

REPORT DOCUMENTATION PAGE			Form Approved OMB NO. 0704-0188	
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1. AGENCY USE ONLY (Leave Blank)		2. REPORT DATE 17 Jun. 03		3. REPORT TYPE AND DATES COVERED Final Progress, 1 Jul, 00 – 31 Mar, 03
4. TITLE AND SUBTITLE Adaptive Membrane Masks for Next Generation Lithographies			5. FUNDING NUMBERS G DAAD 19-00-1-0434	
6. AUTHOR(S) Martin Feldman				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Louisiana State University, Baton Rouge, LA, 70803 Massachusetts Institute of Technology, Cambridge, MA, 02139			8. PERFORMING ORGANIZATION REPORT NUMBER 127 20 5179 R110030	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) U. S. Army Research Office P.O. Box 12211 Research Triangle Park, NC 27709-2211			10. SPONSORING / MONITORING AGENCY REPORT NUMBER 41548-EL • 3	
11. SUPPLEMENTARY NOTES The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.				
12 a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution unlimited.			12 b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words) The overlay accuracy, and hence the minimum useable feature size, in any integrated circuit lithography is often limited by distortions that are present in the mask and wafer. In this work selective heat loads are applied to membrane masks, thereby generating thermal strains to compensate these distortions. Computer models have been developed that describe these effects, obtaining excellent agreement between a finite element model used at LSU and an analytical model developed at MIT. The special case of a scanned exposure, e.g., in SR X-ray lithography, is particularly well understood. Two experimental programs have been implemented, which demonstrate agreement between measured thermally generated displacements and the predictions of the computer models. At LSU the displacements were measured over an 11 x 11 array of alignment sites. Because of lithographic problems not all the sites were functional; however the average displacements showed fair agreement with the computer predictions. At MIT the thermal input was generated by a modified 35 mm slide projector, and a holographic-phase-shift interferometer measured the resulting displacements to sub-wavelength accuracy. Detailed MARKET plots of the MIT data show good agreement with the computer predictions.				
14. SUBJECT TERMS X-Ray lithography, Membrane masks			15. NUMBER OF PAGES 10	
			16. PRICE CODE	
17. SECURITY CLASSIFICATION OR REPORT UNCLASSIFIED	18. SECURITY CLASSIFICATION ON THIS PAGE UNCLASSIFIED	19. SECURITY CLASSIFICATION OF ABSTRACT UNCLASSIFIED	20. LIMITATION OF ABSTRACT UL	

FINAL PROGRESS REPORT

(1) Foreword

As overlay requirements for integrated circuits have tightened, the control of mask distortion has become critically important. Rather than make the mask as rigid as possible, a feedback approach has been suggested in which overlay is measured and corrective displacements are thermally generated in a membrane mask.^{1,2} The principle corresponds to that used in adaptive optics, where an active feedback system is used to maintain perfect wave-fronts by distorting the optical surfaces. An important advantage of adaptive masks is that the feedback may be used either to obtain absolute accuracy, or to incorporate desired displacements, for example to compensate distortions in previous levels patterned on the wafer. We have modeled the thermal distributions needed to compensate arbitrary mask distortions both for full field and scanned exposures. For a scanned exposure, e.g., an X-ray beam on a storage ring, only the line being exposed must be corrected at any given time. This minimizes the heat load on the mask, as well as permitting a simple Fourier analysis. This modeling has been verified in two very dissimilar experimental arrangements.

(4) Statement of the problem studied

Distortion correction may be divided into four sub processes:

- 1) Measuring the distortion, either to (a), an absolute standard, or (b), a level previously printed on a wafer. The measured overlay between the printed pattern and previous levels may be used to generate a displacement distribution that matches the mask to the previous levels. The use of a "send-ahead" wafer to measure alignment offsets is well known to the industry; this procedure expands the function of the send-ahead wafer to correct overlay *within* the exposure field.
- 2) Computing the thermal input required to correct the distortion.
- 3) Applying the thermal correction.
- 4) Observing the resulting correction, and iterating steps (2) and (3), if necessary.

(5) Summary of the most important results

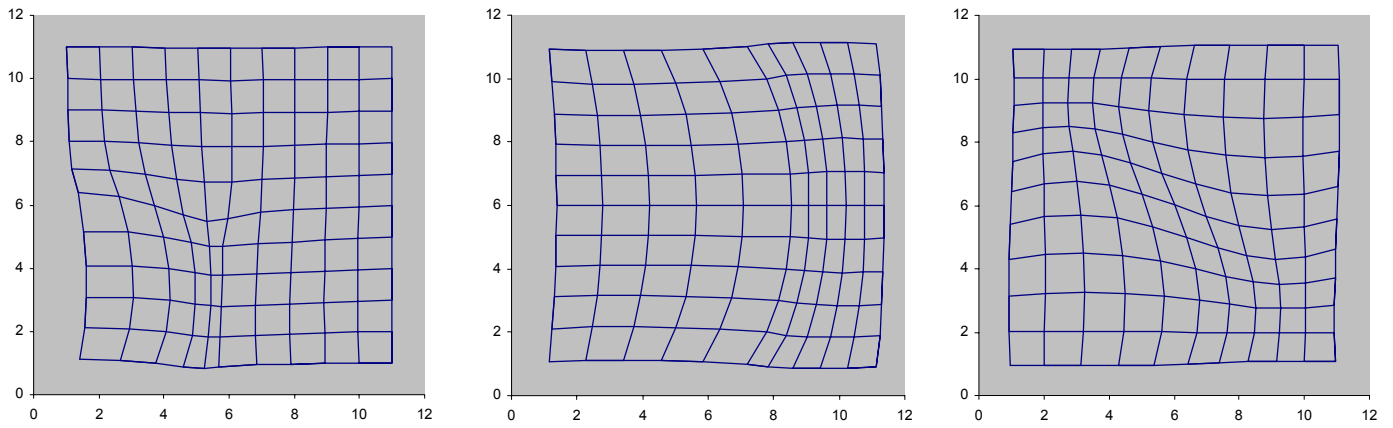
We have measured the absolute accuracy of membrane masks with respect to an interference fringe standard, by first patterning an interference grid on the reverse side of the mask in a Holographic Phase-Shifting Interferometer (HPSI).^{3,4,5} Displacements in the mask, for example those caused by changes in stress during processing, are detected by putting the mask back in the HPSI under identical interference conditions. The HPSI is sensitive to displacements of a few nanometers.

The overlay between a 27 mm square SiN_x membrane mask and a fused quartz wafer was observed using an 11 X 11 array of alignment marks. The marks consisted of linear phase zone plates on a transparent fused quartz wafer and corresponding narrow phase gratings on the aluminized front surface of a membrane mask. The alignment marks were illuminated simultaneously, through the wafer, by a broad HeNe laser beam as the wafer was stepped in 1 μm steps across the mask. After reflection from the mask the diffracted light was detected by a CCD video camera. The intensity measured at each site is a function of the overlay between the mask and wafer.

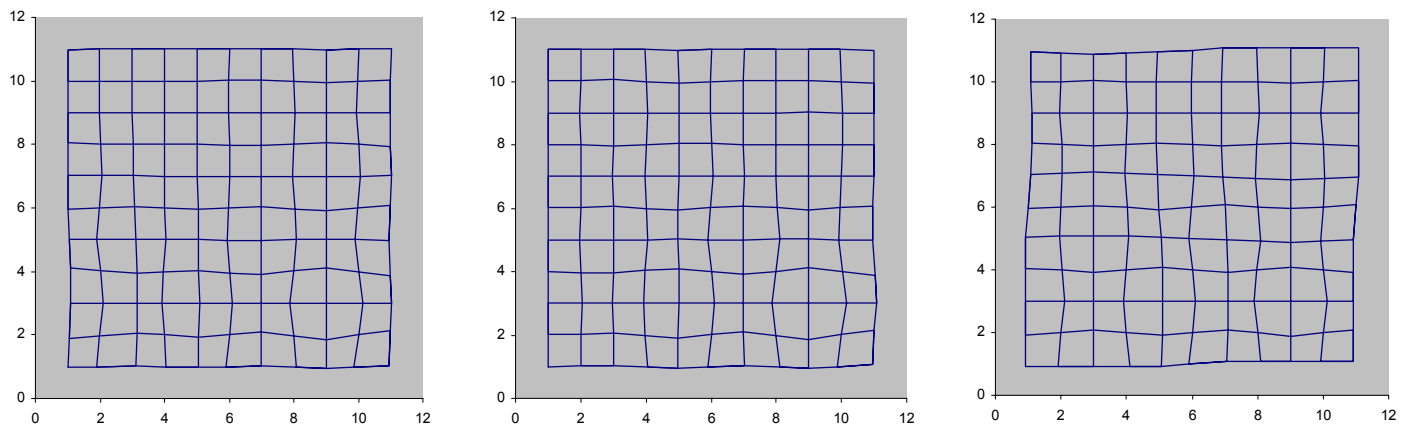
Both the displacements caused by selectively heating portions of a square membrane mask and the inverse problem of determining the two dimensional thermal input pattern required to match, and therefore compensate, a given pattern of distortions were modeled (Fig. 1). The problem was solved both for the general case of a full field exposure, as well as for the special case of an exposure which occurs only along a line scanned across the mask, as occurs with some X-ray exposures on storage rings. Computations were performed using a commercially available finite element analysis program⁶ with the membrane mask divided into a 36 x 36 pixel array as well as an analytical model developed at MIT. Excellent agreement between the two models was obtained.

For a scanned exposure, e.g., with an X-ray beam on a storage ring, the mask need be corrected only along the (horizontal) line being exposed at any given time. Both horizontal (X axis) and vertical (Y axis) corrections must be made. Horizontal displacements may be generated by adding heat along (or near) the line being exposed; vertical displacements may be generated by adding heat into regions just above and just below the exposure line. An advantage of this approach is that the total heat load on the mask is much less than if the entire field were simultaneously corrected.

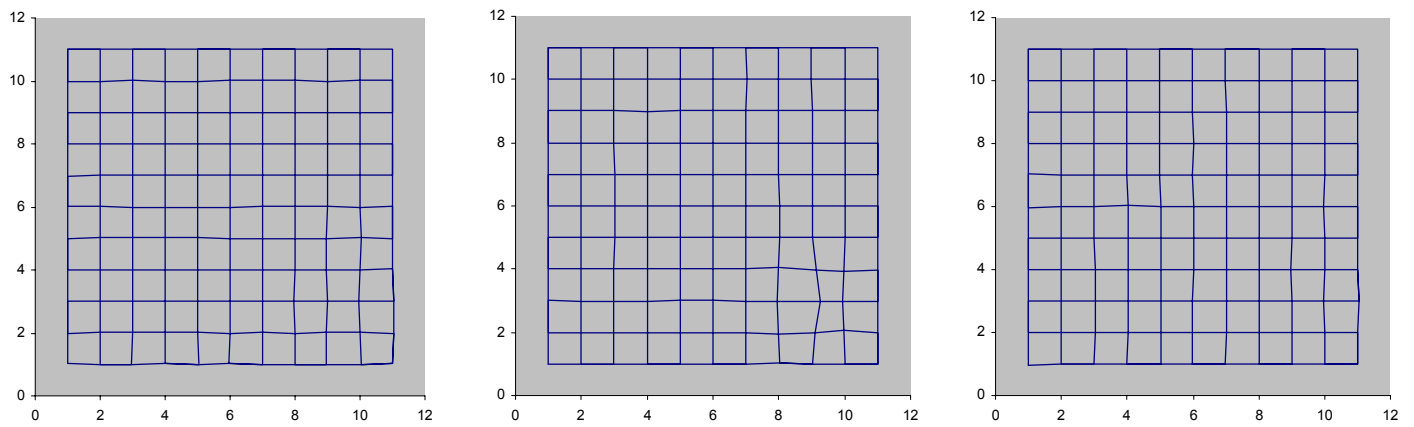
Any arbitrary displacement distribution along a line may be obtained as the sum of horizontal and vertical Fourier components. Figure 2a shows desired horizontal displacement distributions obtained for a spatial frequency of 3, along 6 exposure lines equally spaced between the bottom edge of the mask and the center. These are obtained with minimal unwanted vertical displacements. Figure 2b shows desired vertical displacement distributions, again for a spatial frequency of 3, along the same 6 exposure lines, as well as unwanted horizontal displacements. The results at other spatial frequencies are similar, implying that the level of accuracy depends primarily on the number of spatial frequencies that one wishes to include. By updating these distributions during a scanned exposure a wide range of known distortions on the mask or wafer may be compensated.



(a) Distortions



(b) Corrected using a 6 X 6 array



(c) Corrected using a 12 X 12 array

Fig. 1. Some arbitrary distortion patterns, and the degree to which they may be corrected by heating within a 6 X 6 or a 12 X 12 array of areas on the mask.

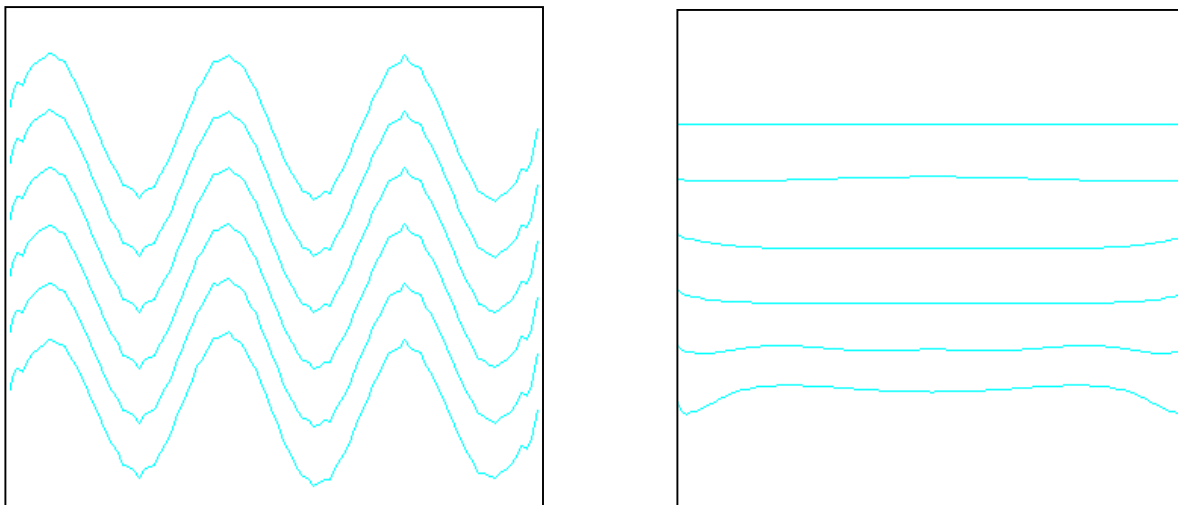


Fig. 2a, Desired horizontal displacements, left, and undesired vertical displacements, right, during a scanned exposure.

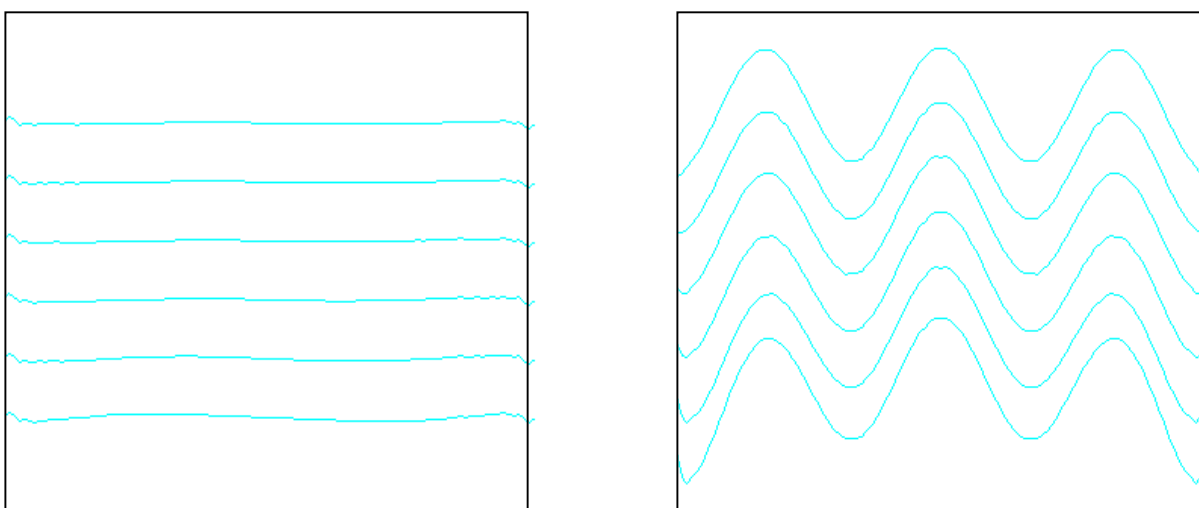


Fig. 2b, Undesired horizontal displacements, left, and desired vertical displacements, right, during a scanned exposure.

Correction for a particularly important distortion, in which the center of the field is displaced with respect to the periphery, is shown in Figure 4. This distortion is difficult to correct, since it cannot be compensated by applying forces around the edge of the mask. However, it can be corrected with a relatively simple temperature distribution in which the left side of the mask is heated, the right side is not heated, and the central part is heated to half the temperature of the left side (Fig. 5). The modeled X-Y displacement distribution resulting from this temperature distribution on a circular mask is plotted in Figure 4a, and the experimental distribution measured with the HPSI is shown in Figure 4b. Although there is some scatter the data agrees well with the predicted distribution.

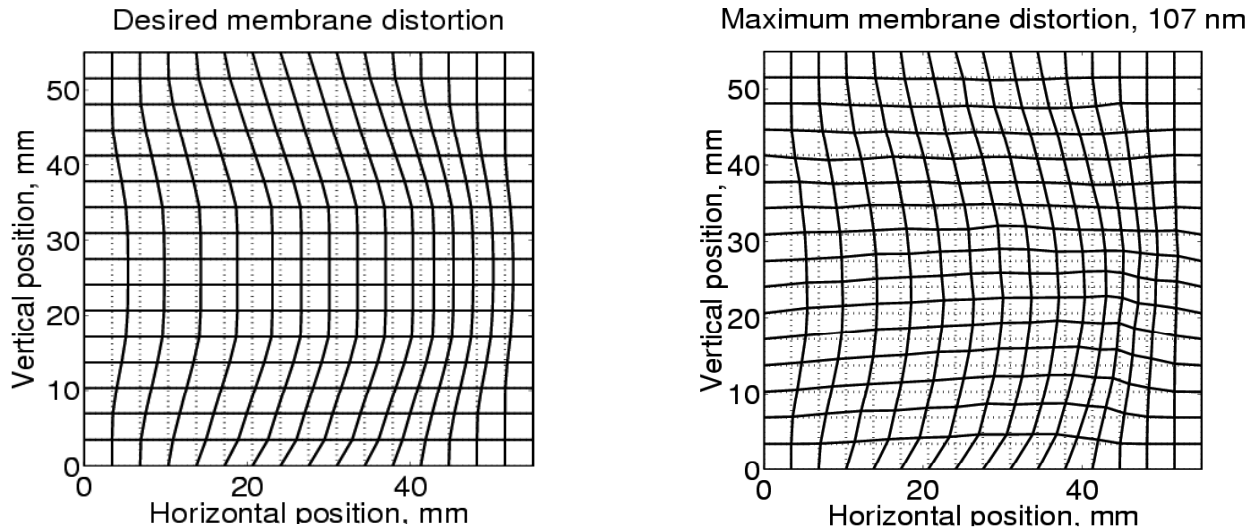


Fig. 4. a. Desired displacement distribution, left. b. Experimentally obtained distribution, right.

QuickTime™ and a
PNG decompressor
are needed to see this picture.

Fig. 5. Temperature distribution used to obtain the displacement distribution in Figure 4b.

Although in principle mask distortion may be measured on line in an exposure tool, it would be awkward to add the additional complexity to already complex machines. Furthermore, some measurements, such as comparisons to previously printed levels, would be almost impossible to perform. Therefore what is proposed is a two step process, in which the desired mask corrections, and the temperature distribution needed to correct these distortions, are measured and computed off line. The thermal input needed to generate the desired temperature distribution is then verified, again off line. The same thermal input is then used within the somewhat different environment of the exposure tool (Fig. 6). The resulting temperature distribution is readily observed within the tool, and a feedback system is used to adjust the thermal input to maintain the proper temperature distribution.

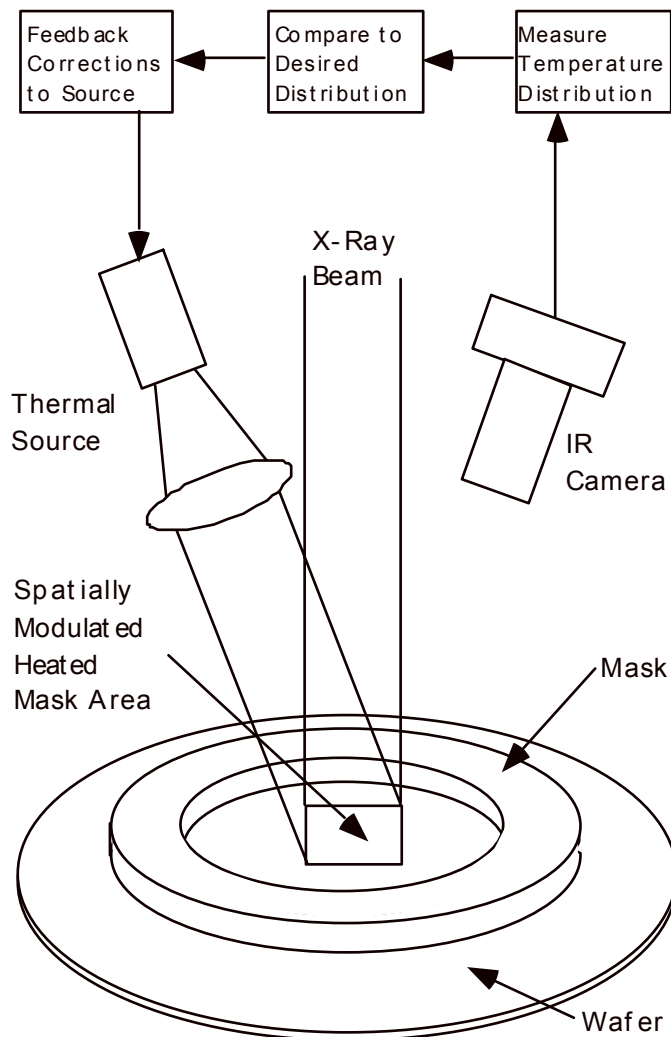


Fig. 6. Feedback system within exposure tool to maintain required temperature distribution.

(6) Listing of all publications and technical reports supported under this grant or contract.

(a) Papers published in peer-reviewed journals

K-I. Murooka, M. H. Lim, and H. I. Smith, J. Vac. Sci. Technol. B **18**, 2966 (2000).

K-I. Murooka, M. H. Lim and H. I. Smith, J. Vac. Sci. Technol. B **19**, 1229 (2001).

X. Zhuang and M. Feldman, J. Vac. Sci. Technol. B **19**, 2631 (2001).

K-I. Murooka, M.H. Lim, and H. I. Smith, J. Vac. Sci. Technol. B **20**, 370 (2002).

(c) Papers presented at meetings, but not published in conference proceedings

M. Feldman, S. Zhuang, M. Lim, K. Murooka, H. Smith, and S. Uchiyama, "Adaptive Membrane Masks," invited talk at workshop on "Non-Conventional Patterning below 50 nm," sponsored by Defense Sciences Research Council, Stanford University, and DARPA, at the Strategic Analysis Corporation, Arlington, VA, January 17, 2001.

M. Feldman, X. Zhuang, M. Lim, S. Uchiyama, and H. I. Smith, "Adaptive Membrane Masks, Not Just for X-Rays," DARPA Advanced Lithography Review, Charleston, South Carolina, April 2-5, 2001.

M. Feldman, X. Zhuang, H. I. Smith, M. Lim, T. O'Reilly, D. Amy, F. Cerrina, M. Khan, and G. Tsvaid, "Adaptive Masks and Focusing Masks," DARPA Advanced Lithography Review, New Orleans, Louisiana, April 8-11, 2002.

Martin Feldman, D. Amy, L. Jiang, H. I. Smith, T. O'Reilly, F. Cerrina, M. Khan, Q. Leonard, S. Liu, J. Murakowski, and D. Prather, "Adaptive Membrane Masks and Focusing Masks," DARPA Advanced Lithography Review, Santa Fe, NM, May 5-8, 2003.

(d) Manuscripts submitted, but not published

X. Zhuang, D. Conkerton, A. Lal, L. Jiang, M. Feldman, T. O'Reilly, and H. Smith, "Adaptive Membrane Masks," submitted to J. Vac. Sci. Technol., Nov./Dec. 2003.

(7) List of all participating scientific personnel

D. Conkerton, BS. awarded

M. Feldman

L. Jiang

A. Lal

M. H. Lim, Ph.D. awarded

K-I. Murooka, Ph.D. awarded

T. O'Reilly

H. I. Smith

S. Uchiyama

X. Zhuang, BS. awarded

(8) Report of Inventions

M. Feldman, “Adaptive Lithography Membrane Masks,” US Patent 6,440,619, August 27, 2002.

M. Feldman, H. Smith, K. Murooka, and M. Lim, “Adaptive Lithography Membrane Masks,” US Patent 6,404,481, June 11, 2002.

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- 4) K-I. Murooka, M. H. Lim and H. I. Smith, J. Vac. Sci. Technol. B **19**, 1229 (2001).
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- 6) ANSYS®, Southpointe, 275 Technology Drive, Canonsburg, PA 15317.