of an optical projection system is governed by the Rayleigh formula. This states that the numerical aperture of the lens, the wavelength of light, and the chemical development process determine the minimum line width that a stepper can print [Thompson, Willson, and Bowen 1994].

\[ L_W = \frac{k\lambda}{N_A} \]  \hspace{1cm} [1.1]

where \( L_W \) is the minimum printable line width (nm), \( N_A \) is the numerical aperture of the lens in the stepper, \( k \) is the factor describing the photoresist development process, and \( \lambda \) is the wavelength of the exposure source (nm).

The minimum printable line width can be reduced by 1) increasing the numerical aperture, 2) improving the processing of the resists, or 3) decreasing the wavelength of the source illumination. The design of lens systems has seen an increase in the \( N_A \) from 0.2 to about 0.73. The proportionality constant \( k \) is a dimensionless number, which is as low as 0.4 for complex multi-layer resist processes along with phase shift masking to 0.8 for standard resist processes. Each generation of microlithography technology has incrementally improved line resolution by incorporating these hardware and process enhancements along with reducing the wavelength of exposing source.

Many of today’s steppers use 248 nm DUV light and there is currently a move to 193 nm argon fluoride excimer laser systems with 157 nm systems in development. Exposure systems with even shorter wavelengths such as x-ray (\( \lambda \approx 1 \) nm) and extreme ultraviolet (EUV or soft x-ray, \( \lambda \approx 13 \) nm) are being
developed in efforts to reduce current line widths. X-ray and EUV offer an order of magnitude potential improvement in line widths.

While some of the processes currently in development have demonstrated the ability to resolve sub-100 nm features in the laboratory, there are technical and cost considerations that must be overcome to realize their potential benefits. These processes require optical exposure systems that are rare and expensive. Also, x-ray lithography requires a helium atmosphere and x-ray masks have stability problems. Furthermore, these processes have throughput problems. The effects of wave diffraction, interference, resist sensitivity, and standing wave effects limit these optical lithography techniques [Chou, Krauss, and Renstrom 1996]. Furthermore, there is the problem of resist transparency as materials that are transparent to DUV light are opaque to EUV and x-ray regions. With many of these issues unresolved, it is near certainty that optical methods will not be adequate for nanoscale (below 100 nm) lithography [Whidden et al. 1996].

High-energy particle lithography schemes such as electron beam (E-beam direct write/project) and ion beam lithography that have been used to produce high-resolution patterns, and is used to write and repair photomasks. However, for wafer processing, they have problems with cost and throughput. These systems operate serially and cannot maintain the level of throughput required for economic manufacture of circuits. Furthermore, there exist proximity effects due to elastic and inelastic particle collisions. These are referred to as forward scattering in the photoresist and backscattering from the substrate. These fundamental technical challenges and high cost clearly necessitate the search for low cost, high-throughput alternatives to optical lithography. SFIL is one such process that has demonstrated the generation of sub 100 nm features.
1.3 STEP AND FLASH IMPRINT LITHOGRAPHY

Step and Flash Imprint Lithography is an innovative, high-throughput, low cost alternative to optical lithography. SFIL can potentially generate circuit patterns with sub-100 nm line widths without the use of projection optics [Colburn et al. 1999] and features as small as 60 nm wide have been previously demonstrated [Choi, Johnson, and Sreenivasan 1999]. SFIL relies mainly on chemical and mechanical processes to transfer patterns from a quartz template to a silicon wafer substrate. The use of a low viscosity liquid etch barrier layer differentiates SFIL from other imprint lithography techniques. The following section provides an overview of the SFIL process. Then some of the current challenges faced by SFIL researchers are discussed. For references to other imprint processes under development, consult [Chou, Krauss, and Renstrom 1996], [Haisma et al. 1996], [Wang et al. 1997], and [Whidden et al. 1996].

1.3.1 Step and Flash Imprint Lithography Process Overview

SFIL is intended to be a reliable and reproducible method for transferring high-resolution patterns from a quartz template to a wafer substrate predominantly through chemical and mechanical processes. Optical elements include the quartz template and the UV exposing source. SFIL operates at room temperature and low pressures, as compared with the nanoimprint lithography process, which occurs at temperatures typically ranging from 140 to 180 °C, and pressures from 600 to 1900 psi [Chou, Krauss, and Renstrom 1996]. These temperature and pressure considerations make SFIL an attractive process as compared with other imprint techniques, especially to fulfill the requirements for
an overlay scheme in multi-layered circuits. High temperatures and pressure can lead to technical difficulties in accurate overlay for multi-layered circuits.

SFIL uses no projection optics and, as with other imprint processes, one could best describe SFIL as a micro-molding process. The traditional photomask has been replaced by a topographical template, which contains the circuit pattern generated by direct write E-beam lithography. The template acts as the master pattern for the etch barrier layer. The key difference between SFIL and other imprint lithography techniques is the use of the liquid etch barrier layer. The etch barrier layer is a low viscosity, photopolymerizable formulation containing organosilicon precursors [Colburn et al 1999]. This low viscosity eliminates the need for high temperatures and pressures to achieve the thin films desired for patterning. Figure 1.2 illustrates the SFIL process.

(Step 1) First, an organic transfer layer is spin-coated on a silicon wafer. This transfer layer adheres to both the silicon wafer and etch barrier layer and functions as a planarization layer during imprinting while providing high etch rate selectivity during the device etch step. (Step 2) Next, a quartz template bearing the relief image of the circuit is brought into proximity of the transfer layer and wafer. The template must be easily wetted by the etch barrier solution, and it must easily release the polymerized etch barrier once it has been exposed. In order to fulfill these requirements, the template is treated with a release layer to modify its surface chemistry. (Step 3) Once the template is brought near the wafer, a micro-fluidic dispensing system dispenses a specific pattern of the photopolymerizable, organosilicon etch barrier fluid. The fluid the fills the gap between the template and transfer layer via a squeeze film effect and capillary action.
Step 1: Spin-coat wafer with transfer layer

Step 2: Place template near transfer layer

Step 3: Dispense etch barrier solution

Step 4: Bring template and transfer layer into near contact and flood expose with UV

Step 5: Remove template

Step 6: Halogen etch through transfer layer

Step 7: Strip polymerized etch barrier with anisotropic oxygen reactive ion etch

Figure 1.2 Step and flash imprint lithography process

(Step 4) The template and transfer layer are then brought into near contact and the etch barrier solution is irradiated with a blanket exposure of broadband UV light from a 500W Oriel lamp having a peak intensity at 365 nm. Features ranging in size from 20 µm to 60 nm have been demonstrated with an exposure dose of 20 mJ/cm² and an imprint force of approximately 5 lbs. (Step 5) Once the etch barrier has polymerized, the template is separated from the substrate leaving low-aspect ratio, high resolution cross-linked etch barrier features remaining on the transfer layer. (Step 6) The residual etch barrier is etched from the transfer
layer using a halogen plasma etch. (Step 7) Finally an anisotropic oxygen reactive ion etch is used to transfer a high aspect ratio image to the transfer layer. These high aspect ratio features in the transfer layer can then be used as a mask for transferring the features into the substrate as in traditional lithography, i.e. metal deposition, etc.

1.3.2 Challenges to Step and Flash Imprint Lithography

In developing the SFIL process, researchers face a number of important technical challenges. An important aspect of the research is in the realm of mechanical engineering, which involves developing a step and repeat machine to implement the process with active control of the orientation stages for parallel alignment of the template with the wafer substrate. This machine would bring the template into the proximity of the transfer layer through a coarse z-axis actuation stage. Then it would dispense the etch barrier solution in the specific pattern using a micro-liter fluid dispensing system. Next, it would bring the template into contact with the transfer layer using high-resolution actuators. Finally, it would illuminate the etch barrier through the backside of the template. A key issue in the machine development is to understand the interaction between the quartz template, the thin-film etch barrier layer, and the wafer substrate.

Once the etch barrier fluid fills the gap between the template and the transfer layer, the template must be pushed towards the wafer in order to minimize the thickness of the remaining etch barrier base layer. Ideally, the base layer would be nonexistent in the final imprint process as the etch process that is used to transfer the image to the transfer layer requires minimal or nonexistent residual base layer. However, this is not practical in the actual implementation as
the etch barrier fluid has an infinite resistance as the base layer thickness asymptotically reaches zero. The residual etch barrier base layer requires a more complex etching process. The thickness of the residual base layer should be uniform and less than the height of the imprinted features (typically 100 nm) in order to maintain high image fidelity during the etch process. With an acceptable base layer thickness, a preliminary etching step can eliminate the base layer without affecting the quality of the process. If the base layer is too thick, the preliminary etching step cannot eliminate the base layer while maintaining the feature geometry accurately [Choi, Johnson, And Sreenivasan, 1999]. Therefore, it is desirable to achieve a high line height to base layer ratio as illustrated in Figure 1.3. Since the etch barrier is exposed by a blanket dosage of UV radiation, the entire layer of etch barrier is polymerized and the etching process strips is able to completely strip away the thinner areas of the etch barrier material in the trenches, i.e. the base layer, and leave the thicker areas, i.e. the lines.

![Figure 1.3 Ratio of line height to base layer thickness](image)

Figures 1.4b, 1.4c, and 1.4d present the undesired base layer deviations from the desired imprint in Figure 1.4a. Figure 1.4b represents a wafer that has a low frequency variation in its height relative to an optical flat. Templates are made from optical flats and are accurate to 20 nm across several inches. However, wafers can have low frequency height variations of several microns.
across their diameter. These oscillations can be addressed by using a flat vacuum chuck with uniform pressure across the supporting surface.

Figure 1.4c shows a wedged base layer that is due to angular misalignment between the template and the wafer. The etch barrier is exposed when the template has an angle of inclination with respect to the wafer substrate. This occurs when the uncorrected misalignment between the opposing surfaces of the template and the transfer layer exceeds the motion capability of the flexure-based template stage. Figure 1.4d shows a thick base layer due to an excessive gap between the template and transfer layer during the exposure. The current process to fill the gap is via squeeze film hydrodynamics and capillary action. In order for the etch barrier solution to fill the gap in a reasonable amount of time, the initial gap needs to be on the order of a few microns. If a 200 nm initial gap is used, the time-to-fill is very high [Choi, Johnson, and Sreenivasan, 1999]. To deal with the two issues of minimizing the base layer thickness and the angle of inclination of the base layer, an active stage system is under development to better control the filling and squeezing of the etch barrier base layers down to about 100 nm prior to UV curing.

Figure 1.4 Base layer types
Researchers at the University of Texas are studying two primary subsystems of an active stage system. The first subsystem is a high-resolution gap-sensing tool that will be incorporated into an active stage test-bed. This gap-sensing device is based on Fast Fourier Transform analysis of spectral reflectivity of optical thin films in the ultraviolet-visible region. UV-VIS spectral reflectometry offers the potential to perform in situ film thickness characterization at sub-100 nm resolution. It will be employed to measure the gap during the squeezing and filling of the etch barrier to provide the feedback information necessary for real-time active control of template stage orientation. The second subsystem is an actuator system that will actively control the template stages. To achieve minimal base layer thickness and reduce the angle of inclination of the template, a control scheme is being developed. This will help achieve thin, uniform base layer required for the etching processes.

The requirements of appropriate surface chemistries for adhesion, photopolymerization kinetics, and etch selectivity for the patterning of high-resolution patterns present significant challenges in the area of chemistry and engineering. There are necessary tradeoffs when choosing, for example, an etch barrier formulation that fully wets the template while not adhering to it. Voids or air bubbles trapped within the thin-film etch barrier will lead to defects in the imprint. At the same time, the etch barrier must adhere to the transfer layer, but not the template once it is cured. A significant portion of the work on this project has focused on developing materials with surface energies and surface tensions that meet these requirements [Johnson 1999].
1.4 Thesis

For SFIL to become a practical technology, real-time control strategies must be developed to in order to generate thin, parallel base layers. To better understand the requirements for the specifications of an active stage system capable of delivering thin, parallel base layers, the fluid film interaction with the template and wafer has been investigated for this thesis. A squeeze film model of the fluid film was used to develop the analytical equations for the fluid pressure, which are a function of the template geometry, orientation, and velocities. For a given template geometry, the pressure is then a function of orientation and velocity.

\[ p = p(x, \theta, \dot{\theta}, \ddot{\theta}) \]  \[1.2\]

The solution for the pressure was obtained from the Reynolds equation, which is the fundamental equation in fluid film lubrication theory. The pressure was then integrated over the spatial domain to obtain analytical solutions for the damping force and torque generated by the fluid. Then, a numerical simulation of the equations of motion for the template assembly was performed to characterize the dynamics of the mechanical system and its interaction with the etch barrier layer. Finally, an experiment was designed to scientifically quantify the squeeze film dynamics of the etch barrier layer. An improved understanding of the squeeze film mechanics is derived from the combined efforts of theoretical, numerical, and experimental analysis.

The remainder of this thesis has been organized into six chapters. Chapter 2 reviews the theoretical background on modeling the squeeze film effects of the etch barrier layer. The model assumptions are explained and a derivation for the Reynolds equations is given. Boundary conditions for specific geometries were applied to obtain appropriate analytical solutions. Chapter 3 discusses the active
stage development. Design requirements and implementation for major subsystems in the active stage are considered. Chapter 4 gives the theory and implementation details of a gap sensing system based on Fast Fourier Transforms of the spectral reflectivity of thin films. Chapter 5 presents the numerical simulation results and an interpretation in the context of SFIL process and machine development. Chapter 6 discusses the design of experiments to validate the model and provide insight into what happens during the squeezing process. Experimental results are correlated to the results from numerical simulations of the squeezing process. Chapter 7 summarizes this research, poses possible extensions, and notes the major contributions of this research to SFIL development.
Chapter 2: Theoretical Analysis

The first step taken to model a physical system is to understand the physics of the system. The SFIL system considered here is comprised of a quartz template (T), a photosensitive, etch barrier fluid (F), and a flat wafer substrate supported by a vacuum chuck (W). The TFW system has been modeled as a squeeze film flow between two flat surfaces. Different assumptions about the geometry of the system lead to slightly modified analytic equations for the pressure distribution due to the liquid etch barrier.

2.1 INTRODUCTION

The development of a reliable, high-throughput step and flash imprint lithography process requires an improved understanding of the interaction between the etch barrier layer and the flexure stages, which orient the template. The step required to expel the excess liquid etch barrier between the template and the wafer substrate is a critical and rate-limiting step in the SFIL process. The etching process requires that the base layer thickness be on the order of the average feature height, which is about 200 nm in the current process. For throughput to be competitive with industry standard processes, this step should be completed in about 0.5 seconds because time must also be allocated for translation of the x-y stage, dispensing the etch barrier, and exposing the etch barrier. In this short time interval, the gap between the template and the substrate has to be reduced from several microns to 100-200 nm. This also requires that the orientation misalignment must be less than 0.5 μrad if the difference between the
minimum and maximum base layer thickness is to be less than 10%. Due to high
damping forces and mechanical compliance, achieving these results is not trivial.

In order to optimize the design of an active stage system, the following
questions must be answered. 1) What mechanisms are dominant during the filling
process as the liquid etch barrier wets the surface of the template and wafer? 2) What characterizes the measured imprinting forces of the etch barrier as the
template and wafer are pressed together. Studying the behavior of the etch barrier
layer and its effect on the dynamics of the actuation system will provide insight
into a method for obtaining thin base layers within a reasonable amount of time
from actuation forces that can be achieved by commercially available actuators.

The behavior of the etch barrier can be described by that of squeeze films,
which commonly occur in lubrication theory. It has been observed, in the current
SFIL process using a multi-imprint stepper [Choi, Johnson, and Sreenivasan
1999], that the characteristic imprinting force as a function of time is
approximately a step function. Intuitively, the greater the viscosity of the etch
barrier, the larger the force required to reduce the thickness of the fluid layer; or
alternatively, for a given force more time is required to achieve the desired base
layer thickness. Furthermore, it has been observed that the fluid has very high
resistance at a base layer thickness below 100 nm. From these observations, the
etch barrier has been modeled as a squeeze film lubrication flow.

The lubrication flow of squeeze films has been widely studied in the past
century in the context of tribology applications, where oil is typically the
lubricant. Researchers have examined the effect of roughness on squeeze film
lubrication flow through stochastic models of surface roughness. Assuming
surfaces with known statistical properties, i.e. Gaussian distributions with known
mean and standard deviations, averaged Reynolds equation flow models were
derived [Tripp 1983; Patir and Cheng 1978]. The effects of sinusoidal
corrugations on the flow behavior of parallel plate squeeze films have been studied from a theoretical and numerical perspective [Freeland 2000]. Freeland developed analytic and numerical solutions for two and three-dimensional geometries for flows found in both SFIL and nanoimprint lithography. The non-inertial sinkage of a flat, inclined plate has been thoroughly studied. However, the effect of the asymmetry in the pressure distribution across the plate was neglected in computing the sinkage rate [Moore 1964]. Moore proceeded with the assumption of a pressure distribution, which is a parabola for any section perpendicular to the directions spanning the plate. This assumption neglects the corner effects, but is useful in approximating the three-dimensional pressure due to a specified load condition. In this thesis, the effect of a non-symmetric pressure variation across a smooth template is treated analytically and applied to a numerical simulation of the equations of motion for the SFIL machine.

In this chapter, the Reynolds equation has been used to study the case of a squeeze film flow between a flat, quartz template and flat, rigid wafer substrate. First a derivation of the incompressible Reynolds equation is given. Next, a reduced form of the Reynolds equation is considered. The two-dimensional Reynolds equation can be applied to flow geometries where side leakage can be neglected in one of the lateral directions; the squeeze film in the $y$ direction can be considered infinite. The case of an infinite, flat surface that is parallel to a substrate is presented. This is extended to the case of an infinite, flat surface that is inclined relative to a substrate. Applying specific boundary conditions, analytical solutions for the pressure, force, and torque are obtained from the two-dimensional Reynolds equation.

The analytical solutions to the three-dimensional problem (finite plate geometry) are reviewed as used as a benchmark for comparing the two-dimensional solutions. The three-dimensional solution for the case of a parallel
square plate with fluid completely filling the gap is considered. Finally, the
closed-form solution to the case of parallel circular plates is presented. The
axisymmetric case has a readily available solution to the problem of a growing
fluid boundary layer.

2.2 THE INCOMPRESSIBLE REYNOLDS EQUATION

The Reynolds equation is the basic equation for fluid lubrication. It
provides a relationship between the thickness of a fluid film and the pressure.
Since the problem of interest is not a traditional lubrication flow, it is a
prerequisite that careful consideration be given to the assumptions used in
modeling the squeeze film effect of the etch barrier liquid. The characteristic
length for the expulsion step in the SFIL process is on the order of hundreds of
nanometers. A desired final base layer thickness of 100 - 200 nm is virtually at
the limit of contacting plates in most traditional engineering contexts. For a fluid
layer at these thicknesses, does the assumption of the fluid as a continuum remain
valid? An empirical criterion such as the Stribeck Curve\(^2\) shows that for films
above about 10 nm, the lubricant film behavior can be described by bulk,
continuum properties [Bhushan 1995]. Also, at this scale of motion, the effect
of van der Waals forces could become important as compared with the pressure
forces from the bulk fluid and the external forces. The pressures created by the
van der Waals forces are proportional to

\[ P_{yw} \propto \frac{A}{6\pi h_{avg}^3} \text{ or } h_{avg} \propto \sqrt[3]{\frac{A}{6\pi P_{applied}}} \]  \hspace{1cm} [2.1]

\(^2\) Refer to page 292 of the Handbook of Micro/Nanotribology by Bharat Bhushan.
where $A$ is the Hamaker constant ($\sim 10^{-20}$ J), $h_{\text{avg}}$ is the average distance between the plates (m), and $P_{\text{applied}}$ is the applied pressure (Pa).

Assuming the applied pressures on the order of 1 psi, $h_{\text{avg}}$ is about 4 nm when van der Waals forces are on the same order as the pressures of interest [Freeland 2000]. Also, Moore documents that it has been agreed that molecular influence can extend outward from a surface no more than 0.5 µin (13 nm). A base layer thickness of approximately 100 nm, well above these limits of continuum fluid mechanics, justifies a few of the following assumptions.

In deriving the Reynolds equation, the assumptions that are to be made must be considered:

1. Body forces are neglected, i.e. van der Waals forces.
2. The pressure is constant through the thickness of the film. Since the thickness of the films considered here are about ten microns or smaller, while the length scales in the plane of the template are measured in centimeters, it is reasonable to assume that $\frac{\partial p}{\partial z} = 0$.
3. There is no slip at the boundaries. There has been much work on this and it is universally accepted [Cameron 1976].
4. The fluid is Newtonian, i.e. $\tau = \mu \frac{\partial u}{\partial z}$. Shear stress is proportional to the rate of shear strain. This assumption is valid when the lubrication is in the bulk regime (minimum film thickness above 10 nm).
5. The flow is laminar. The Reynolds number based on gap height is less than one for the range of gap heights and velocities. $\text{Re}_h \ll 1$
6. Fluid inertia is neglected since the kinematic viscosity is large and the length scale is small.
7. The fluid is assumed incompressible since the etch barrier and water are liquids.

8. The viscosity can be considered constant throughout the fluid layer since the SFIL process operates at room temperatures.

9. The flow is quasi-steady. This assumption asserts that the velocity and pressure fields adjust instantaneously to the movements of the boundary.

The incompressible Reynolds equation is derived from the principles of mass conservation and momentum equations for an infinitesimal fluid volume element of height $h$ and base $dx \times dy$ as illustrated by Figure 2.1. The principle of mass conversation demands that the rate at which mass is accumulating in the volume element must be equal to the difference between the rates at which mass enters and leaves.

![Figure 2.1 Continuity of flow in an infinitesimal fluid element](image)

Referring to Figure 2.1 and performing a mass balance, it is seen that

$$q_x \, dy + q_y \, dx + w_h \, dx \, dy = \left( q_x + \frac{\partial q_x}{\partial x} \right) dy + \left( q_y + \frac{\partial q_y}{\partial y} \right) dx + w_0 \, dx \, dy. \quad [2.2]$$
The left hand side of equation 2.2 is the volume flow rate into the fluid element and the right hand side is the volume flow rate out of the fluid element. Canceling common terms and factoring appropriately gives

\[
\left( \frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} + (w_h - w_0) \right) dxdy = 0.
\]  \[2.3\]

Note that the term \(dxdy\) is arbitrary and nonzero and that the template and wafer surfaces are impermeable, therefore \((w_h - w_0) = \frac{\partial h}{\partial t}\). Thus, equation 2.3 is written more succinctly as,

\[
\nabla \cdot \mathbf{q} + \frac{\partial h}{\partial t} = 0.
\]  \[2.4\]

This is the continuity equation for incompressible flow, where \(\nabla\) is the two-dimensional gradient operator and the latter term is the average rate at which the template approaches the wafer.

To obtain the momentum equation take a small element of fluid with side lengths \(dx \times dy \times dz\), consider the forces in each of the principle directions. First, consider only the forces in the \(x\) direction as shown in Figure 2.2. A summation of the forces in the \(x\) direction gives,

\[
\left( p + \frac{\partial p}{\partial x} dx \right) dydz + \tau dx dy = p dydz + \left( \tau + \frac{\partial \tau}{\partial z} dz \right) dx dy.
\]  \[2.5\]
Collecting like terms, this can be simplified

\[ \frac{\partial p}{\partial x} = \frac{\partial \tau}{\partial z}. \]  \[2.6\]

Recall that the fluid is assumed Newtonian, thus

\[ \frac{\partial p}{\partial x} = \frac{\partial}{\partial z} \left( \mu \frac{\partial u}{\partial z} \right). \]  \[2.7\]

Similar reasoning is applied in the \( y \) direction to obtain

\[ \frac{\partial p}{\partial y} = \frac{\partial}{\partial z} \left( \mu \frac{\partial v}{\partial z} \right). \]  \[2.8\]

Recalling that \( \frac{\partial p}{\partial z} = 0 \) from assumption no. 2, a balance of the pressure and shear forces on an equilibrium element yields the momentum equation.

\[ \frac{\partial^2 u}{\partial z^2} = \nabla p \]  \[2.9\]

where \( u = u e_x + v e_y \).

Consider equation 2.7 further. This can be integrated since \( p \) is not a function of \( z \), thus

\[ \mu \frac{\partial u}{\partial z} = \frac{\partial p}{\partial x} z + C_1. \]  \[2.10\]

A further integration gives
\[
\mu u = \frac{\partial p}{\partial x} \frac{z^2}{2} + C_1 z + C_2. \tag{2.11}
\]

The boundary conditions due to the no slip condition is the speed of the surface, so on, \( z = h \)
\[ u = U_1 \]
and on \( z = 0 \)
\[ u = U_2 \]
where \( U_1 \) and \( U_2 \) are the two surface speeds.

Substituting these into equation 2.11 produces \( C_2 = \mu U_2 \) and
\[ C_1 = \frac{\mu(U_1 - U_2)}{h} - \frac{\partial p}{\partial x} \frac{h}{2}. \]

The velocity in the \( x \) direction at any point in \( z \) in the film is given by
\[ u = \frac{\partial p}{2\mu \partial x} \left( z^2 - zh \right) + \left( U_1 - U_2 \right) \frac{z}{h} + U_2. \tag{2.12} \]

The velocity gradient is
\[ \frac{\partial u}{\partial z} = \frac{\partial p}{\mu \partial x} \left( z - \frac{h}{2} \right) + \left( U_1 - U_2 \right) \frac{1}{h}. \tag{2.13} \]

The integral \( \int_0^h u \, dz \) equals \( q_x \), the flow rate in the \( x \) direction per unit width of \( y \).

Integrating equation 2.12 gives
\[ q_x = \left[ \frac{\partial p}{2\mu \partial x} \left( \frac{z^3}{3} - \frac{z^2 h}{2} \right) + \left( U_1 - U_2 \right) \frac{z^2}{2h} + U_2 \right]_0^h. \tag{2.14} \]

Putting in the limits and simplifying, the result is
\[ q_x = -\frac{h^3}{12\mu} \frac{\partial p}{\partial x} + \left( U_1 + U_2 \right) \frac{h}{2}. \tag{2.15} \]

Following the same procedure for \( y \) it is easily found that
\[ q_y = -\frac{h^3}{12\mu} \frac{\partial p}{\partial y} + \left( V_1 + V_2 \right) \frac{h}{2}. \tag{2.16} \]
where $V_1$ and $V_2$ correspond to $U_1$ and $U_2$.

Going back to the continuity equation and replacing the terms $q_x$ and $q_y$ in equation 2.3 by (2.15) and (2.16) gives

$$\frac{\partial}{\partial x}\left( (U_1 + U_2) \frac{h}{2} - \frac{h^3}{12\mu} \frac{\partial p}{\partial x} \right) + \frac{\partial}{\partial y}\left( (V_1 + V_2) \frac{h}{2} - \frac{h^3}{12\mu} \frac{\partial p}{\partial y} \right) + \frac{\partial h}{\partial t} = 0. \quad [2.17]$$

This can be somewhat simplified to read

$$\frac{\partial}{\partial x}\left( \frac{h^3}{\mu} \frac{\partial p}{\partial x} \right) + \frac{\partial}{\partial y}\left( \frac{h^3}{\mu} \frac{\partial p}{\partial y} \right) = 6\left\{ \frac{\partial}{\partial x}(U_1 + U_2)h + \frac{\partial}{\partial y}(V_1 + V_2)h + 2\frac{\partial h}{\partial t} \right\}. \quad [2.18]$$

This is the Reynolds equation in three dimensions. There exist no general closed-form solutions to this generalized form of the Reynolds equation. The following section simplifies the equation 2.18 with the appropriate model assumptions.

### 2.3 THE TWO-DIMENSIONAL REYNOLDS EQUATION

#### 2.3.1 Derivation of the Two-Dimensional Reynolds Equation

The generalized form of Reynolds equation from equation 2.18 can be reduced to a two-dimensional form, which can be applied for certain plate geometries and boundary conditions. For relatively low interface pressures in hydrodynamic lubrication, the viscosity of fluids can be assumed to be constant [Bhushan 1999]. Also, if the motion is restricted to normal approach such that sliding velocities are zero ($U_1 = U_2 = V_1 = V_2 = 0$), equation 2.18 reduces to

$$\frac{\partial}{\partial x}\left( h^3 \frac{\partial p}{\partial x} \right) + \frac{\partial}{\partial y}\left( h^3 \frac{\partial p}{\partial y} \right) = 12\mu \frac{\partial h}{\partial t} \quad [2.19]$$

In the process of expelling the excess etch barrier, the side motion of the template relative to the wafer is negligible due to the design of the flexure stages,
which are selectively compliant. In the multi-imprint machine, these flexures are passive compliant and allow $\alpha$-$\beta$ rotations, as shown in Figure 2.3, and $z$ translation while minimizing $\gamma$ rotations and $x$-$y$ translations.

The selective compliance of the distributed flexure allows the flexure to self-correct any orientation alignment within its range of motion to minimize the base layer wedge profile when the etch barrier is squeezed towards the edges of the template. During the separation step excessive lateral displacements may destroy transferred images, therefore an important design criterion for the orientation stages is to minimize the motions that would cause catastrophic defects in the UV-exposed etch barrier. Thus, the modeled fluid pressures are generated from a pure squeeze action and the first two terms on the right hand side of equation 2.18 disappear.

![Figure 2.3](image_url)

**Figure 2.3** Two flats showing orientation alignments$^3$

The template is treated as infinite in the $y$ direction and only the middle of the template along the $x$ direction is considered. This is equivalent to neglecting side leakage so that all $y$ derivatives are zero. The two-dimensional Reynolds equation becomes

---

$^3$ Figure taken from Choi et al 2000.
\[
\frac{d}{dx} \left( h^3 \frac{dp}{dx} \right) = 12\mu \frac{dh}{dt}.
\]

[2.20]

2.3.2 Squeeze Film Due to a Parallel Surface of Infinite Width

Figure 2.4 shows a parallel-surface squeeze film flow where the fluid completely fills the gap between the upper and lower surfaces. Making use of symmetry, the origin is placed at the midpoint of the upper surface.

For the case of parallel plates, the pressure distribution is symmetric about \( x = 0 \). Integrating equation 2.20 once gives

\[
\frac{dp}{dx} = \frac{12\mu}{h^3} \frac{dh}{dt} x + C_1.
\]

[2.21]

Integrating again gives

\[
p = \frac{6\mu}{h^3} \frac{dh}{dt} x^2 + C_1 x + C_2.
\]

[2.22]
The boundary conditions are \( p = 0 \) when \( x = \pm \frac{L}{2} \). From the boundary conditions, \( C_1 = 0 \) and \( C_2 = \frac{6\mu L^2}{4h^3} \frac{dh}{dt} \). Substituting for \( C_1 \) and \( C_2 \) gives

\[
p_{parallel}(x) = \frac{3\mu}{2h^3} \frac{dh}{dt} \left(4x^2 - L^2\right). \tag{2.23}
\]

The pressure distribution is parabolic and symmetric about \( (x = 0) \). For parallel plates the normal damping force per unit width is simply

\[
f_{parallel} = \int_{-L/2}^{L/2} p(x)dx = -\frac{\mu L^3}{h^3} \frac{dh}{dt} \tag{2.24}
\]

From equation 2.24, it is observed that the fluid layer generates large damping forces that scale as \( \frac{1}{h^3} \) and is directly proportional to both the approach velocity of the template and the viscosity of the fluid.

### 2.3.3 Squeeze Film Due to an Inclined Surface of Infinite Width

In the case of a flat, inclined plate approaching a surface, the height of the plate relative to the surface it approaches varies linearly along the \( x \) direction. The template geometry and flow profile are shown in Figure 2.5. The gap height is \( h(t, x) = h_x = \bar{h}(t) + x \tan \theta(t) \) and \( \frac{\partial h}{\partial t} = \dot{\bar{h}} + x \dot{\theta} \sec^2 \theta \).
The height at the midpoint of the template at $x = 0$ is given by $\bar{h}(t)$ and the velocity is $\frac{dh}{dt}$. The domain is specified on $x \in [x_\alpha(t), x_\beta(t)]$. The integration domain grows as a function of time due to the fluid being squeezed out from the midpoint.

The height of the template at the left and right boundaries are $h_\alpha = \bar{h} + x_\alpha \tan \theta$ and $h_\beta = \bar{h} + x_\beta \tan \theta$, respectively. The initial conditions at the boundaries of the flow at $x = x_\alpha$ and $x = x_\beta$ are determined by the volume of the fluid dispensed and the average height of the template. For example, if the volume of fluid dispensed is 0.1 µL or $1 \times 10^{-10}$ m$^3$, $d = \frac{1 \times 10^{-10}}{\bar{h}L/2}$ in meters where $d = |x_\alpha| = x_\beta$. However, the half-length of the template constrains $x_\alpha$ and $x_\beta$ so that $\frac{L}{2} \geq |x_\alpha|, x_\beta$. Since the height is a function of $x$, the integration to obtain the
Pressure distribution is tedious and only the result follows. Integrating the two-dimensional Reynolds equation once gives

\[ \frac{dp}{dx} = \frac{1}{h_x^3} \left\{ 12\mu \left( \frac{\hat{h} x + x^2 \theta \sec^2 \theta}{2} \right) + C_1 \right\}. \tag{2.25} \]

Integrating again gives

\[ p(x) = -\frac{6\mu \hat{h} (\hat{h} + 2x \tan \theta)}{h_x^2 \tan^2 \theta} + 6\mu \hat{\theta} \sec^2 \theta \left\{ \frac{3\hat{h}^2 + 4\hat{h} x \tan \theta}{2h_x^2} \right\} \]

\[ + \ln \left( \frac{h_x}{h_{x\beta}} \right) - \frac{C_1}{2h_x^2 \tan \theta} + C_2. \tag{2.26} \]

For the unsubmerged plate-surface system, meniscus effects at the outer periphery of the squeeze film, and capillary pressure opposes the squeeze film pressure [Moore 1965]. Assuming the liquid perfectly wets the surfaces of the plate and substrate, i.e., zero contact angles, the pressure at the boundary is given by

\[ p(x) = -\frac{2\gamma}{h_x}. \]

Applying the boundary conditions \( p(x = x_\alpha) = -\frac{2\gamma}{h_\alpha} \) and \( p(x = x_\beta) = -\frac{2\gamma}{h_\beta} \), the integration constants, \( C_1 \) and \( C_2 \), are obtained.

\[ h_{x\alpha} = \tilde{h} + x_\alpha \tan \theta, \quad h_{x\beta} = \tilde{h} + x_\beta \tan \theta, \quad k = \frac{6\mu \hat{\theta} \sec^2 \theta}{\tan^3 \theta}, \]

\[ \bar{C}_1 = \frac{-6\mu \hat{h} (\hat{h} + 2x_\beta \tan \theta)}{\tan^2 \theta h_{x\beta}^2} + k \left\{ \frac{(3\hat{h}^2 + 4\hat{h} x_\beta \tan \theta)}{2h_{x\beta}^2} + \ln \left( \frac{h_{x\beta}}{h_{x\alpha}} \right) \right\}, \]

\[ \bar{C}_2 = \frac{-k (3\tilde{h}^2 + 4\tilde{h} x_\alpha \tan \theta) + 6\mu \hat{h} (\hat{h} + 2x_\alpha \tan \theta)}{2h_{x\alpha}^2 \tan^2 \theta}, \]
\[ C_1 = \frac{2h_{\alpha \beta}^2 \tan \theta}{(h_{\alpha \alpha}^2 - h_{\beta \beta}^2)} \left( P_{\beta} - P_{\alpha} + C_1 + C_2 \right), \quad \text{and} \quad C_2 = \frac{C_1}{2h_{\alpha \alpha}^2 \tan \theta}. \]

Equation 2.26 numerically converges to the result of equation 2.23 for a certain range of small \( \theta \), but due to integration of equation 2.25 the limit as \( \theta \) tends to zero becomes ill posed and the numerical result becomes unstable for small \( \theta \). However, using a Taylor series expansion of the height \( h(x) \) gives a result that converges to the parallel plate solution for \( \theta = 0 \). The height is rewritten as \( h(x) = \hat{h} \left( 1 + \frac{x}{\hat{h}} \tan \theta \right) \). When the ratio of the wedge height to the average height is small, i.e. \( \frac{x}{\hat{h}} \tan \theta << 1 \), a Taylor approximation can be used for the term \( \frac{1}{h^3} = \frac{1}{\hat{h}^3 \left( 1 + \frac{x}{\hat{h}} \tan \theta \right)^3} \) in equation 2.25. Substituting into equation 2.25 the Taylor approximation \( \frac{1}{h^3} \approx \frac{1}{\hat{h}^3} \left( 1 - 3 \frac{x}{\hat{h}} \tan \theta \right) \), the resulting pressure distribution is

\[
p = \frac{12\mu}{\hat{h}^3} \left\{ -\frac{3\hat{h} \sec^2 \theta \tan \theta}{8\hat{h}} x^4 + \left( \frac{\hat{h} \sec^2 \theta \tan \theta}{6} - \frac{\hat{h} \tan \theta}{\hat{h}} \right) x^3 \right. + \left. \left( \frac{\hat{h} \tan \theta}{2} + \frac{C_1 \tan \theta}{8\mu \hat{h}} \right) x^2 - \frac{C_1}{12\mu} x \right\} + C_2
\]

where \( C_1 \) and \( C_2 \) are given by

\[
C_1 = \frac{2\hat{h}^4}{2\hat{h}(x_\alpha - x_\beta) + 3 \tan \theta (x_\beta^2 - x_\alpha^2)} \left\{ P_{\beta} - P_{\alpha} + \left[ -\frac{3\hat{h} \sec^2 \theta \tan \theta (x_\beta^4 - x_\alpha^4)}{8\hat{h}} \right] \right. + \left. \left( \frac{\hat{h} \sec^2 \theta \tan \theta}{6} - \frac{\hat{h} \tan \theta}{\hat{h}} \right) \right\} \]

\[
C_2 = \frac{C_1}{2h_{\alpha \alpha}^2 \tan \theta}.
\]
\[
\left( \frac{\theta \sec^2 \theta}{6} - \frac{\hat{h} \tan \theta}{h} \right) (x_\alpha^3 - x_\beta^3) + \frac{\hat{h}}{2} (x_\alpha^2 - x_\beta^2)
\]

\[
C_2 = P_{x\beta} - \frac{12\mu}{h^3} \left\{ \left( - \frac{3\dot{\theta} \sec^2 \theta \tan \theta}{8h} x_\beta^4 + \left( \frac{\theta \sec^2 \theta}{6} - \frac{\hat{h} \tan \theta}{h} \right) \right) x_\beta^3 + \left( \frac{\hat{h}}{2} + \frac{C_1 \tan \theta}{8\mu h} \right) x_\beta^2 - \frac{C_1}{12\mu} x_\beta \right\}
\]

Equation 2.27 is valid for small values of \( \frac{\max(|x_\alpha|, x_\beta)}{h} \tan \theta \). Note that equation 2.27 is a polynomial equation in \( x \). It can be shown that in the limit, as \( \theta \) approaches zero, the pressure distribution approaches that of a parallel plate (equation 2.23).

In Figure 2.6, the pressure distributions for both parallel and nonparallel plates are presented. The pressure distribution for the case of nonparallel plates is skewed and generates a torque to correct the deviation of \( \theta \) from zero. Figure 2.6 shows that for small angles, the pressure distribution is nearly symmetric and that the location of the maximum pressure moves away from \( x = 0 \).

The damping force resulting from the squeeze film pressure is obtained by the integration of the pressure over the projected area of the wetted portion of the template. This damping force is given by

\[
f = \int_{\alpha}^{\beta} \int_{\alpha}^{\beta} p(x) dx dy. \quad [2.28]
\]

The result of this integration is

\[
f = L \left[ \frac{12\mu}{h^3} \left( \frac{3\dot{\theta} \sec^2 \theta \tan \theta}{40h} (x_\alpha^5 - x_\beta^5) + \left( \frac{\theta \sec^2 \theta}{24} - \frac{\hat{h} \tan \theta}{4h} \right) (x_\beta^4 - x_\alpha^4) + \right) \right]
\]
\[
\left( \frac{\hat{h}}{6} + \frac{C_1 \tan \theta}{24 \mu h} \right) \left( x_{\beta}^3 - x_{\alpha}^3 \right) + \frac{C_1}{24 \mu} \left( x_{\alpha}^2 - x_{\beta}^2 \right) \right) + C_2 \left( x_{\beta} - x_{\alpha} \right) \]. \quad [2.29]

**Figure 2.6** Two-dimensional pressure distribution

Figure 2.6 shows the two-dimensional pressure along the template for parallel plates solution from equation 2.23 (solid line), inclined plate solution from equation 2.26 (dash-dotted line), and inclined plate solution from equation 2.27 (dashed line). Results are for \( \bar{h} = 1 \) µm, \( \dot{h} = -0.5 \) µm/s, \( \theta = 10 \) µrad, and \( \dot{\theta} = -10 \) µrad/s with boundary conditions

\[
p \left( x = \pm \frac{1 \times 10^{-10}}{\bar{h}L/2} \right) = -\frac{2 \gamma}{h}. \quad L = 1 \text{ inch.}
\]

The damping torque is given by

\[
\tau = \int_0^L \int_a^b xp(x) \ dx \ dy \quad \text{[2.30]}
\]
and the result is

\[
\tau = L \left[ \frac{12 \mu}{\hat{h}^3} \left\{ \frac{3 \dot{\theta} \sec^2 \theta \tan \theta}{48 \hat{h}} \left( x_\alpha^6 - x_\beta^6 \right) + \left( \frac{\dot{\theta} \sec^2 \theta}{30} - \frac{\hat{h} \tan \theta}{5 \hat{h}} \right) \left( x_\beta^5 - x_\alpha^5 \right) + \right. \right.
\]

\[
\left. \left. \left( \frac{\hat{h}}{8} + \frac{C_1 \tan \theta}{32 \mu \hat{h}} \right) \left( x_\beta^4 - x_\alpha^4 \right) + \frac{C_1}{36 \mu} \left( x_\alpha^3 - x_\beta^3 \right) \right\} + \frac{C_2}{2} \left( x_\beta^2 - x_\alpha^2 \right) \right] \quad [2.31]
\]

### 2.4 THREE-DIMENSIONAL PROBLEM

#### 2.4.1 3D Pressure Distribution for Parallel, Rectangular Plates

In the previous two-dimensional case, the plates were considered to be infinite in the \( y \) direction. In the three-dimensional case, the plate dimensions are finite. For a flat, rectangular plate moving parallel towards a flat surface with fluid completely filling the gap, i.e. there is no capillary effect; the pressure distribution in the squeeze film is relatively complex owing to the introduction of corner effects and the absence of rotational symmetry. For a rectangular plate of length \( L \) and width \( B \) where the shape ratio \( B/L \) gives a characteristic shape factor, \( f(B/L) \). Hays assumed an infinite, double Fourier series solution for the pressure distribution of the following form

\[
p = \sum_{M}^{\infty} \sum_{N}^{\infty} A_{MN} \sin M\theta \sin N\phi \quad [2.32]
\]

where \([M, N = 1, 3, 5, ..., \infty], \ \theta = \frac{\pi x}{L} \text{ and } \phi = \frac{\pi y}{B} \ [Moore 1965] \). This satisfies the zero boundary conditions such that the pressure is the same atmospheric pressure
at the plate edges. Freeland obtained the series coefficients, $A_{MN}$, in the case of a flat, square template, i.e. $B = L$. The pressure distribution is given by

$$
p = -\frac{48\mu L^2}{\pi^3 h^3} \frac{dh}{dt} \sum_{n=0}^{\infty} \left\{ \frac{\cosh((2n+1)\pi) - 1}{\sinh((2n+1)\pi)} \sinh((2n+1)\pi) - \cosh((2n+1)\pi) + 1 \right\} \frac{\sin((2n+1)\pi\alpha)}{(2n+1)^3} \tag{2.33}
$$

When the pressure is integrated with respect to $x$ and $y$, the force due to the squeeze film between flat parallel plates is

$$
F = -\frac{48\mu L^4}{\pi^7 h^5} \frac{dh}{dt} \sum_{n=0}^{\infty} \left\{ \frac{\cosh((2n+1)\pi) - 1}{\sinh((2n+1)\pi)} \left[ \cosh((2n+1)\pi) - 1 \right] - \sinh((2n+1)\pi) + (2n+1\pi) \right\} \tag{2.34}
$$

The summation of this infinite Fourier series gives the shape factor for a square plate as $\frac{f(B/L)\mu L^4}{h^3} \frac{dh}{dt}$ where $f(B/L) = 0.4217$. Therefore, the force is simply

$$
F = \frac{-0.4217\mu L^4}{h^3} \frac{dh}{dt} \tag{2.35}
$$

From the assumptions of negligible inertia effects, the gap height as a function of time can be obtained for a constant applied force.

$$
h(t) = \sqrt{\frac{1}{\frac{1}{h_i^2} + \frac{2Ft}{0.4217\mu L^4}}} \tag{2.36}
$$

Figure 2.8 shows sample results for the gap height as a function of time for constant applied force. Equation 2.36 can be rearranged to give
This gives a relationship between the time and force required to squeeze a film from an initial to a final thickness. Equations 2.36 and 2.37 break down for $h$ less than ~10 nm.

\[
t_f = \frac{0.4217 \mu L^4}{2F} \left( \frac{1}{h_f^2} - \frac{1}{h_i^2} \right).
\]  

**Figure 2.7** Gap height as a function of time for a flat, square template

In Figure 2.7 the different cases are for an applied constant force of 10 (dotted line), 50 (dashed line), 100 (dashed-dotted line), and 500 lbs (solid line), respectively. Initial height $h_i = 2\mu$m, viscosity $\mu = 1$ cp and template size $L = 2$ cm. For the insert, the forces are 10, 20, 30 and 40 lbs, respectively.
For the case of 10 psi of pressure, over 75 seconds are required for the film thickness to be reduced from 2 $\mu$m to 100 nm. The times to reach 100 nm and 200 nm base layers are summarized in Table 2.1.

<table>
<thead>
<tr>
<th>Applied Force (lbs)</th>
<th>Time to 100 nm (s)</th>
<th>Time to 200 nm (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>75.6</td>
<td>18.8</td>
</tr>
<tr>
<td>20</td>
<td>37.8</td>
<td>9.4</td>
</tr>
<tr>
<td>30</td>
<td>25.2</td>
<td>6.2</td>
</tr>
<tr>
<td>40</td>
<td>18.9</td>
<td>4.7</td>
</tr>
<tr>
<td>50</td>
<td>15.1</td>
<td>3.7</td>
</tr>
<tr>
<td>100</td>
<td>7.5</td>
<td>1.9</td>
</tr>
<tr>
<td>500</td>
<td>1.5</td>
<td>0.37</td>
</tr>
</tbody>
</table>

Table 2.1 Time required to reach desired base layer thickness with constant force application for the case of a flat, square template.

Parameters used in equations 2.36 and 2.37 were $h_i = 2 \mu$m, $\mu = 1$ cp and $L = 2$ cm.

2.4.2 3D Pressure Distribution for Parallel, Circular Plates

An analytic solution to the squeeze film pressure distribution for a finite fluid drop centered between a flat, circular plate in parallel sinkage is considered. Due to the rotational symmetry, an analytic solution is readily found. The Reynolds equation in cylindrical coordinates and the derivation for the analytic solutions to the pressure distribution and the force are given in Appendix A. The pressure is a paraboloid of revolution of the form
\[ p = \frac{3\mu(r^2 - r_b^2)}{h^3} \frac{dh}{dt} - 2\gamma \]  

[2.38]

The force is obtained by integrating with respect to \( r \) and \( \theta \)

\[ F = 2\pi \left( \frac{-3\mu r_b^4}{4h^5} \frac{dh}{dt} - \frac{\gamma r_b^2}{h} \right) \]  

[2.39]

Equations 2.38 and 2.39 were used to perform numerical simulations of the equation of motion where fluid is modeled with boundary conditions that evolve as the fluid is squeezed out from between the surfaces. This is discussed in Chapter 4.

2.5 TOPOGRAPHY EFFECTS

The ratio \( \frac{h}{\sigma} \) is an important parameter showing the effects of surface roughness. For \( \frac{h}{\sigma} \gg 3 \), the roughness effects are not important, and the pressure distribution for corrugated surfaces are qualitatively the same as for flat plate film theory. The roughness effects become important as \( \frac{h}{\sigma} \rightarrow 3 \) [Patir and Cheng 1978]. The local film thickness is \( h_r = h + \delta_1 + \delta_2 \) where \( h \) is the nominal film thickness defined as the distance between the mean levels of the two surfaces. \( \delta_1 \) and \( \delta_2 \) are the roughness amplitudes of the two surfaces measured from their mean levels with zero mean and standard deviations \( \sigma_1 \) and \( \sigma_2 \). The parameter \( \sigma \) is the composite standard deviation of surface heights \( \sigma = \sqrt{\sigma_1^2 + \sigma_2^2} \).

Assume that the height of the features on the templates is on average 200 nm, and that to maximize the density of the circuit elements, the line widths (LW)
are the same as the width of the trenches (TW). Figure 2.8 shows this idealized case. The composite standard deviation of the surface heights for the template surface would be about 100 nm. Therefore, the topography of the template would be significant for \( h \) less than 300 nm. Inversely, this would mean topography effects are significant when the base layer thickness is less than 200 nm.

![Figure 2.8 Idealized template topography](image)

Freeland studied the effects of regular, sinusoidal roughness on the lubrication flow. For corrugation with \( \beta \) greater than 1000\( \pi \), described by the dimensionless angular wave number \( \beta = \frac{2\pi L}{\lambda} \), the lubrication flow that is produced nearly approaches flow that arises due to a flat plate where the effect height is given by \( h_{\text{eff}} = \left\{1 + 3\left(\frac{\delta}{h}\right)^2\right\}^{1/3} h \). Assuming a 1-inch template (about 2 cm of imprint area) and an average line width of 100 nm, corresponding to a wavelength \( \lambda \) of 200 nm, \( \beta = 200,000\pi \). For \( \frac{h}{\sigma} \gg 3 \), the rate of compression of frequently corrugated plates is qualitatively the same as that of flat plates with an effective height.
Chapter 3: Active Stage Design

The practical development of the SFIL process requires that the base layers are thin and uniform. An active stage machine is currently being designed and implemented to allow scientific studies of the imprinting process. This machine will have independent, high-resolution actuators and a feedback control system to squeeze the etch barrier fluid prior to UV exposure. The requirements and embodiment of such an active stage system are presented in this chapter.

3.1 Optimizing Base Layer Thickness, Orientation Alignment, and Throughput

The ideal imprint process would lead to an etch barrier with a zero base layer thickness. However, a zero base layer thickness cannot be obtained in finite time with finite pressure. From the analysis in chapter 2, it can be seen that for a finite pressure an infinite time is required to obtain a zero base layer thickness. Experimental results from the multi-imprint machine support this theoretical result in that base layers below 100 nm have been very difficult to achieve. In reality, there is a tradeoff between throughput and base layer thickness since a thinner base layer would require more time to achieve. If a base layer of uniform thickness and of the order of the imprinted features (typically 200 nm) is obtained, then a preliminary etching can eliminate the base layer without affecting the fidelity of the imprinted features. Therefore, a base layer thickness in the range of 100 to 200 nm would provide an optimal solution to both throughput requirements and imprinted feature fidelity.

In the initial test beds for SFIL development, a coarse, micron-level pre-calibration stage ensures that any initial orientation misalignment of the template
orientation stages relative to the substrate is within the range of motion for the template orientation stage to self-correct during the filling and squeezing process. In the multi-imprint stepper, there are no means to determine if the template and substrate are parallel during the imprint process, orientation correction is based-on design of flexures that self-correct during the squeezing process. Base layer thickness is determined experimentally for various loading conditions and controlled by moving the template towards the wafer until a specified load is measured, which corresponds to the desired base layer thickness.

The template orientation stages are passively, selectively compliant. These flexure stages have been implemented to minimize angular misalignment between the template and wafer. The flexure stages provide the advantage of having repeatable linear response through small displacements without generating particles. However, a problem with thick, wedge-shaped base layers remains as a major challenge to SFIL research. Furthermore, the current process relies heavily on force sensing to determine the film thickness during the filling and squeezing process. There is not enough correlative data to determine absolute gap thickness and orientation information from force measurements. Therefore, it is highly desirable to be able to characterize the absolute base layer thickness in real-time. An active stage design may be necessary to investigate solutions to these challenges.

3.2 Active Stage Components

To achieve a repeatable, uniform base layer thickness in the range of 100 to 200 nm, it may be necessary to have an active stage to provide precise control over the base layer thickness as well as orientation alignment between the
template and the wafer. As a part of the research for this thesis, an active stage test bed is being developed. The motion capability of the active stage system is based on the ideal Revolute Prismatic Ball (RPB) stage. The RPB platform has been thoroughly analyzed [Johnson 1999].

The systems that make up this test bed are 1) a wafer stage assembly, 2) template orientation stages 3) a micro-fluidic etch barrier dispensing system, 4) a high-resolution actuation system, 5) a gap sensing/orientation measurement system, and 6) a force measurement system. Each system must be designed or purchased as a modular component so that design modifications can be implemented or customized within reasonable costs and time constraints. The following discussion will provide some insight into the design requirements of the subsystems relevant to this research. The details of the gap sensing theory and implementation are given in chapter 4. A complete discussion of the entire active stage project is beyond the scope of this thesis, as the active stage test bed is currently in its infancy stage.

3.2.1 Wafer Stage Assembly

The wafer stage must bring the wafer substrate to within the motion range of the DC Mike motor and hold the wafer in place during imprinting. The wafer chuck must hold the wafer with minimal distortion by providing a uniform pressure across the backside of the wafer. Current wafer manufacturers provide wafers with low frequency height variations across their diameter. Using a flat vacuum wafer chuck with uniform pressure across the supporting surface can minimize these oscillations. Figure 3.1 shows the current embodiment of the wafer stage assembly. Air solenoids lift the wafer to within the motion range of the actuation system.
3.2.2 Template Orientation Stages

The motion requirement for the template orientation stage is that the center of rotation of the stage is at the geometric center of the surface of the template (see Figure 3.2). The template orientation stages from the multi-imprint stepper fulfill this requirement by using the four-bar linkage flexure mechanism shown in Figure 3.3. Each stage provides a decoupled motion capability about one axis, a rotation about the $x$ axis ($\alpha$) and a rotation about the $y$ axis ($\beta$).

Figure 3.2 Motion requirement for template orientation

---

4 Taken from Choi et al 2000.
To study the effect of the etch barrier on orientation alignment, only one orientation direction is required to decouple the effect of the pressure distribution on $\alpha$ and $\beta$ misalignment. A semi-circle notched flexure design was used to provide the necessary kinematics. This stage is shown in Figure 3.4. It can be seen in the equations\(^5\) developed by Paros and Weisbord, that the flexure is compliant about only one axis. The notched flexure acts as a revolute joint where its center of rotation coincides with an axis on the surface of the template that passes through the center of the template surface.

---

\(^5\) See Appendix B.
The one degree-of-freedom template orientation stage was designed to experimentally study the imprinting forces and gap sensing tool as well as to validate the numerical model of the squeeze film flow of the etch barrier. The torsional stiffness of this stage was designed to be similar to the template stages from the multi-imprint stepper. The stiffness coefficient for each of the template orientation stage (Figure 3.3) from the stepper was approximately 55 N-m/rad. From equation B.1, the radius \( R \) for the notched flexure was chosen as 1.27 mm, the equivalent depth \( b \) was 8.9 mm, and the minimum cross-sectional thickness \( t \) was 1 mm. This results in a torsional stiffness of 64 N-m/rad.

As of the writing of this thesis, the design of a complete template orientation stage to provide the appropriate kinematics for the active stage test bed has not been finalized.

3.2.3 High-Resolution Actuation System

In order to minimize undesirable grinding motion, each actuation leg consists of a revolute flexure joint (R), a motorized micrometer (P), a.k.a. DC-Mike actuators, a quartz force sensor, and a universal joint (U) connected in series. One RPU actuation leg is shown in Figure 3.5. Each actuation leg is connected in parallel with a distributed flexure ring to the active stage base structure. Three actuation legs form a tripod for an RPU stage, where the three attachment locations on the distributed flexure ring specify the orientation plane. Each component of the actuation system must be stiff in the lateral directions.
A distributed flexure ring, shown in Figure 3.6, is used to provide the appropriate kinematic constraints for the linear actuators. The distributed flexure ring allows the high-resolution actuators to bring the template and wafer surfaces into parallel alignment and squeeze the etch barrier down to an optimal base layer thickness while minimizing lateral motion between the template and wafer. The actuators generate pushing/pulling motions on the distributed flexure ring to provide a three-point position control of the template orientation as shown schematically in Figure 3.7. Actuation force needs to be large enough to generate 15 psi when the flexure ring is fully deflected in one direction.
Based on these motion requirements, Physik Instrumente M-222.50 DC Mike actuators were selected. This actuator has a travel range of 10 mm with a designed encoder resolution of 8.5 nm; the encoder ratio is 118,567.90 counts/mm. However, the minimum incremental motion is 50 nm. Each actuator is capable of 100 N (22.5 lbs) of force. An optional piezoelectric actuator, which would fit at the tip of the DC Mike actuator, is being considered for extremely high resolution, high force output. The piezoactuator’s resolution would be dependent on the number of bits of a D/A converter as well its travel range. The actuators are controlled by a closed-loop DC motor controller. Physik Instrumente provides the C-842 four-channel precision DC motor controller with a LabVIEW™ development package. The C-842 motor controller has an onboard trajectory profile generator, which can generate smooth s-curve position profiles.
3.2.4 Force Sensing System

In order to characterize the forces during the squeezing or separation process, dynamic forces must be measured in real-time. Force sensors are placed in series with the DC Mike actuators and coupled to the flexure ring via universal joints to prevent edge loading or bending moments. Consistent with the active stage design, these force sensors must be stiff in the lateral direction.

PCB Piezotronics™ 208C02 piezoelectric quartz force sensors were used to obtain force data. These piezoelectric force sensors can be used for dynamic force measurements providing a fast response in both compression and tension. These sensors have a dynamic range of ±450 N, compression and tension. Furthermore, the stiffness of the sensors is comparable to solid steel, \( k = 1 \times 10^9 \) N/m.

3.3 Implemented Design

The active stage kinematics or RPU stage is similar to the ideal RPB stage, which has been thoroughly analyzed using screw system theory. Figures 3.8 and 3.9 show the active stage system prototype. This test bed can be used to study the effect of the etch barrier on the orientation alignment for passive, selectively compliant stages. Separation of the template from the UV-exposed etch barrier can also be studied using the active stage.
Figure 3.8 Active stage prototype, side view

The active stage prototype consists of a rigid mounting structure (1), which is mounted to an optical table. The wafer chuck assembly (2) brings the wafer to within the motion range of the distributed flexure ring (3). The flexure ring is connected to three quartz force sensors (5) via universal joints. The quartz force sensors will measure the imprinting/squeezing force as well as the separation force. A rigid inner ring (4) will hold the template orientation stage or a vacuum based template holding mechanism. The high-resolution actuators (7) are connected to the revolute joints (6).
Figure 3.9 Active stage prototype, isometric view
Chapter 4: Real-Time Gap Sensing Via Fast Fourier Transforms of Spectral Reflectivity

As part of an active stage system, a feedback control system is required to accurately align the template and the wafer substrate. Several techniques were considered to obtain real-time gap information at several locations between the template and wafer. Based on specific design requirements, FFT-based spectral reflectometry is a relatively low-cost method that promises to deliver real-time gap sensing for SFIL.

4.1 INTRODUCTION

In the multi-imprint stepper, the template calibration stages can align the template and wafer to within a single interference fringe across a one-inch template. However, the initial orientation of the template may become misaligned beyond the calibration specifications due to excessive forces, hard contact with the wafer, etc. Correction requires that the template be removed and the calibration to be repeated. A real-time gap sensing method implemented in an active stage system will help to solve the issues of calibration, base layer thickness, and wedged base layers. During the squeezing process, an in situ spectral reflectometry technique based on Fast Fourier Transform (FFT) analysis will provide the necessary gap and orientation information. Orientation information is obtained in the form of gap information between two flats at three points.

Other optical methods to measure film thickness have been proposed which employ spectral or Fourier analysis of the reflectivity data from thin films. [Bouldin et al 2000], [Chalmers 2001], [Chason 2000], and [Sakurai and Iida 1992]. However, these methods are either not commercially available or not
directly applicable to in situ gap sensing in SFIL. Some of these methods require precise angular sweeps such as the X-ray method described by Sakurai and Iida. Others can be quite computationally complex, requiring comparisons between experimental and theoretical waveforms, which are stored in a database for a particular film with known optical properties such as the index of refraction. This search for matching waveforms can be time-consuming. In this research, a real-time gap sensing method that can potentially measure thin films down to 50 nm has been applied to measure the gap between the template and the substrate during the squeezing process. This chapter attempts to provide the background in the optical theory necessary to understand the basis for this innovative tool.

4.2 Analysis of Spectral Reflectivity

When an optical flat is placed in near contact with another optically flat surface, dark and bright bands will be formed. These bands are known as interference fringes, caused by constructive (bright bands) and destructive interference (dark bands) of light, and their shape gives a visual representation of the flatness and parallelism of the surface being tested. The parallelism and thickness of the gap is indicated by the amount of curvature and spacing between the interference fringes. Straight, parallel, and evenly spaced interference fringes indicate that the two flat surfaces are parallel along one axis. Spectral reflectometry relies on this constructive-destructive interference property of light.

For optically thin films in the visible wavelength range, the oscillations in the reflectivity are periodic in wavenumber \(k = 2\pi/\lambda\) such as shown the by the equation for the reflectivity of a single optical thin film
\[
R(\lambda) = \frac{\rho_{1,2}^2 + \rho_{2,3}^2 e^{-2\alpha d} - 2\rho_{1,2} \rho_{2,3} e^{-\alpha d} \cos\left(\frac{4\pi nd}{\lambda}\right)}{1 - \left(\rho_{1,2} \rho_{2,3}\right)^2 e^{-2\alpha d} + 2\rho_{1,2} \rho_{2,3} e^{-\alpha d} \cos\left(\frac{4\pi nd}{\lambda}\right)}
\]  

[4.1]

where \( \rho_{i,i+1} \) are the reflectivity coefficients at the interface of the \( i-1 \) and \( i \) interface, \( n \) index of refraction, \( d \) is the thickness of the film, and \( \alpha \) is the absorption coefficient of the film. Generally speaking, the index of refraction \( n \) varies with wavelength \( \lambda \).

Equation 4.1 was derived by assuming that the substrate exhibits perfect reflection and no absorption. It can be shown that equation 4.1 can be reduced to the general form

\[
R(\lambda) = A + B \cos(2knd)
\]

[4.2]

To better understand equation 4.2, take a simple optical thin film composed of the template, air, and the substrate. Since the template is very thick, the light passing through it does not see the effect of the template. Figure 4.1 illustrates this example with a thin film of air above the substrate. Incident light, with energy \( E_I \), is reflected off the template-gap interface with energy \( E_{R0} \) and partially transmitted into the gap and this is in turn reflected off the substrate. The light reflected from the substrate is then partially reflected off and transmitted through the interface through the template. When the light \( E_{R0} \) and \( E_{R1} \) are in phase, they will add constructively. When the light \( E_{R0} \) and \( E_{R1} \) are out of phase by they will add destructively.
Gap sensing is based on the periodicity of the reflectivity spectrum, as seen in equation 4.2. Since the spectral reflectivity is periodic in wavenumber, for 400 ~ 800 nm. Fourier analysis can be used to perform a spectral decomposition. The calculation of the thickness of an optical thin film is trivial once this information is obtained. The thickness of a film can be computed as

\[
d = \frac{i_{FFT} \cdot Mag}{2n_{\text{avg}} \cdot \Delta W_n},
\]

where \(i_{FFT}\) is the index of the FFT maximum and \(n_{\text{avg}}\) is the wavenumber averaged index of refraction. The ratio of sampled points in the wavenumber spectrum taken at even intervals over a spectral range, \(\Delta W_n = \frac{1}{\lambda_{\text{min}}} - \frac{1}{\lambda_{\text{max}}}\), to the number of points in the FFT is defined as the magnification factor, \(Mag\) \cite{Colburn 2001}. This method can measure film thickness down to about 350 nm based on a wavenumber averaged refractive index of 1.5 and has been demonstrated to be in good agreement with spectral ellipsometry and profilometry. For films below 350 nm, Inflection-Maximum-Minimum Analysis (IMMA) is used to compute the film thickness. The reader is referred to Chapter 8 of Colburn’s dissertation for more detailed information the theoretical background of FFT-based spectral reflectometry. This gap sensing system is under development for Dissolution
Rate Monitoring and is adapted for measuring film thickness during the squeeze film experiments.

Equation 4.2 is demonstrated for a simulated film with a thickness of 500 nm. In Figure 4.2, the theoretical reflectivity is plotted as a function of wavelength. The plot resembles an expanding sine wave. However, when the reflectivity is plotted as a function of wavenumber in Figure 4.3, it is clearly seen that this is a periodic signal.

![Graph](image)

**Figure 4.2** Normalized intensity of a 500 nm film as a function of wavelength
**Figure 4.3** Normalized intensity of a 500 nm film as a function of wavenumber

The Power Spectral Density (PSD) is computed for the corresponding signal and plotted as a function of the thickness, which is proportional to the index of the Fourier transform and is given by equation 4.3. From Figure 4.4, it can be seen that the peak at 500 nm corresponds to the thickness of the film.

The resolution of the algorithm is given by

\[
\text{resolution} = \frac{\text{Mag}}{2n\Delta w_n}
\]  

[4.4]

The size of the FFT improves the resolution, while it increases the processing time. Further, the spectral range of the data also affects the resolution. In the visible range, 400 – 800 nm, with an index of refraction of 1.5 and taking 128 \((2^7)\) sample points of data and performing a 16384-point FFT \((2^{14})\), results in a resolution of 2 nm. This theoretical work was the proving ground for the embodiment used in the experiments. The implementation details are further discussed in chapter 6. This includes accounts of the hardware used, signal processing issues, and areas for improvement.
Figure 4.4 PSD of theoretical reflectivity signal with a 500 nm thickness.

In Figure 4.4, the index of refraction was taken as 1.5; $2^7$ points were used from the signal and $2^{14}$-point FFT, i.e. $Mag = \frac{2^7}{2^{14}}$. 
Chapter 5: Numerical Simulations

A series of numerical simulations to predict the performance of the imprinting systems used in SFIL are discussed in this chapter. A model of the mechanical system was developed, which considered two primary modes of compliance - axial and torsional. Initial conditions were selected to be similar to those in the actual SFIL experiments. The actuation was assumed to have an ideal feedforward controller. The equations of motion were simulated using a fourth order accurate Runge-Kutta scheme with adaptive time marching. Simulation results are presented in this chapter for the case of an inclined surface of infinite width with both single and double s-curve position control. Finally, the case of a parallel, circular plate with a single fluid drop was simulated.

5.1 Dynamic System Model

In this section the equations governing the dynamic response of the imprinting system are presented. The dynamic equations are developed assuming an imprinting system where the motion is governed by compliance in two directions: the axial direction along the motion axis of the actuators and a rotational direction about an orthogonal axis. The template holding mechanism based on semi-circle notched flexures discussed in chapter 3 (see Figure 3.4) was designed to be consistent with this assumption and is implemented in the active stage test bed. Equivalently, a single rotational axis can be the orientation axis of the template in the multi-imprint stepper where the axis of rotation is an axis that is a linear combination of the motion provided by the \( \alpha-\beta \) stages. This axis also passes through the center of the template surface (see Figure 3.2). Henceforth
the multi-imprint and active stage systems will be referred to as the mechanical system.

These equations are developed neglecting lateral motions in the $x$-$y$ directions. If the output of each actuation leg is assumed to be identical, then the mechanical system can be modeled as a lumped parameter system as seen in Figure 5.1. This system has two degrees of freedom, $z$ and $\theta$. The actuator motions, $z_A$ and $\dot{z}_A$, are taken as inputs into the mechanical system. The structural stiffness in the $z$ direction has been modeled as a single composite stiffness parameter, $K_Z$, with damping coefficient $C_Z$. The template orientation stages are compliant in torsion with stiffness $K_\theta$ and damping coefficient $C_\theta$. The force, $f$, and torque, $\tau$, due to the pressure from the etch barrier layer are treated as nonlinear forcing terms in the equations of motions of the system.

![Figure 5.1 Lumped Parameter Model](image)

The equations of motions for the mechanical system are derived from Lagrange’s equations. The motion in the vertical and torsional directions of Figure 5.1 is essentially the classic mass-spring-damper system with active
damping from the etch barrier. The dynamic behavior of such systems can be described by

\[ M \ddot{z} + C_Z (\dot{z} - \dot{z}_A) + K_Z (z - z_A) = f(z, \dot{z}, \theta, \dot{\theta}) \]  \[ \text{[5.1]} \]

and

\[ I \ddot{\theta} + C_\theta \dot{\theta} + K_\theta (\theta - \theta_0) = \tau(z, \dot{z}, \theta, \dot{\theta}) \]  \[ \text{[5.2]} \]

where the fluid force and torque are functions of position and orientation. The fluid couples the two, otherwise independent, motions. In the following sections, the set of model parameters are presented with details on the selection of initial conditions for the simulation.

### 5.2 System Parameters for Numerical Simulation

#### 5.2.1 Etch Barrier Fluid Properties

The capillary pressure is obtained using the surface tension coefficient for the etch barrier formulation. The surface tension of the various etch barrier formulations, which is composed of free radical generators and cross-linking agents dissolved in a solution of organic monomer, silylated monomer, and dimethyl siloxane oligomer derivatives, are all nearly identical to within experimental error at 28 dynes/cm [Colburn et al 1999]. If the fluid between the plates is water instead of etch barrier, the surface tension is 72 dynes/cm at 20°C. From this, the boundary conditions due to the capillary pressure for the fluid volume can be computed. The viscosity of the etch barrier layer is the same as that of water at room temperature and atmospheric pressure, which is about 1 cP \((1 \times 10^{-3} \text{ N} \cdot \text{s/m}^2)\). Both the etch barrier and water were considered to have a constant viscosity and to be incompressible.
5.2.2 Composite Stiffness and Damping Coefficients

The composite vertical stiffness, $K_Z$, of the mechanical system was computed from a distributed spring system as shown in Figure 5.2. The vertical and torsional stiffness of flexure components with torsional compliance were computed using equations from Paros and Weisbord. The relevant Paros and Weisbord equations used to compute the stiffness for the components with notched flexure joints are presented in Appendix B. These components include the revolute joint ($K_{RJ}$), the universal joint ($K_{UJ}$), and the template holder ($K_{TH}$).

![Figure 5.2 Stiffness in the z direction of the active stage system](image)

The stiffness of the actuator was approximated by assuming an aluminum tube of 50 mm in length with a 5 mm inner radius and 6 mm outer radius. The equation for the stiffness is then

$$k = \frac{EA}{L}$$  \[5.3\]

where $E$ is Young’s modulus for aluminum, $A$ is the area seen by a vertical force and $L$ is the actuator length as shown in Figure 5.3. The length is an approximate
length between the clamped-clamped ends of the actuator since this length will vary when the actuators push and pull.

![Figure 5.3 Model of actuator for stiffness computation](image)

Beam bending equations approximate the stiffness of the distributed flexure ring for each actuation arm. Each one-third segment of the distributed flexure can be modeled as a fixed-fixed beam as shown in Figure 5.4. Equation 5.4 describes the bending of a fixed-fixed beam under a vertical load.

![Figure 5.4 Fixed-fixed beam](image)

\[
F = \frac{192EI}{L^3} \delta_z = k \delta_z \tag{5.4}
\]

where \( I = \frac{bh^3}{12} \). The flexure ring is machined from 7075-T6 aluminum alloy with a Young’s modulus, \( E \), of 72Gpa. The median radial length of the flexure ring is 3.5 inches. The flexure ring is 1 inch wide and 50 mils thick. With a total
clamping length of 1.5 inches, this gives total of \( L_{\text{eff}} = \frac{(2\pi R - 1.5)}{3} \). The resulting stiffness of each segment of the flexure ring is \( 1.2 \times 10^4 \text{ N/m} \). Each segment of the flexure will deflect 2 mm for a 24 N (5.4 lb) load.

Table 5.1 summarizes the stiffness of each component in the actuation arm. The actuators are the most compliant members of the RPU leg. As seen in Figure 5.2, the members of the RPU leg are connected in series, thus the dynamics of the mechanical system are governed by the actuator stiffness. To see this point, take a simple case with two linear springs in series. The equivalent stiffness of such a system is

\[
\frac{1}{k_{eq}} = \frac{1}{k_1} + \frac{1}{k_2}
\]

\[ k_{eq} = \frac{k_1 k_2}{k_1 + k_2} \]  \[4.5\]

If \( k_2 \ll k_1 \), then

\[
k_{eq} = \frac{k_1 k_2}{k_1 + k_2} = k_2 .\]

\[4.6\]

Thus, the stiffness of the more compliant component governs the dynamics.

The last row of table 5.1 shows the composite system stiffness in the axial direction. The multiplication by 3 results from the three legs of the actuator system being in parallel.
<table>
<thead>
<tr>
<th>Component</th>
<th>Symbol</th>
<th>Z-Stiffness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Revolute Joint</td>
<td>$K_{RJ}$</td>
<td>$4.1 \times 10^9$</td>
</tr>
<tr>
<td>DC Mike Actuator</td>
<td>$K_{DC}$</td>
<td>$5.0 \times 10^7$</td>
</tr>
<tr>
<td>Quartz Force Sensor</td>
<td>$K_{FS}$</td>
<td>$1.0 \times 10^9$</td>
</tr>
<tr>
<td>Universal Joint</td>
<td>$K_{UJ}$</td>
<td>$4.7 \times 10^9$</td>
</tr>
<tr>
<td>Template Holder</td>
<td>$K_{TH}$</td>
<td>$7.2 \times 10^8$</td>
</tr>
<tr>
<td>Distributed Flexure Ring</td>
<td>$K_{RF}$</td>
<td>$1.2 \times 10^4$</td>
</tr>
<tr>
<td>Composite System Stiffness</td>
<td>$K_Z$</td>
<td>$4.4 \times 10^7 \times 3$</td>
</tr>
</tbody>
</table>

**Table 5.1** Mechanical system stiffness values

The equivalent inertial terms, M and I, were computed from Pro/ENGINEER® solid models. The equivalent mass is approximately 1.5 kg. The equivalent inertia is approximately $5 \times 10^{-6}$ kg⋅m$^2$. It is assumed that the damping factor, $\zeta$, for the mechanical system is 0.05. This gives the damping coefficients as $C_{eq} = 2\zeta \sqrt{K_{eq} M_{eq}}$, thus $C_Z = 1400$ N⋅s/m and $C_\theta = 2 \times 10^{-3}$ N⋅m⋅s.

5.2.3 Model of Actuation System

The actuator motion is taken as input into the mechanical system and assumed to have an ideal control scheme. The actuators are controlled by a PID controller, which comes on board the Physik Instrument C-842 motor controller.
Figure 5.5 Ideal s-curve (solid line) and actual encoder data (squares)

Figure 5.5 show the ideal s-curve and the actual encoder data during squeezing process. The encoder data was averaged from 10 sets of data with both air and water as fluid. The 5th order polynomial ideal s-curve in this case is 

$$z_A(t) = -30t^5 + 75t^4 - 50t^3 + 5$$

where $z_A$ is in microns. To achieve this output from the actuators, inputs into the s-curve profile generator for the C-842 motor controller were: velocity = 0.05 mm/s, acceleration = 0.015 mm/s$^2$, and jerk = 0.025 mm/s$^2$. PID terms were 300, 50, and 1200, respectively. The PID parameters were determined through experimental tuning using data from the motor encoders.

5.3 NUMERICAL METHOD

5.3.1 Fourth Order Accurate Runge-Kutta with Adaptive Time Step

The fourth order Runge-Kutta method was used to obtain the solutions to the equations of motion, which are initial value ordinary differential equations
(ODE). With any numerical simulation both accuracy and stability of the method in computing the solutions to the dynamics equations are important considerations. The fourth order Runge-Kutta scheme has an increased region of stability as compared with other explicit schemes such as second order Runge-Kutta and explicit Euler. The stability diagram for the fourth order Runge-Kutta scheme includes eigenvalues on the imaginary axis with a small portion involving both positive real eigenvalues when the imaginary component is nonzero, i.e. \( \lambda_c = \lambda_r + i\lambda_i \) where when \( \lambda_r \neq 0, \lambda_r > 0 \) [Collis 2000].

The problem is conditionally stable. Since the initial gap is small, the time step must be chosen carefully to maintain numerical stability. Numerical instability exists in the analytical solution to the fluid damping force and damping torque. Firstly, the film thickness cannot be less than zero. This would result in the breakdown of the Reynolds equation. The pressure becomes infinite at zero film thickness. Furthermore, hard contact between the template and wafer cannot be modeled by the Reynolds equation. Secondly, the damping force and torque are dependent on the state variables, \( f(z, \dot{z}, \theta, \dot{\theta}) \) and \( \tau(z, \dot{z}, \theta, \dot{\theta}) \). Thus the solution could become unstable since the eigenvalues of the system change during the simulation. This phenomenon is observed during the simulations. For example, an initial time step of \( 1 \times 10^{-7} \) seconds or 0.1 microseconds will result in a stable solution for the first part of the simulation when the base layer thickness is large. Then this time step must be decreased for the solution to remain stable. When the base layer thickness is below 500 nm, a time step of 1 nanosecond is required to maintain numerical stability. With a very small time step such as 1 nanosecond, a 1 second simulation could easily extend over 24 hours in a C++ implementation on an 850 MHz computer with 128 MB of RAM and 256KB of level 2 cache memory (L2 cache operations are faster than RAM). An adaptive
time marching is required to minimize computational time and provide accurate solutions. This adaptation was done manually by providing the largest stable time step as input into the simulation. These time steps were determined by brute force. Each simulation was broken into several simulation time intervals. Then the time step was decreased by a factor of 10 when the simulation showed signs of instability. This was repeated until each run of the simulation was complete.

5.3.2 Modeling the Initial Conditions for an Imprint

The equations of motion for the mechanical system represent an initial value problem. This ODE system requires a set of known initial conditions. The set of initial conditions was chosen to reflect those existing in the imprinting process. A further requirement was that these could be replicated in the experimental setup.

The initial gap between the template and the wafer was assumed to be 2 \( \mu \text{m} \). The initial conditions at the left and right boundaries of the flow at \( x = x_\alpha \) and \( x = x_\beta \) are determined by simple volumetric calculations. For a template of one square inch and a base layer thickness of 200 nm to completely fill the gap, this requires that the volume of fluid dispensed is 0.13 \( \mu \text{L} \) (1.3 \( \times 10^{-10} \text{ m}^3 \)). This minimizes material wastage as well as the force required to squeeze out the fluid. The placement of this fluid volume is assumed to be a line of 2 mm width, which completely wets the template along its length and is along the centerline of the template surface. A 2 \( \mu \text{m} \) column of fluid 2.54 cm (1 inch) long and 2mm wide is about 0.1 \( \mu \text{L} \). This fluid volume would thus fill the gap at a base layer thickness of between 100 and 200 nm.
The feature sizes are typically on the order of 100-200 nm. Precalibration of the template orientation stages can align the template and wafer to within two interference fringes across a one-inch template, which is equivalent to a wedge height of approximately 340 - 440 nm. The wedge can be computed as

$$W = L \tan \theta$$  \[5.5\]

where $W$ is the wedge height (m), $L$ is the length of the template (0.025 m), and $\theta$ is the angle between the template and the wafer (rad). Thus through careful pre-calibration, the initial angle between the template and wafer is about $2 \times 10^{-5}$ rad. Being slightly less conservative, a wedge of $2.5 \times 10^{-5}$ rad was used. Table 5.2 summarizes the initials conditions and the system parameters used in the numerical simulation.

<table>
<thead>
<tr>
<th>Parameter Description</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>$M$</td>
<td>1.5 kg</td>
</tr>
<tr>
<td>Stiffness constant in the axial direction</td>
<td>$K_z$</td>
<td>$1.3 \times 10^8$ N/m</td>
</tr>
<tr>
<td>Damping constant in axial direction</td>
<td>$C_z$</td>
<td>1400 N⋅s/m</td>
</tr>
<tr>
<td>Inertia</td>
<td>$I$</td>
<td>$5 \times 10^{-6}$ kg⋅m²</td>
</tr>
<tr>
<td>Stiffness constant in the torsional direction</td>
<td>$K_\theta$</td>
<td>64 N⋅m/rad</td>
</tr>
<tr>
<td>Damping constant in the torsional direction</td>
<td>$C_\theta$</td>
<td>$2 \times 10^{-3}$ N⋅m⋅s/rad</td>
</tr>
<tr>
<td>Template width</td>
<td>$L$</td>
<td>2 cm</td>
</tr>
<tr>
<td>Viscosity of the etch barrier</td>
<td>$\mu$</td>
<td>1 cp</td>
</tr>
<tr>
<td>Surface tension of the etch barrier</td>
<td>$\gamma$</td>
<td>28 dynes/cm</td>
</tr>
<tr>
<td>Initial base layer thickness</td>
<td>$h_i$</td>
<td>2 micron</td>
</tr>
<tr>
<td>Initial angular misalignment</td>
<td>$\theta_0$</td>
<td>$2.5 \times 10^{-5}$ rad</td>
</tr>
<tr>
<td>Initial boundary</td>
<td>$x_{x,y}$</td>
<td>$\pm$ 1 mm</td>
</tr>
</tbody>
</table>

Table 5.2 Simulation Parameters Reflecting Experimental Setup
5.4 SQUEEZE FILM DYNAMICS OF INCLINED SURFACE OF INFINITE WIDTH

5.4.1 Single S-Curve Motion Profile

The parameters in table 5.2 were used to simulate equations of motion for the imprinting system. The results of these simulations using a single s-curve actuator motion profile are shown below in Figures 5.6 through 5.8. The single s-curve actuator motion profile is shown in Figure 5.6. The total downward motion of the actuator was 4 microns (this value is consistent with the value chosen for the double s-curve motion profile presented in the following section where the actuation forces and final base layer thickness were reasonable).

![Simulated single s-curve actuator motion profile](image)

**Figure 5.6** Simulated single s-curve actuator motion profile
Figure 5.7 Base layer thickness corresponding to single s-curve actuation

The results from the simulation show that this system has very high damping due to the etch barrier fluid as expected. With this type of actuation, the final base layer thickness at 0.5 seconds was approximately 440 nm while the imprinting force was nearly 25 lbs. However, the force is not significant until the latter half of the simulation time interval. The end result is that very thin base layers are not easily achieved with low actuation forces.

A base layer of this thickness cannot be properly etched. However, to achieve thinner base layers with single s-curve position control, the actuation force would be significantly larger since the force scales as $\frac{1}{h^3}$. In the following section, an improved method of actuation is proposed that results in thinner base layers.
5.4.2 Double S-Curve Motion Profile

From both the experiments and the simulation, it was noticed that the results, especially in the final base layer thickness and measured forces could be improved, at the least, through a better feedforward actuation scheme. Furthermore, since the force is proportional to the approach velocity of the template and inversely proportional to $h^3$, this actuation was separated into two segments. The first segment occurs for large base layers. For large base layers, say above 500 nm, the actuators should move the template assembly faster than for thinner base layers. The motion profile of the actuators for this scheme is illustrated in Figure 5.9. It was assumed that the motors could provide the specified motion and that the controller was an ideal high bandwidth controller. The simulation time was $0 \leq t \leq 0.5$ seconds. In the first 0.05 seconds, the
actuators move down 3 µm and in the last 0.45 seconds, the actuators move down 1 µm.

![Graph showing actuator height over time](image)

**Figure 5.9** Simulated double s-curve actuator motion profile

It is seen in Figure 5.10 that with this actuation scheme, a base layer of 200 nm can be achieved in 0.5 seconds without an excessive amount of force. This is a big improvement over the previous case of a single s-curve profile where the base layer thickness was more than double the current final base layer thickness.

The maximum force of the actuators used in this research is specified at 100 N per actuators. This means that the actuators are capable of delivering a total output of over 60 lbs. Figure 5.11 shows the resulting force-time profile. The force rises very quickly in this case because the velocity of approach is high in the first interval of the actuation. Then, as the base layer becomes smaller, the velocity decreases so that the forces remain reasonably low. It is possible to
improve upon these results by tuning the s-curve profile. However, this improvement is marginal and research efforts were focused instead on other areas.

![Graph of base layer thickness versus time](image1)

**Figure 5.10** Base layer thickness corresponding to double s-curve actuation

![Graph of force versus time](image2)

**Figure 5.11** Force corresponding to double s-curve actuation
5.5 **Squeeze Film Dynamics of Parallel, Circular Plates**

The analytical squeeze film damping force for parallel, circular plates was applied to the equations of motion of the mechanical system. The analytical equations for the fluid pressure for a parallel circular plate with a circular drop from chapter 3 were applied to this simulation.

In this section, the results of a numerical simulation of the squeeze film dynamics are presented. The results from numerous simulations show very similar trends. The results presented here are nearly optimal when considering final base layer thickness, required actuation forces, and the time to achieve the desired base layer thickness. The results of the simulation in this section show similar behavior as in the previous section where the solution of the two-dimensional Reynolds equation was applied.

![Graph of base layer thickness vs. time](image)

**Figure 5.12** Base layer thickness corresponding to the case of finite, parallel circular plates
Again, Figure 5.12 shows that a base layer thickness of 200 nm can be obtained within reasonable force limits of the actuators. The actuation scheme in this case resulted in an improved force-time profile similar to the double s-curve actuation in the previous section.

Figure 5.13 Force corresponding to the case of finite, parallel circular plates
Chapter 6: Experimental Results

6.1 INTRODUCTION

In order to verify the validity of the numerical simulations and scientifically quantify the effects of the etch barrier layer on the dynamics of the mechanical system, experiments were performed using the active stage prototype. The data collected during the experiments included: 1) the motor shaft encoder outputs from each of three high-resolution DC micrometer actuators, 2) the dynamic force reading from each of three quartz force sensors mounted in series with the actuators, and 3) gap sensing/film thickness measurements at two locations across the template. The following sections discuss the process of collecting this data and present the experimental results.

6.2 EXPERIMENTAL SETUP

6.2.1 Experimental Adaptations of the Active Stage Test Bed

Since a few of the subsystems of the active stage test bed have not been fully implemented, a couple of adaptations were required to complete the experiments and gather the necessary data. First, a wafer chuck system was not readily available. In the active stage, the wafer chuck holds the spin-coated wafer during the imprinting process and air solenoids pneumatically lift the wafer towards the template stage. Thus, a temporary holding device to approximate the semblance of an actual wafer chuck was designed and used. This component had to be stiff in the lateral directions and hold the substrate close to the template surface. It was designed to hold a $2.54 \times 2.54 \times 0.635$ cm ($1 \times 1 \times 1/4$ inch)
optically flat quartz plate coated with a layer of chromium. This chromium-plated quartz plate acted as the wafer and is shown in Figure 6.1. The chromium has a high reflectivity and acts as a first surface mirror, which has similar optical properties to a wafer with a transfer layer. Setscrews were used to hold quartz substrate in place. To minimize bending in the quartz, aluminum plates were used at the interface between the setscrews and the quartz to distribute the force from the setscrews evenly across the sides of the quartz and provide a flat, uniform clamping surface. This minimizes high contact stresses and distortion of the quartz.

Figure 6.1 Chromium-Plated Quartz Substrate Fixture

Second, a fluid dispensing system that could accurately dispense about 0.1 µL of fluid in the gap between the quartz substrate and the template surface was not available. The simulations model the fluid as a line with boundaries that grow outward from the center. The dispensing system in the actual SFIL process writes a fluid pattern that leaves no air bubbles trapped in the etch barrier and reduces the amount of force required to squeeze the fluid to ultra-thin film
thickness. Without the benefit of an accurate dispensing system, the next best alternative was to completely fill the gap between the template and substrate. The template is raised over 20 micron above the substrate, then water is dispensed and fills the gap via capillary action.

Third, the etch barrier has the same viscosity as water so that water has the same fluid mechanic effects as the etch barrier. This can be easily seen in the incompressible Reynolds equation (see equation 2.10). The dominant fluid property that affects the squeeze film pressure is viscosity. The different surface tensions of the two fluids have a negligible effect in the overall squeeze film pressure because when the fluid completely fills the gap, the boundary effects become insignificant. Furthermore, working with etch barrier to perform squeeze film experiments also poses unknown health risks without the use of the automated dispensing system. Therefore, it was determined that water could be used as a substitute for the etch barrier fluid.

6.2.2 Data Acquisition Hardware

The data acquisition hardware consists of an 800 MHz computer with a National Instruments AT-MIO-16XE-50 data acquisition board capable of 20K samples per second. The gap sensing system consists of an Ocean Optics® SQ2000 four channel UV-VIS fiber optic spectrometer containing a 25 µm slit, a 600 line grating blazed at 500 nm, and 2048 pixel CCD array. The bandwidth of the spectrometer is from 350 to 1000 nm. With a minimum 3-millisecond integration time, this system has a maximum spectral acquisition rate of 300 Hz. Two spectrometer channels were used to obtain film thickness results. Each fiber
optic probe was illuminated with a Tungsten-Halogen lamp. The broadband light was focused onto the fiber optic probes with collimating lens.

The fiber optic probes are positioned with their axis spaced 0.7 inches apart. A view of the physical setup is shown in Figure 6.2.

![Figure 6.2 Physical layout of the experimental setup](image)

6.2.3 Control Software

Control software for the experiment was developed using National Instruments™ LabVIEW™ 6i. This control software was optimized for speed during the data collection since the duration of actuation lasts only one second. To collect enough data during this short duration, the sampling rate must be at least 10 Hz. As mentioned above, the data acquisition is not limited by the hardware. The sampling rates quoted by the manufacturers of the respective
hardware systems are for stream-to-disk or RAM buffer operations. For in situ sampling, or in this case, when time stamps of the corresponding encoder, force sensor, and spectral data are required, the data cannot be streamed to the RAM buffer for post-processing. LabVIEW™ limited the sampling frequency. In optimizing the software for speed, there was a trade-off between speed, robustness, and memory usage. The spectrometer CCD array has 2048 pixels and the LabVIEW™ software drivers provided by Ocean Optics® output the entire data array. If the amount of memory allocated to store this array is large, this limits the speed at which the spectral data can be sampled. Therefore, data was collected for up to 2 seconds. This resulted in a sampling frequency of 13 Hz, which is adequate to see trends in the motion profile. This sampling frequency is an example for this particular embodiment and is not a limitation of the processing capability for in situ gap sensing. An implementation in C/C++ or other high level language would yield vastly improved processing speed.

Figure 6.3 shows a screenshot of the current implementation in LabVIEW™. Notice that the two charts, on the left of Figure 6.3, displaying an FFT of the signal are exemplary. Removing the periodic information contained in the reference signal was initially difficult since measuring reflectivity data through quartz was not performed in dissolution rate monitoring. This problem was overcome by recognizing that when the template is far away from the substrate, a reference signal can be taken because there is no interference at large gaps. This distance still needs to be quantified, however, this is a signal processing issue. Some discussion of the signal processing issues will be provided later in section 6.4 of this chapter.
Figure 6.3 Screenshot of control software to perform experiments.
Also, as shown in Figure 6.3, the parameters passed to the LabVIEW™ drivers for the motor controller are given in tables 6.1 and 6.2. The PID terms were selected based on experimental tuning of the actuator outputs. The actual motion profiles were visually compared against the desired motion output and the PID terms were adjusted so that the desired and actual motions were closely matched.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Recommended</th>
<th>Range</th>
<th>Actual</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proportional-Term</td>
<td>250</td>
<td>100 to 300</td>
<td>300</td>
</tr>
<tr>
<td>Integral-Term</td>
<td>12</td>
<td>0 to 50</td>
<td>50</td>
</tr>
<tr>
<td>Derivative-Term</td>
<td>800</td>
<td>0 to 1200</td>
<td>1200</td>
</tr>
<tr>
<td>Integration-Limit</td>
<td>2000</td>
<td>0 to 2000</td>
<td>2000</td>
</tr>
</tbody>
</table>

Table 6.1 PIDL parameters, recommended and actual settings for the C-842

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity</td>
<td>0.05 mm/s</td>
</tr>
<tr>
<td>Acceleration</td>
<td>0.015 mm/s²</td>
</tr>
<tr>
<td>Jerk</td>
<td>0.025 mm/s²</td>
</tr>
</tbody>
</table>

Table 6.2 Parameters passed to the C-842 onboard s-curve profile generator⁶

---

⁶ The reader is referenced to the operating manuals from Physik Instrumente (PI).
6.3 **Experimental Procedure**

Experiments were performed using the active stage prototype. Prior to performing each experiment, the gap and angle of inclination was initialized with air as the lubricating fluid in the gap. The alignment was performed by moving the actuators independently until there were three or four fringes, which were parallel to the center of rotation of the template holding stage. These fringes could be easily seen and counted with the naked eye. Then the actuators were uniformly raised by 20 micron and distilled water was dispensed into gap and allowed to fill the gap completely. It was discovered in the course of the experiments that particle contamination was a major factor contributing to the quality of the experimental results. However, due to the lack of automation, improved results could not be obtained within a reasonable time frame. Thus, the experimental results presented in this thesis are meant to illustrate the trends in the data.

It is noted that many more sets of data were taken than is shown here, however due to the lack of automation, it was difficult to attain a controlled set of initial conditions. Since the data sets have differing initial conditions, the data cannot be easily compared or statistically analyzed. The data provided in this thesis are meant to exemplify trends in the results as opposed to specific values.

6.4 **Experimental Results**

6.4.1 Verification of the Simulation Results by Experiments

Several parameters were estimated in the modeling of the active stage system. It was hypothesized that the composite axial stiffness parameter has a higher amount of uncertainty than the other system parameters. Based on this,
the composite stiffness was calibrated using the results from one experimental data set (known as the calibration set). The calibrated composite stiffness was used to perform simulations that were then correlated to an independent set of experimental results (known as the correlation set). From the simulation results, it is inferred that the actual composite stiffness was less than previously estimated. A comparison of the correlation set and the simulation supports the hypothesis. The data show similar trends and are reasonably close. However, there are still discrepancies, especially at large times, which may be due to particles and other unknown parameters that have not been calibrated. These issues require further investigation. The following details the process used in calibrating the composite stiffness parameter.

A calibration simulation was performed taking initial conditions that approximate the conditions for a specific set of measured data. With the fiber optic spectrometer probes spaced 0.7 inches apart, the measured gap thickness for each probe was 4780 nm and 2360 nm and the probe locations are assumed to be symmetric about the center of rotation of the template holding mechanism. This leads to an average height of 3570 nm with $\theta \sim 1.36 \times 10^{-4}$ radians and total actuation of 5 $\mu$m. These initial conditions were used to perform a simulation of the squeeze film dynamics of the active stage system.

The composite axial stiffness and damping were systematically decreased until the agreement between the film thickness from the experiments and the simulations were within five percent. The axial stiffness was $1.5 \times 10^6$ N/m and the damping constant was 75 N-s/m. The remaining system parameters in the numerical simulation were taken from table 5.2. Figure 6.4 shows the data set used in the calibration of the composite stiffness. The simulated film thickness and the experimentally obtained film thickness values are within two percent.
Figure 6.4 Average film thicknesses from simulation results (solid line) and experimental results (circles). Calibration set.

The trends in the motion for both the experimental results and the simulation results are very similar. The influence of the s-curve actuation profile is evident in Figure 6.4. At the beginning of the actuation where the velocity is small, there is no change in the base layer thickness. As the actuators accelerate downward, the base layer thickness decreases and the rate of sinkage of the template is fairly constant. Then as the actuators slow down the rate of sinkage also decreases and the base layer thickness levels off. It is observed in the experiments that after the actuators stop moving, the base layer thickness continue to decrease at a slow rate until the strain energy is minimized.

An encouraging result seen in both the experiments and the simulation is that there is a corrective torque in the fluid damping that corrects the initial angular misalignment of the template relative to the substrate. The angle of inclination from simulation and experiments are in good agreement. This
indicates that the analytical estimate of the torsional stiffness is very close to the actual stiffness of the one degree-of-freedom flexure.

**Figure 6.5** Angle of inclination from simulation results (solid line) and experimental results (circles). Calibration set.

**Figure 6.6** Force due to fluid pressure from simulation results (solid line) and experimental results (circles). Calibration set.
Figure 6.6 shows that the force due to the squeeze film pressure follow the same trend for the simulation and the experiments. The maximum force in the experimental data was 1.75 lbs. The maximum force in the simulation was 1.35 lbs. The relative difference between the two results is 23%, which is quite significant. This discrepancy could be due to several possibilities.

First, compliance estimates for the mechanical system contribute to difference in the actual and expected forces. In the actual setup, there are certain compliances that are not modeled, for example, the substrate is modeled as rigid, however, the chuck, which holds the chromium substrate has compliance. Second, there existed some topography due to macroscopic scratches on the chromium substrate. Since chromium is a fairly soft material, maintaining a clean, flat surface was extremely difficult. The third cause relates to the previous in that there were particles observed on the substrate and template surfaces under the magnification of a microscope. These particles could not be eliminated due to handling of these components. The combined effects of all these factors are not fully understood and more research is needed in this area.

![Figure 6.7 Average film thicknesses from simulation results (solid line) and experimental results (circles). Correlation set.](image)
Figure 6.8 Angle of inclination from simulation results (solid line) and experimental results (circles). Correlation set.

Figure 6.9 Force due to fluid pressure from simulation results (solid line) and experimental results (circles). Correlation set.

Figures 6.7 through 6.9 show a set of experimental results that is independent from the calibration set. Again, the trends in the dynamics are very
similar. In Figures 6.7 and 6.8, the simulation results follow the experimental data for small values of time. For large $t$, there seems to be a DC offset in the data. This discrepancy could be due to the factors previously discussed.

Despite the differences in the actual values, these results indicate that the assumption of a lubrication flow governed by Reynolds equation can be used to model the squeezing process in SFIL. Further refinements can be made in both the simulations and the experimental setup to obtain improved data, especially for smaller film thickness measurements. An automated system that allows actual imprinting of the template onto a wafer substrate would probably yield repeatability in the data and be less prone to particle contamination.

6.4.2 Experiments with Unfiltered Water

The following data presented here are for two conditions. Initially, the water used was unfiltered distilled water. It was believed that this water was sufficiently clean. However, it was decided that filtering this water with 0.02-micron filters could not adversely the results. Therefore, the first set of data is from unfiltered distilled water and the second set is from filtered distilled water. In this section results from the experiments with unfiltered water are presented.

Figure 6.10 shows that the gap decreases very little for six microns of downward actuation. Further, the change in the angle of inclination relative to the substrate seems to be negligible. This suggests that particles between the template and substrate have been squeezed very hard. Visual inspection through the quartz template shows that there are isolated particles distributed across the surface of the substrate. However, only an automated active stage system can potentially eliminate particles.
Figure 6.10 Film thickness during squeezing with six microns of downward actuation. Spectrometer probe 1 (circles) and probe 2 (squares)

For Figure 6.11, the effect of particle contamination is not as apparent as in Figure 6.10. This is because the initial film thickness is larger. In this case, the gap is able to decrease much more. The initial angular misalignment is large with a wedge of 2.4 µm across 0.7 inches. At the end of two seconds, the wedge is less than 0.7 µm across 0.7 inches. The gap at probe 1 decreases by a significant amount as compared with the gap at probe 2. This suggests that the fluid is generating a damping torque, which assists in correcting the angular misalignment. Figure 6.11 amplifies the point that an initial error in the alignment may be corrected if flexure stages are used to orient the template during imprinting.
6.4.3 Experiments with Filtered Water

It was determined that particle contamination in the fluid may be a factor in the minimum possible gap height that could be achieved. The water used in the current set of results was filtered through a 0.02-micron filter. The filter removes particles that are larger than 20 nm from the water. For thin base layers, the data shown in Figure 6.12 represents the best set of data obtained over the course of the experiments. It was shown that the gap heights achieved after filtering the water (Figure 6.12) was appreciably smaller than for unfiltered water (Figure 6.10). Unfortunately, performing the experiments with filtered water poses the same problem as unfiltered water when the particles are introduced by the handling of the substrate and template.
Figure 6.12 Film thickness during squeezing with five microns of downward actuation. Spectrometer probe 1 (circles) and probe 2 (squares)

6.4.4 Experimental Squeeze Film Force

Figure 6.13 Force due to fluid pressure from experimental results for varying values of average approach velocity
Figure 6.13 shows the force-time plot for four different instances of motion supplied by the actuators. In all of the cases, the actuators move for about 1 second. This translates into a higher average approach velocity. In Figure 6.13, the maximum force due to the squeeze film pressure increases when the approach velocity is higher. The force increases proportionally with the approach velocity, but since the film thickness of each case is different, this increase in Figure 6.13 is not linear.

6.5 OBSERVATIONS AND DISCREPANCIES

6.5.1 Particle Contamination

Although the experiments were performed in a class 100 clean-room, particle contamination was a fundamental problem in achieving the desired thin fluid layers of 100 – 200 nm. During the course of the experimental work, it became evident that is would not be possible to eliminate all particles without an automated process. Particles could be caused by manual handling of the experimental components. Furthermore, the fluid itself may have particles. The water was filtered using 0.02-micron filters. This resulted in slight improvements in the minimum attainable gaps. The substrate was placed under a microscope with a magnification of 100× to detect particles. This was done immediately after the substrate and template were cleaned in a solution of acetone followed by an isopropyl alcohol rinse and a filtered air bath. A comparison with a clean wafer, i.e. one that was not previously handled, showed that any handling beyond a moving the wafer from its container to the imprinting machine would result in particle contamination.
In the imprinting process, it has been shown that defects due to particle contamination can be removed by first using a sacrificial wafer to perform initial imprinting to remove the particles. Upon repeated imprinting, particles remain on the sacrificial wafer. However, for the active stage test bed, there is no current capability to perform this imprinting. Thus, it is very difficult to obtain particle-free gap between the quartz and substrate.

6.5.2 Signal Processing

In the process of collecting gap data, noise or distortion is introduced into the reflectivity intensity data. Consider that the light received by the spectrometer consists of three components as follows:

\[
R\left(\frac{n}{\lambda}\right) = I\left(\frac{n}{\lambda}\right) \ast S(\lambda) \ast K(t)
\]  

[6.1]

where \(I\left(\frac{n}{\lambda}\right)\) is the actual reflectance of the film under consideration. It is a function of the index of refraction \(n\) and wavelength \(\lambda\). \(S(\lambda)\) is a function, which characterizes the wavelength dependence of the optical components of the system. \(K(t)\) is a function that allows for time-dependent intensity variations such as changes in the illumination intensity of the light source (in this case the tungsten-halogen lamp), sample placement, angle of incidence, focus, etc.

In the best-case scenario, \(S(\lambda)\) and \(K(t)\) do not contain periodic data. Typically, this can be assumed for \(S(\lambda)\), since spectrometer manufacturers usually design these optical systems taking this into consideration. However, it was observed that \(K(t)\) does contain periodic information and generates a signal
in the FFT that is not indicative of the true signal \( \frac{n}{\lambda} \). A method is proposed for the minimization of the distortion introduced by \( K(t) \) is described.

The intensity is normalized by a reference signal. It was observed that the normalization of the intensity spectrum is very sensitive to the reference spectrum. The reference spectrum should be at zero gap or film thickness and through a material with the same index of refraction. However, if the reference cannot be taken for these conditions, the Fourier transform of the intensity spectrum will contain a false peak that belongs to the reference signal. This leads to incorrect detection of the true signal since the magnitude of the reference is dominant in this case.

Fortuitously, it was discovered that the intensity signal when the gap is infinite, or practically speaking when interference is negligible, is identical to that of zero gap. This allows the fiber optic probes to be placed at the measurement locations and a reference to be taken through the quartz template. The template is moved up from the substrate 100 microns and then a reference signal is captured. Without this capability, taking a proper reference is not trivial since the reference must be taken with the template removed and then the template must be put back into place before the experiment can proceed. However, in doing this, the reference has been slightly modified because the index of refraction of quartz is not unity, the sample placement has changed, and the measurement angle has changed.

Height and angle of the probe also make a difference when obtaining the reference signal. In the case of the reference, its period also changes as a function of the optical path length. This is affected by the angle and focus of the signal. Changes to these parameters can affect the measured gap thickness or lead to failure in the FFT. Thus, the reference should be collected at large gap where the
minimum gap size at which the reference should be taken still needs quantification. It is believed that by taking a reference in this way, the effect of $K(t)$ can be eliminated.

In addition to collecting a reference signal, a dark signal can also be collected to account for the effect of ambient illumination. This dark signal is taken with the tungsten-halogen lamp momentarily off. The dark signal can then be subtracted from both the reference signal and intensity signal before the intensity is normalized by the reference as in equation 6.2. The PSD of the normalized intensity is then taken.

$$\tilde{R} = \frac{\text{intensity} - \text{dark}}{\text{reference} - \text{dark}}$$  \hspace{1cm} [6.2]

![Figure 6.14](image)

**Figure 6.14** FFT of the intensity of the reflectivity data (a) $2^{13}$-point FFT (b) $2^{14}$-point FFT

Figure 6.14 shows the effect of the reference signal in the FFT of the reflectivity data. A low frequency false peak appears which has relatively large magnitude. This poses a problem because the false peak masks the true peak
when measuring thin layers in the range of about 300 to 400 nm. Figure 6.15 illustrates the case when a false peak masks the true peak. The difference between 6.14a and 6.14b is that the number of zeros used to pad the FFT has been increased by a power of two. This stretches the FFT out and the spectral leakage is increased, however, note that the index at the maximum of the FFT has now been approximately doubled. Spectral leakage is the smearing of energy across the FFT domain, which results in wider peaks. This doubles the resolution since a peak at an FFT index of 200.5, which cannot be resolved in 6.14a, is now equal to a peak at an FFT index of 401 in 6.14b, for example.

![FFT peak example](image)

**Figure 6.15** False signal masking the true signal in FFT

6.5.3 Template/Substrate Deformation

The template and substrate can be deformed when using setscrews to constrain their positions. The setscrews cause local stress concentrations that are undesirable. This leads to possible bowing of the template and substrate. To minimize the effect of stress concentrations on the bowing of the template and substrate, flat aluminum plates were placed between the setscrews and the quartz pieces.
Chapter 7: Closing Remarks

7.1 SUMMARY OF RESEARCH

This research has encompassed a broad range of areas including analytical modeling, numerical simulations, and experimental analysis. It has also incorporated a medley of software/hardware issues and spectral analysis. By interpreting the analytical models, numerical simulations, and experimental results, it has been shown that the Reynolds equations for squeeze film damping is a valid and useful tool for understanding the dynamics of the mechanical systems in SFIL.

The fluid pressure plays a significant role to orient the passively compliant stages used in the multi-imprint stepper and the single imprint machines. It has been shown that the pressure tends to correct the angular misalignments by generating a damping torque and the pressure asymmetry cannot be ignored. Thus, the original intent of the passive stage designs has been proven to work. The passive stages self-correct due to the coupling between the mechanical system and the liquid etch barrier. Although presence of the etch barrier aides in correcting the misalignment, it also limits the rate at which imprinting can be done since, thinner base layers require more time to achieve. However, with an appropriate control scheme, based on a two s-curve motion profile, this problem can be solved. Furthermore, the theoretical and measured forces can be achieved by the actuation systems currently implemented.

An additional contribution of this research work has been the application of a real-time gap-sensing tool in measuring the film thickness of the fluid during the squeezing process. In developing an active stage system to perform SFIL, this
is a major milestone. The next step would be to use this information to perform real-time control of the base layer thickness and template orientation.

Step and Flash imprint lithography has the potential to become a manufacturing technology within several years. It offers high-resolution capability, high-throughput, and cost effectiveness. Much progress has been made in the way of appropriate chemistries for the etch barrier, transfer layers, etc. Significant work has been done to understand the kinematics of the machines necessary to perform imprinting. Several imprinting prototypes have been developed and are currently being used to meet the ongoing challenges in the research. There are several milestones that must be surpassed before SFIL can become a full manufacturing technology. The following sections attempt to illuminate the reader on these specific tasks.

7.2 Future Work

7.2.1 Numerical Solution to the Generalized Reynolds Equation

In deriving the analytical solution to the pressure distribution, the topography of the template has been neglected. Also, three-dimensional effects could be significant enough to warrant a full numerical solution to the generalized Reynolds equation, which would include topography, growth of the fluid boundary, and angle of inclination as well as lateral motions. A practical issue in modeling with the generalized solution to the Reynolds equation is computational complexity since the solution would need to be numerical as opposed to analytical. Complete fluid-structure coupling may require a high number of floating-point operations and complex numerical algorithms to solve for the
pressure distribution. Then this pressure must be numerically integrated to obtain the force and torque.

7.2.2 Distributed parameter model of the mechanical system

The mechanical system has been modeled as a lumped parameter mass-spring-damper model leading to a two degree of freedom mechanical system. Structural interaction leads to an increase in the number of degrees of freedom. For example, the revolute joint adds another rotational degree of freedom that has not been modeled in this research. Screw systems theory could be used to model such mechanical systems with a large number of degrees of freedom.

7.2.3 Measurements with Patterned Templates

The current gap-sensing scheme can be used to measure the gap between the template and substrate for base layers down to 350 nm without using the IMMA algorithm. This algorithm has not been successfully applied to the computation of thin base layers. A workaround to this problem is to have a step in the template. For the area that is not used for imprinting, there can be a 300 nm recess in the template, for example. This is illustrated in Figure 7.4. Measurements using patterned templates can then be performed without exceeding the limits of the gap sensing tool.

![Figure 7.1 Recessed depth to aide in gap sensing with pattern templates](image-url)
7.2.4 Control scheme

The ultimate goal of an active stage system is to actively control the orientation of the template relative to the substrate. A better understanding of the fluid mechanical effects gives insight in the process of developing a feedforward or feedback control system. In a feedback control scheme, the controller would take as input the gap sensing information and perform real-time control at 10 Hz or better. Ultra-high resolution, high bandwidth actuation can be supplied by piezoelectric actuators, which are capable of nanometer resolution motions.
Appendix A: Axisymmetric Problem

The Reynolds equation for the geometry of a flat, circular plate approaching a flat surface is given as

$$\frac{\partial}{\partial r} \left( r^3 \frac{\partial p}{\partial r} \right) + \frac{1}{r} \frac{\partial}{\partial \theta} \left( h^3 \frac{\partial p}{\partial \theta} \right) = 12 \mu r \frac{dh}{dt}. \quad [A.1]$$

If the plate is parallel as it approaches the surface, then for a drop fluid with radius $r_b$, axial symmetry exists and the pressure is only a function of the radius. Thus in the case of an axisymmetric squeeze film, the Reynolds equation is given as

$$\frac{d}{dr} \left( r^3 \frac{dp}{dr} \right) = 12 \mu r \frac{dh}{dt}. \quad [A.2]$$

Integrating gives

$$r^h \frac{dp}{dr} = 6 \mu r^2 \frac{dh}{dt} + A. \quad [A.3]$$

Dividing through,

$$\frac{dp}{dr} = \frac{6 \mu r}{r^3} \frac{dh}{dt} + \frac{A}{r} \frac{r^3}{dh}. \quad [A.4]$$

and since $\frac{dp}{dr} \neq \infty$ when $r = 0$ then $A = 0$. Hence,

$$\frac{dp}{dr} = \frac{6 \mu r}{r^3} \frac{dh}{dt}, \quad [A.5]$$

and a further integration gives

$$p = \frac{3 \mu^2}{r^3} \frac{dh}{dt} + B. \quad [A.6]$$
Assuming the liquid perfectly wets the surfaces of the plate and substrate, i.e., zero contact angle, the pressure at the boundary is given by \( p = -\frac{2\gamma}{h} \) when \( r = r_b \). Therefore \( B = \frac{-2\gamma}{h} - \frac{3\mu r_b^2}{h^3} \frac{dh}{dt} \).

\[
p = \frac{3\mu(r^2 - r_b^2)}{h^3} \frac{dh}{dt} - \frac{2\gamma}{h}
\]  

[A.7]

The force is given by the integration of the pressure in the \( r \) and \( \theta \) directions

\[
F = \int_0^\pi \int_0^{r_b} r p(r) dr d\theta .
\]  

[A.8]

Integrating with respect to \( r \) and \( \theta \), the squeeze film force is then

\[
F = 2\pi \left( -\frac{3\mu r_b^4}{4h^3} \frac{dh}{dt} - \frac{\gamma r_b^2}{h} \right).
\]  

[A.9]
Appendix B: Design of Semi-Circular Notched Flexures

Paros and Weisbord developed analytic equations for the compliance of elliptical flexure hinges. The equations developed by Paros and Weisbord have been widely used in the field of precision engineering to design selectively compliant components that provide linear, precise, repeatable motion without the problems of backlash, stiction, and particle generation. Figure B.1 illustrates the geometry of a simple semi-circular notched flexure.

![Semi-circular notch flexure hinge](image)

**Figure B.1** Semi-circular notch flexure hinge

The geometric parameters that describe the compliance of the flexure are the radius of the semi-circle $R$, the thickness at the thinnest cross section $t$, the
base $h$ (for a semi-circular notch, $h = t + 2R$), and the width $b$. Two characteristic non-dimensional parameters are $\beta = \frac{t}{2R}$ and $\gamma = \frac{h}{2R}$.

The torsional compliance about the $z$-axis is

$$\frac{1}{k_{\theta x}} = \frac{3}{2EbR^2} \left[ \frac{1}{2\beta + \beta^2} \right] \left\{ \frac{1 + \beta}{\gamma^2} + \frac{3 + 2\beta + \beta^2}{\gamma(2\beta + \beta^2)} \right\} \sqrt{1-(1+\beta-\gamma)^2} +$$

$$\left[ \frac{6(1+\beta)}{(2\beta + \beta^2)^{1/2}} \right] \tan^{-1} \left( \frac{2+\beta}{\sqrt{1-(1+\beta-\gamma)^2}} \right) \right\}$$

[Equation B.1]

The stiffness along the $x$-axis is

$$k_{\delta x} = Eb \left[ -2 \tan^{-1} \sqrt{2-\gamma} + \frac{2}{2\tan^{-1} \sqrt{2-\gamma}} \right]^{-1}$$

[Equation B.2]

The motion capability of the notched flexure with respect to other directions is not significant as compared the rotational deflection about the $z$ direction and linear deflection along the $x$ direction [Paros and Weisbord 1965].
References


Choi, B. J., S. Johnson, and S.V. Sreenivasan. 1999. A high resolution imprint lithography machine for patterning flat and curved substrates, Department of Mechanical Engineering, The University of Texas at Austin. DARPA Interim Report.


Vita

Anh Quoc Nguyen was born in Vungtau, Vietnam on July 22, 1976, the eldest son of Mai Thi Dinh and Ban Van Nguyen, deceased. After completing his work at Rockport-Fulton High, Rockport, Texas, in 1995, he entered Rice University in Houston, Texas. He received the degree of Bachelor of Science in Mechanical Engineering from Rice University in May 1999. In September 1999, he entered The Graduate School at The University of Texas at Austin.

Permanent Address: 108 North Twelfth Street
P.O. Box 117
Fulton, Texas 78358

This thesis was typed by the author.