Advanced Mask Modeling Accuracy and Stability Study-
University of Wisconsin Mask Modeling

International SEMATECH
Technology Transfer # 00063964A-ENG

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Abstract: This report presents progress on finite element (FE) modeling of the pattern transfer process to investigate pattern-specific image displacement resulting from mask manufacturing and application in a system for extreme ultraviolet (EUV), scattering with aperture limited projection lithography (SCALPEL), and 157 nm optical lithography.

Keywords: Finite Element Modeling, Pattern Generators, Photomasks

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1 EXECUTIVE SUMMARY

As lithography error budgets on pattern placement become more stringent for sub-130 nm technology, it is imperative that all mask-related distortions be quantified, controlled, and minimized. It will be essential to identify the influence of thin film stress on pattern placement errors. In this research, the effect of mask material properties, manufacturing, and usage on image placement will be evaluated. Finite element (FE) models have been developed to simulate this pattern transfer process, using equivalent modeling techniques. Analytical, experimental, and FE procedures have been combined to accurately determine these effects on final pattern distortions.

2 INTRODUCTION

Semiconductor manufacturing continues to sustain product innovation at a rate unparalleled in any other industry. Historically, advances in semiconductor devices have resulted from scientific and technological developments, which have steadily decreased the size of circuit features that can be achieved in silicon under volume-production requirements. Smaller features—narrower lines spaced more closely together—imply increased circuit densities. Increased densities in turn permit more features per chip, faster circuits, and reduced power requirements per function. Fueled by a market ever hungry for more sophisticated semiconductor devices, the relationship known as Moore’s Law charts the historic doubling of chip complexity every 18 months for the past three decades. Lithography is a key technology in scaling devices to smaller geometries. It is the process that transforms complex circuit diagrams into working patterns on the surface of a silicon wafer. In principle, optical lithography is similar to the process used to print conventional photographs. A mask containing an image of one layer of circuitry is flooded with a beam of ultraviolet light. The light reacts with a thin layer of resist—a photosensitive coating spun onto the surface of the wafer—and the mask pattern is imaged into the exposed resist. A succession of exposure and processing steps is used to form a number of layers of insulator, conductor, and semiconductor materials, superimposed on the wafer surface, with a typical packaged integrated circuit requiring 8–25 lithography steps and several hundred intervening processing steps. The next generation of semiconductor devices, projected to reach commercial production around the year 2005, will realize integrated circuits with critical dimensions (CDs) on the order of 100 nm [ITRS, 1999]. While industry standard optical (ultraviolet) lithography will continue to be used for non-critical mask levels with geometries at and above 130 nm, imaging the critical dimensions of next-generation chips will require an advanced lithography technology employing an exposure beam with a wave length shorter than that of deep ultraviolet light. Electron-beam, focused ion beam (FIB), X-ray, extreme ultraviolet (EUV), and other technologies can meet these requirements. A critical element for these technologies is the ability to produce precise images.

The accurate placement of images on a wafer is a combination of tolerances throughout the imaging process. When the mask image is formed, the resist is exposed with the appropriate image. This imaging process is normally performed by an e-beam writing directly on resist on the surface of the mask. The process of exposing the image in the resist causes minute, but important, deformations in the physical properties of the resist. This deformation translates into a displaced image on the mask. After processing, the image may be transformed into a different configuration. Finally, the mask is used to produce images on the production wafers. This process has similar deformations to the process described above. With the shrinkage of the geometries required for the images, even the slightest deformation may have a significant impact on the yield of production devices. There is not a body of work that understands this process over the various non-optical technologies.

The purpose of this project is to investigate pattern-specific image displacement resulting from mask manufacturing and application in a system for X-ray, EUV, scattering with aperture limited projection lithography (SCALPEL), ion beam, and 157 nm optical lithography ("the Five Technologies"). The primary focus of this effort will be on EUV, SCALPEL, and 157 nm. The long-term effort will evaluate the effect of the image displacement on wafer images.

The objective of this effort is to understand the image reproduction process employed in lithography through computer modeling of the imaging process effects. This effort will focus on the forces that impact the accuracy of image placement during the manufacture of an image mask and the subsequent stability of the image transfer to a wafer.

The initial phase of this work will be an analysis of the image placement accuracy on the mask during imaging employing a symmetrical pattern. The impact of adding a pellicle will be analyzed. After imaging, the stability of the image during mask processing will be evaluated. The final step will be to evaluate the impact of any displacement on the final image as developed on the process wafer. The key result will be the analysis of this impact on the overlay precision of two different patterns. An understanding of the mask dynamics during clamping, aligning, and subsequent heating during wafer imaging needs to be reviewed (thermo-mechanical stress induced by the application). Additional efforts will be to replace the symmetrical images with pattern-specific ones that are typical of memories, microprocessors, and ASIC devices. Since each of these patterns has a different component layout, the distortion is anticipated to be different.

For each lithographic technique, the key areas of research will focus on the following:

- Evaluate image placement accuracy on completed masks
- Evaluate the mechanical impact of mounting and the thermal impact of using the mask in a system
- Evaluate the relative placement accuracy of complementary images produced by two masks
- Apply the findings of the most promising technologies to patterns that are representative of memory devices, microprocessors, and ASICs
- Evaluate the impact of employing a pellicle in 157 nm optical lithography

The project has been in place since 1997. The original intent was to narrow the scope of the technologies being investigated and provide detailed information on a reduced number of technologies over the following years. In 1998, the Next Generation Lithography Task Force recommended that International SEMATECH focus on a reduced number of technologies: namely EUV and SCALPEL. Consequently, the scope of work was reduced to focus on these technologies to obtain the desired data. While some additional work on ion projection lithography (IPL) and X-ray was needed, it was clearly relegated to lower priority and, taken together, should represent no more than 15% of the total contract effort. In addition, with this extension, there is a continuing need to compare the models with actual mask data. The following table served as a guideline for the level of effort on the five technologies to be addressed.

Table 1 Focus of Modeling Activities Throughout Project Lifetime

	1997	1998	1999	2000
SCALPEL	35%	30%	30%	25%
IPL	35%	30%	15%	0%
X-ray	30%	30%		
EUV	0%	0%	20%	25%
193 & 157 nm optical	0%	10%	35%	50%

This report contains the latest research efforts on the mask modeling for 157 nm, EUV, and SCALPEL. Modeling results are updated, and future work is outlined. Individual member companies with which International SEMATECH collaborated and interacted have been identified in the reports.

3 METHODOLOGY

The supplier for this activity has been Professor Roxann Engelstad, from the University of Wisconsin-Madison College of Engineering. Within her Computational Mechanics Center (UW-CMC), her team has the unique capability of using numerical methods, namely FE modeling to facilitate the prediction and propose correction methodologies for pattern displacements in lithographic masks during manufacturing and usage. To predict image placement errors, the commercial FE code ANSYS was employed to create FE models of the physical mask structure and sample DRAM/SRAM pattern layouts. However, given the scale difference of the pattern features (nanometers) and the physical structure of the mask (centimeters), it is nearly impossible to generate and implement complete FE models of the entire mask. Consequently, equivalent models have been developed to predict the global pattern distortions while circumventing the time and intense computational requirements. These equivalent models are developed using localized models and analytical methods to ensure their effectiveness. Models have been built that include all aspects of the mask manufacturing process and usage including:

- Fabrication
  - Blank Processing
  - E-Beam Writing
    - Thermal Effects
      - Resist Stress Relief
      - Dynamic Effects
      - Mounting
  - Pattern Transfer
  - Pellicle Mounting
- Application
  - Mounting
  - In Situ Thermal/Mechanical Response
  - Environmental Conditions
    - Radiation Damage
    - Particle Contaminants

The FE models for each mask life step are generated to accommodate the unique features of each lithographic mask. The basis element type is chosen based on the type of material modeled (e.g., substrate, thin films, or membranes). Equivalent models are used to identify pattern placement errors without having the FE model physically replicate all of the mask features. The material properties, such as the modulus of elasticity, Poisson's ratio, and shear modulus are entered into the structural models. The heat transfer FE models include the full exposure system with heat conduction, convection, and radiation where known. Based on known and assumed input parameters, both in-plane and out-of-plane displacements of the mask are computed. All models are benchmarked and verified with experimental data whenever possible. The FE method has been demonstrated to give excellent results for many different models compared with experimental data obtained at UW and additional data provided by International SEMATECH member companies. Unknown and new material properties are also determined at the UW-CMC in a thin films laboratory. Accurate measuring techniques and devices are implemented to provide the necessary data for the FE modeling.

4 RESULTS

Because the output of this activity has been extensive, only an overview of the selected results will be presented here. For more detail, see Section 6, references, or the International SEMATECH website under project LITH130. Reports completed in 1999 include the following:

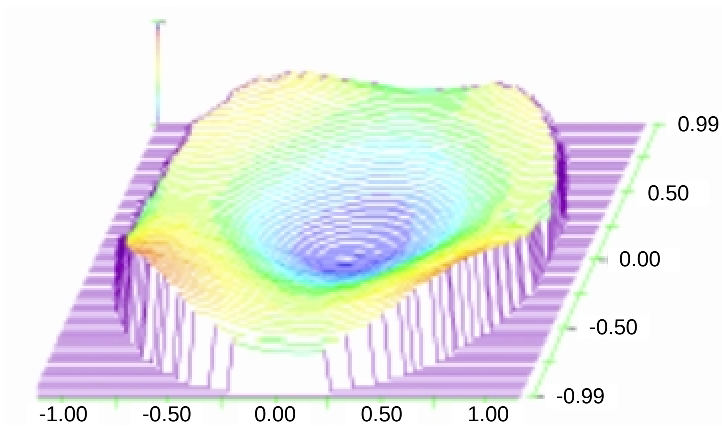
- Milestone 7: Final Model Refinements, March 31, 1999
- Milestone 8: Evaluations from Final Models – Primary Technology, March 31, 1999
- Milestone 9: Evaluation from Final Models, June 30, 1999
- Milestone 10: Concentrated Analysis of Selected Technologies, June 30, 1999
- Milestone 11: Final Report through Modification 01, August 31, 1999
- Milestone 12a: Summary Report on X-ray Mask Modeling, September 30, 1999
- Milestone 12b: Summary Report on Stencil Mask Modeling, September 30, 1999
- Milestone 13: Summary Report on 157 nm Optical Mask Modeling, November 15, 1999
- Milestone 14: Summary Report on EPL Mask Modeling, November 15, 1999
- Milestone 15: Summary Report on EUV Mask Modeling, November 15, 1999

4.1 Optical Mask Modeling

4.1.1 Reticle Distortion Due to Film Stress

4.1.1.1 Chrome Film Metrology

Chrome stress has been identified as one of the principal factors contributing to pattern transfer inplane distortion (IPD). However, the magnitude and uniformity of the chrome stress is often not measured and generally not reported in the literature. In this activity, photomask distortion was measured for a number of standard photomasks, and the resultant film stress was calculated as the first step in understanding the influence of film stress on pattern placement. A "standard" 4" × 4" × 0.090" and three 6" × 6" × 0.25" mask blanks (resist-coated) were measured on a Zygo phase shifting interferometer. Surface displacement measurements (see Figure 1) were completed on each mask blank with resist, without resist, and without resist and chrome. The measured surface displacements were converted to film stress values for the various plates, with the chrome stress calculated for the endpoints of the chrome thickness specification. The results are summarized in Table 2.



Note: The peak valley amplitude is 1290 nm.

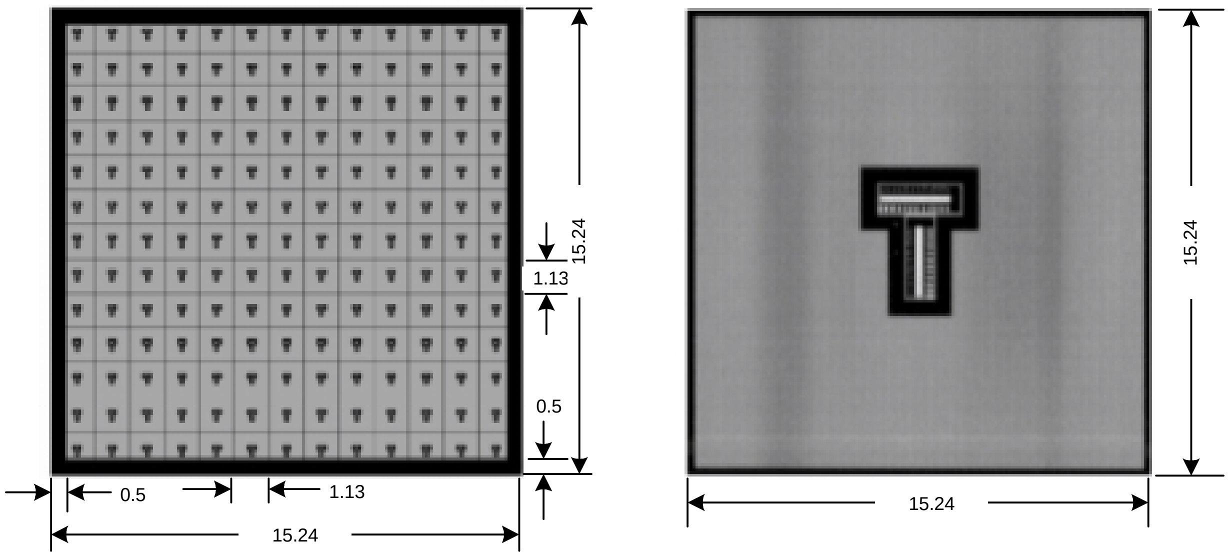
Figure 1 Chrome-Induced Shape of a 4.0-Inch Unpatterned Optical Reticle

Table 2 Calculated Film Stress From Surface Displacement Measurements

	Size	Resist	Chrome	Chrome
Thickness		450 nm	100 nm	110 nm
Blank 1	4 × 4	9.0 MPa	729 MPa	
Blank 2	6 × 6	2.2 MPa	330 MPa	301 MPa
Blank 3	6 × 6	3.9 MPa	350 MPa	318 MPa
Blank 4	6 × 6	5.2 MPa	350 MPa	318 MPa

4.1.1.2 Pattern Transfer Experimental Results

An experiment was performed on a 6-inch photomask to determine the effects of pattern transfer on image placement. A standard 6-inch photomask was purchased from a commercial supplier with a 13 × 13 CD monitor pattern distributed across the surface. In addition to the metrology pattern, an anisotropic pattern (nominally 2 ×10 µm bars) covered the remaining surface (see Figure 2).

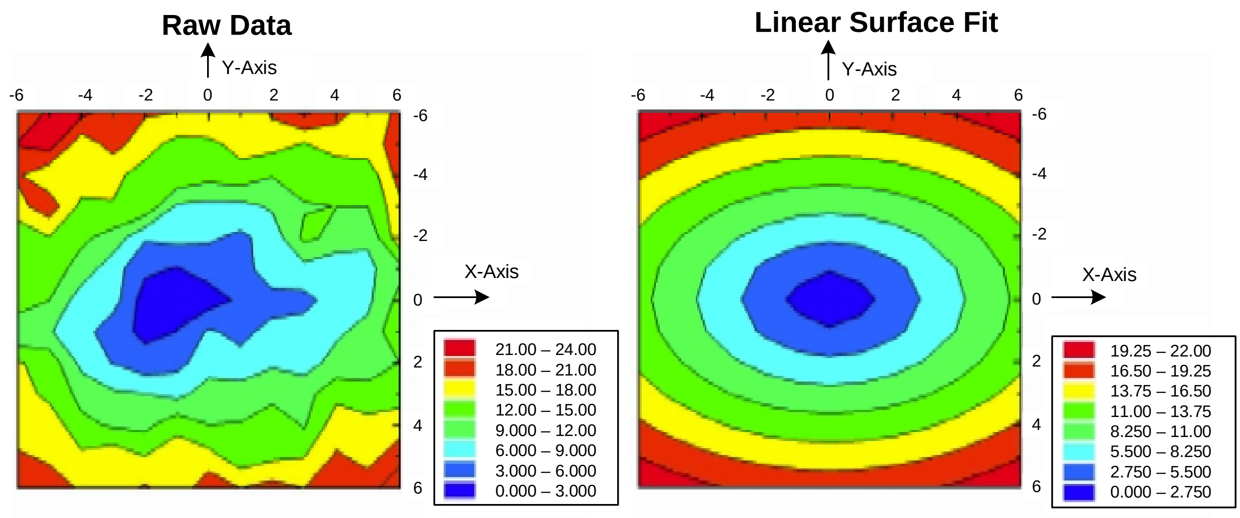


a) Complete Reticle **b) Image of One Cell**

Figure 2 Scanned Image of Actual Photomask Used for Experiments

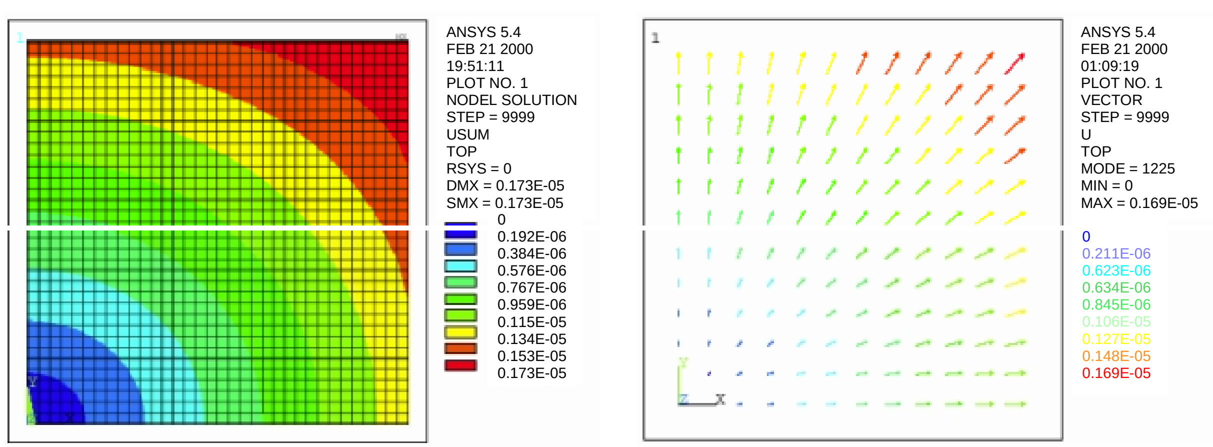
Image placement metrology was performed on a Leica IPRO after resist development and again after chrome etch. Each of the alignment marks was measured 10 times and the results averaged. The difference between the two metrology steps was calculated and assumed to represent pattern distortion resulting from the pattern transfer step only. Figure 3 shows a summation of these results and a linear fit to the results.

Initial FE simulations accounted for the large anisotropic pattern, but did not incorporate the metrology site within each cell. Quarter symmetry models were used for computational efficiency. Inputs for film stress values were those measured previously. Figure 4 shows the computed displacement for the manufacturing process. The largest displacement predicted was 17 nm, slightly below the amount seen experimentally (~22 nm). It is known that the Leica metrology tool performs some on line corrections to the data map based on previous knowledge of the mounting deformations. It is expected that including these corrections and the metrology cell into the FE simulation will bring the simulations in line with the experiments. Work will continue throughout the year on these activities.



a) Experiment **b) Simple Linear Fit**

Figure 3 Contour Plot of Image Placement Changes before and After Pattern Transfer: a) Experiment; b) Simple Linear Fit



Note: Maximum predicted distortions (17 nm) are slightly below experimental results (22 nm)

Figure 4 Simulated (quarter symmetry) Image Placement Errors

4.1.2 Pellicle Mechanical Characteristics

The final fabrication step of a photomask before use is the application of a pellicle. The pellicle is typically an organic film stretched over a frame that is then attached to the photomask to shield the patterned area from particulates that would contribute to imaging errors. It has been proposed that the application of the pellicle and frame could contribute to image placement errors in the completed mask. The disturbing part is that these errors would not be included in the error budget of the mask since the pellicle is applied after all metrology has been performed.

To understand the magnitude of the issue, an experimental program has been put in place to measure the effects of mounting pellicles, measure pellicle mechanical properties, and build FE models to calculate the resultant image distortion on the completed photomask. Experiments are in place to measure the out-of-plane distortions on the photomask resulting from the pellicle film and reticle frame. These curvature results will allow film stress to be calculated and be used as input to the FE model. Resonant frequency measurements will also be performed on the pellicle film, since the film stress is expected to be low. From the resonant frequency data, shape, and material properties, the pellicle film stress will be verified. A unique challenge to the resonant frequency testing, trapped air between the mask surface and the suspended film will be compressed, which may have an effect on the measured resonant frequency. To avoid this complication, masks with pressure relief holes (see Figure 5) drilled in the glass will be prepared to prevent this from happening.

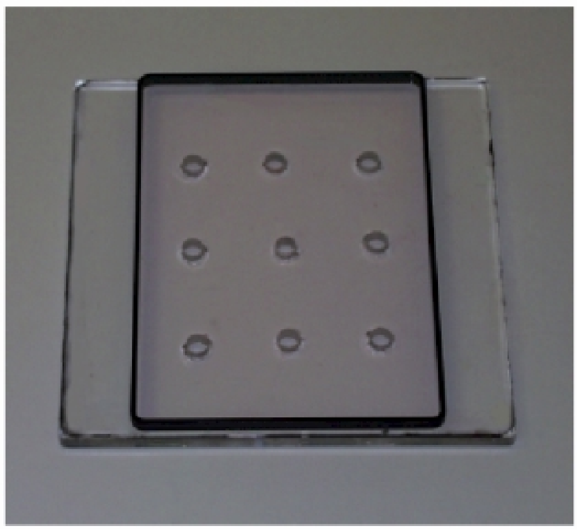


Figure 5 Reticle with Pressure Relief Holes for Pellicle Stress Measurement Test

4.1.3 E-beam Patterning of CaF_2 substrates

Experimental results for substrate heating in e-beam patterning of CaF_2 photomask blanks were generated in late 1998. FE models have been built in an effort to understand the experimental results and provide a methodology for reducing image placement errors due to the mask patterning manufacturing step. Equivalent models have been built that account for the surface heat flux and volumetric heat generation in simulating the energy deposition in the different layers of the mask. The models include conduction and radiation heat transfer mechanisms and assume adiabatic boundary conditions. Simulations are then run that predict resultant temperature distributions and global in-plane distortions. Initial results (see Table 1) do not compare well with experimental findings. Investigation into the experimental conditions and the model algorithm are ongoing in an effort understand the discrepancy.

Table 3 Preliminary Reticle Heating Modeling Results in Comparison with Experiments

	Max. Temp. Rise (K)	Max IPD (nm)
ISMT Experiments	Unmeasured	~500
ETEC Modeling	0.015	15.9
UW-CMC Modeling	0.025	51.1

4.2 Electron Projection Lithography (EPL) Mask Modeling

4.2.1 Fabrication

To supplement the development of the SCALPEL mask, the finite element method is being used in conjunction with a series of designed experiments to efficiently identify the parameters that most heavily influence distortions of the mask. After the most influential parameters and their interactions have been identified, this knowledge will be applied to the latest SCALPEL mask design to determine its adequacy. Experimental data are being collected to substantiate the modeling effort. Surface maps (out-of-plane measurements) of two SCALPEL masks, before and after etching, are being taken to ascertain the change in out-of-plane displacement (OPD) from etching. This data can then be compared to the modeling prediction. Good correlation will show the effectiveness of the modeling.

The initial structural model for Motorola's 200 mm EPL mask has been completed, and pattern placement error resulting from fabrication and pattern transfer has been determined using the target process parameters. The FE model is now being modified to explore the effects of film stress and thickness variation within the process envelope. Design changes for this mask are anticipated; they will be incorporated into the model as they are issued by Motorola.

Transient thermal and structural analyses of the mask behavior during the e-beam scanning of a single cell have been completed. The transient deflections will be analyzed to discern the distortions into image placement and image blur components pending input from Lucent. In addition, full mask models are being used to determine the effects of cell location in the mask on the resulting thermal distortion.

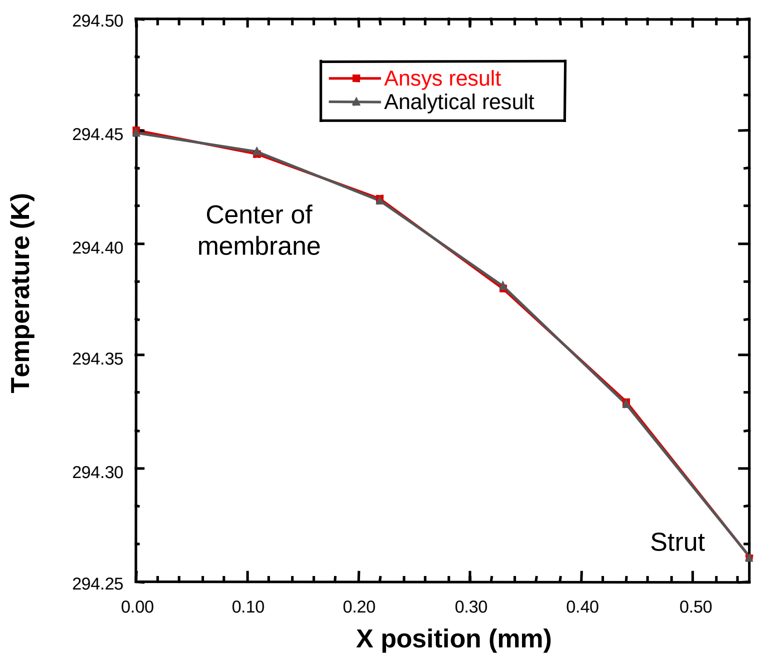


Figure 6 Temperature Distribution Across a SCALPEL Mask Membrane Under Typical E-beam Patterning

4.2.2 Exposure

Transient thermal and structural analyses of the mask behavior during the e-beam scanning of a single cell have been completed. Energy can be diffused into the surroundings by radiation and into the mask structure by conduction. If the induced heat in the membrane due to the e-beam energy deposition, can be considered localized and confined within the area of the exposed field, the mask wafer outside of the pattern area can be eliminated and a simple FE model can be developed using equivalent boundary conditions. The transient deflections are being analyzed to discern the distortions into image placement and image blur components pending input from Lucent (see Figure 7). In addition, full mask models are being used to determine the effects of cell location in the mask on the resulting thermal distortion.

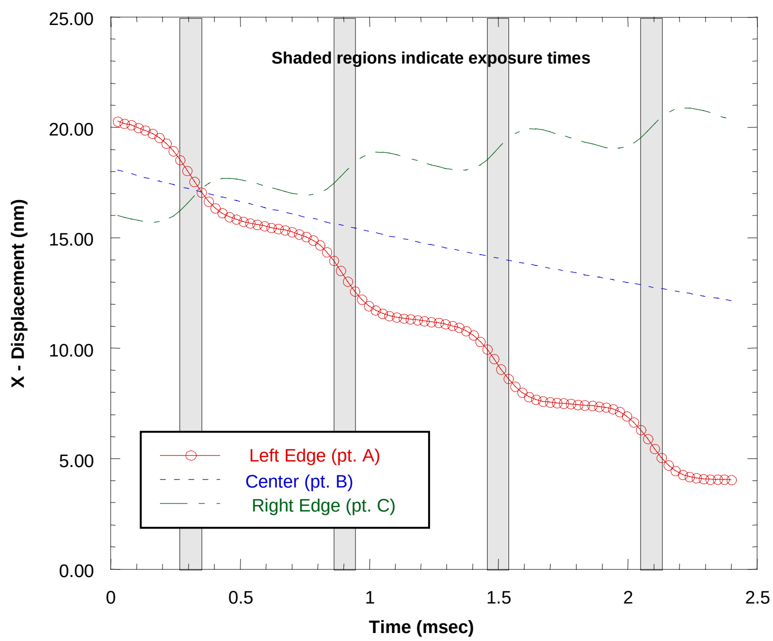


Figure 7 X Displacement of Mask Membrane Edge Under Wafer Exposure Conditions

4.2.3 PreVail Modeling

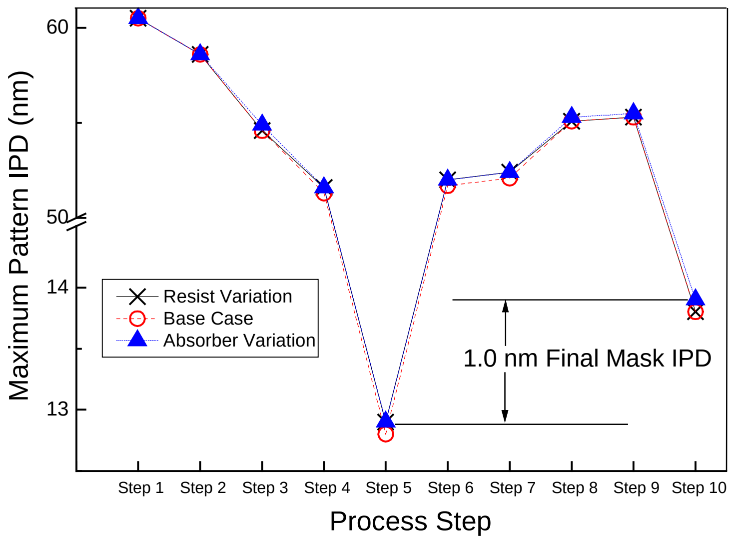
Process flow schematics of the mask fabrication procedure have been drawn; however, thickness values and stress levels are still unknown. In addition, ProEngineer drawings of the entire mask structure have been made, but questions on actual pattern sizes are still unanswered. The schematics have all been forwarded to IBM to see if further information can be acquired for the modeling efforts.

4.3 EUV Mask Modeling

All of the basic models have been completed to simulate mask fabrication and pattern transfer in the EUV mask. The results in general show that the mask has very little IPD distortion (< 2 nm for most cases) through all of the fabrication steps. This is assuming perfectly flat clamping during e-beam writing and the subsequent exposure step. The effects of stress gradients in the resist and multi-layer stack have also been evaluated (see Figure 8). Essentially, IPD is still negligible. Modeling imperfections during the clamping of the reticle will be considered in future FE models.

Preliminary finite element models to simulate e-beam patterning of the EUV mask are being developed. A literature search is currently underway to determine all the necessary thermo-mechanical material properties needed for input into the models.

Models to simulate the exposure of the EUV mask are currently under development (Table 4). Input parameters are currently being obtained from the literature.



Note: Results assume an ideal chuck.

Figure 8 IPD Change as a Function of Variation in Film Stress

Table 4 IPD From 50% Light/Dark Pattern

IPD Due to Pattern Transfer and Exposure Mounting		
Mask Type	**Without Magnification Correction**	**With Magnification Correction (anisotropic)**
EUV	1.7 nm	0.6 nm
Optical	16.4 nm	2.4 nm

Note: EUV reticle assumes ideal chucking; Optical reticle assumes traditional mounting scheme.

5 STATUS AND OUTLOOK FOR 2000

The project continues to run well. In 2000, the focus will be on generating data on pattern specific processing and on understanding the Pareto of effects that drive image placement errors. The activities will focus on optical masks, reflective EUV masks, and both membrane and stencil EPL masks. Professor Engelstad has begun to ramp down her team in an effort to be self-supporting and conclude the contract. To keep the information flowing to the member companies, the monthly teleconferences will continue to be held throughout the life of the project. At present, the project is scheduled to close at the end of 2000 with no further extensions. International SEMATECH is evaluating the need to continue efforts on the 157 nm, EPL, and EUV programs. Additional activities covering pellicle mounting, thermal heating under patterning, and common mounting schemes are areas that need further investigation in 2001.

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9. "Analysis, Design, and Optimization of Ion Beam Lithography Masks," *Emerging Lithographic Technologies II*, SPIE, Vol. 3331, pp. 621–628, (R. Tejeda, R. Engelstad, E. Lovell and I. Berry), 1998.

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11. “Mask Blank Fabrication and Pattern Transfer for Electron-Beam Lithography (SCALPEL) Masks,” *Proceedings of TECHCON ‘98*, (G. Dicks, R. Engelstad, E. Lovell and J. A. Liddle), September 1998.
12. “Transient Analysis of the In-Plane Distortions of a SCALPEL Mask,” *Proceedings of TECHCON ‘98*, (W. Semke, R. Engelstad, E. Lovell and J. A. Liddle), September 1998.
13. “Predicting In-Plane Distortions due to Radiation Damage in X-ray Mask Membranes,” *Proceedings of TECHCON ‘98*, (E. Cotte, R. Engelstad and E. Lovell), September 1998.
14. “Mechanical Mounting Distortions in Advanced Optical Reticles,” *Proceedings of TECHCON ‘98*, (A. Mikkelson, R. Engelstad and E. Lovell), September 1998.
15. “Film Stack Stress Measurements for the SCALPEL Mask,” *Proceedings of TECHCON ‘98*, (M. Schlax, R. Engelstad, E. Lovell and J. A. Liddle), September 1998.
16. “Mechanical Distortions in Advanced Photomasks,” *Proceedings of SPIE’s 18th Annual BACUS Symposium on Photomask Technology and Management*, Vol. 3546, pp. 413–421, (A. Mikkelson, R. Engelstad and E. Lovell), 1998.
17. “Effects of Material Properties on Patterning Distortions of Optical Reticles,” *Proceedings of SPIE’s 18th Annual BACUS Symposium on Photomask Technology and Management*, Vol. 3546, pp. 214–220, (B. Shamoun, R. Engelstad, E. Lovell and W. Trybula), 1998.
18. “Finite Element Modeling of SCALPEL Masks,” *Emerging Lithographic Technologies III*, SPIE, Vol. 3676, pp. 128–139, (R. Engelstad, E. Lovell, G. Dicks, C. Martin, M. Schlax, W. Semke, J. A. Liddle and A. Novembre), 1999.
19. “Modal Analysis of the SCALPEL Mask using Experimental and Numerical Methods,” *Emerging Lithographic Technologies III*, SPIE, Vol. 3676, pp. 556–567, (W. Semke, M. Schlax, R. Engelstad, E. Lovell and J. Liddle), 1999.
20. “Stress Mapping Techniques for the SCALPEL Mask Membrane System,” *Emerging Lithographic Technologies III*, SPIE, Vol. 3676, pp. 152–161, (M. Schlax, R. Engelstad, E. Lovell, J. Liddle and A. Novembre), 1999.
21. “Mechanical Distortions in Advanced Optical Reticles,” *Emerging Lithographic Technologies III*, SPIE, Vol. 3676, pp. 744–755, (A. Mikkelson, R. Engelstad, E. Lovell, T. Bloomstein and M. Mason), 1999.
22. “Thermo-mechanical Distortions of Advanced Optical Reticles during Exposure,” *Emerging Lithographic Technologies III*, SPIE, Vol. 3676, pp. 756–767, (J. Chang, A. Abdo, B. Kim, T. Bloomstein, R. Engelstad, E. Lovell, W. Beckman and J. Mitchell), 1999.
23. “Finite Element Modeling of Ion-Beam Lithography Masks for Pattern Transfer Distortions,” *Emerging Lithographic Technologies III*, SPIE, Vol. 3676, pp. 768–778, (G. Frisque, R. Tejeda, E. Lovell and R. Engelstad), 1999.
24. “Thermo-mechanical Distortions of Ion-Beam Stencil Masks during Exposure,” *Emerging Lithographic Technologies III*, SPIE, Vol. 3676, pp. 779–785, (P.-T. Lee, B. Kim, G. Frisque, R. Tejeda, R. Engelstad, E. Lovell, W. Beckman and J. Mitchell), 1999.
25. “Predicting Mechanical Distortions in X-ray Masks,” *Emerging Lithographic Technologies III*, SPIE, Vol. 3676, pp. 429–440, (E. Cotte, R. Engelstad, E. Lovell and C. Brooks), 1999.

6.5 Presentations

1. "Magnification Control -- Temperature Analysis" presented at the DARPA Technical Interchange Meeting (TIM) at IBM in Burlington, VT, on June 24, 1997.
2. "Stencil Mask Modeling," presented at Ion Microfabrication Systems (IMS) in Vienna, Austria, on September 22 and 23, 1997.
3. "Modeling of Mask Structures for Ion Beam Lithography," presented at the University of Stuttgart in Stuttgart, Germany, on September 26, 1997.
4. "Mechanical Modeling of SCALPEL Masks," presented at the SEMATECH Program Review at Lucent Technologies in Murray Hill, NJ, on October 21, 1997.
5. "Mechanical Modeling of Stencil Masks," presented at the SEMATECH Program Review of the European Ion Beam Projection Lithography (IPL) Project in Hopewell Junction, NY, on October 23, 1997.
6. "The Virtual Mask Laboratory: An Overview of Advanced Mask Modeling," presented at the DARPA Program Review in San Antonio, TX, on January 29, 1998.
7. "Mask Stability Program," presented at SVG Lithography in Wilton, CT, on March 25, 1998.
8. "Advanced Mask Design for 0.1 μm Technology," presented at the IEEE Lithography Workshop in Banff, Canada, on April 15, 1998.
9. "Mask Stability Program - Optical Masks," presented at MIT - Lincoln Labs in Lexington, MA, on April 22, 1998.
10. "Stencil Mask Modeling and Simulation," presented at the SEMATECH Next Generation Lithography (NGL) Critical Review Meeting in San Francisco, CA, on May 6, 1998.
11. "Modeling of Membrane Masks," presented at the 1998 Gordon Research Conference on the Chemistry and Physics of Nanostructure Fabrication in Tilton, NH, on June 23, 1998.
12. "Stencil Mask: Finite Element Modeling," presented at the International Meeting on Ion Projection Lithography in Vienna, Austria, on September 18, 1998.
13. "Modeling and Simulation of Membrane Distortions in NGL Masks," presented at the 1998 International Conference on Micro- and Nano-Engineering in Leuven, Belgium, on September 24, 1998. (This was an invited Plenary Talk.)
14. "Simulations of Mask and Wafer Distortions," presented at ASM Lithography in Veldhoven, The Netherlands, on September 25, 1998.
15. "Modeling of SCALPEL and Stencil Masks" presented at The Third International Workshop on High Throughput Charged Particle Lithography in Waikoloa, Hawaii, on November 13, 1998.
16. "Mask Distortion Modeling" presented at Mask Advisory Steering Council Mtg. in Ft. Lauderdale, FL, on January 13, 1999.
17. "Lithographic Mask Modeling" presented at International SEMATECH in Austin, TX, on January 29, 1999.
18. "Stencil Mask Modeling" presented at the International Ion Projection Beam Lithography Meeting at the University of Kassel in Kassel, Germany, on February 17, 1999.
19. "Advanced Mask Accuracy and Stability Study" presented at Sandia National Laboratory in Livermore, CA, on February 22, 1999.

20. “Advanced Mask Modeling” presented at the DARPA Programs Review in Arlington, VA, on April 13, 1999.
21. “Thermo-mechanical Modeling of Advanced Optical Reticles” presented at Intel Corporation in Santa Clara, CA, on April 30, 1999.
22. “Cross-Cutting Issues for NGL Masks” presented at The 43rd International Conference on Electron, Ion, and Photon Beam Technology and Nanofabrication (EIPBN ‘99) in Marco Island, FL, on June 4, 1999.

6.6 Theses/Dissertations

- **Ph.D. Students Graduated:**

1. Fisher, Adam H. 5/1998 Ph.D. thesis: “Analysis and Simulation of Pattern Placement Errors in Advanced Lithographic Masks”
2. Semke, William H. 5/1999 Ph.D. thesis: “Dynamic Analysis of Advanced Lithographic Masks”

- **M.S. Students Graduated:**

1.	Schlax, Michael P. M.S. thesis:	12/1997 “Mechanical Characterization of X-ray and SCALPEL Lithographic Masks”
2.	Vicum, Lars M.S. Thesis	5/1998 “Local Heating during Electron Beam Patterning of Lithography Masks”
3.	Tejeda, Richard M.S. thesis:	12/1998 “Analysis, Design and Optimization of Ion-Beam Lithography Masks”
4.	Abdo, Amr M.S. thesis:	12/1999 “Modeling the Thermal Response and the Thermal Distortion of Optical Masks during the Optical Lithography Exposure Process”
5.	Chang, Jaehyuk M.S. topic:	8/1999 “Thermal Distortions in Photomasks during Exposure”
6.	Sohn, Jaewoong M.S. topic:	12/1999 “Thermal Modeling of Optical Reticles During Patterning”
7.	Mikkelson, Andrew R. M.S. thesis:	12/1999 “Mechanical Distortions in Optical Reticles”

- **B.S. Thesis Students Graduated:**

1. Richard, Owen T. 5/1999
   B.S. thesis: "Fabrication Distortions in X-ray Mesa Masks"
2. Silver, Mark J. 5/1999
   B.S. thesis: "Equivalent Dynamic Modeling of Perforated Membranes"
3. Weisbrod, Eric 12/1999
   B.S. thesis: "The Design and Analysis of a Vibratory Cleaning Process for Advanced Optical Reticles"

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