A New Phase Shifting Technique for Deep UV Excimer Laser Based Lithography

Zsolt Bor*, Joseph Cavallaro, Miklós Erdélyi*, Motoi Kido, Chaitali Sengupta, Michael Smayling, Gabor Szabó*, Frank Tittel, and William Wilson

Rice University, Department of Electrical and Computer Engineering, Houston Texas 77251
*Jate University, H-6720, Szeged, Hungary

ABSTRACT

This paper reports simulation and experimental details of a novel phase shifting technique based on laser interferometry. Phase shifting is one of the most promising techniques [1, 2] for the fabrication of high density DRAM's. In recent years many kinds of phase shifting methods have been proposed to extend the resolution limit and contrast of image patterns [3]. These techniques however, have several problems that result from the phase shift elements on the mask, especially when applied to UV excimer laser illumination

A new technique will be described that is based on a one-layered reticle which is used as both a reflective and transmisive mask, irradiated from both the front and the back sides. A combination of both off-axis illumination, as well as phase shift are used in this new method. Both the relative path length of the two beams as well as their amplitude can be manipulated in such a way that near 100% contrast can be achieved in the final image. Experimental as well as simulation data are used to demonstrate this new method.

Keywords: photolithography, phase shift, excimer laser

1. INTRODUCTION

The drive towards greater device densities on Very Large Scale (VLS) and Ultra Large Scale (ULS) integrated circuits is constantly challenging the state of art for photolithography. As feature size shrinks, lithographers have two choices for decreasing the resolvable linewidth, d_w, of their instrument. From the relationship

$$d_w = k_1 \frac{\lambda}{NA} \tag{1}$$

it is obvious that a smaller d_w can result from either a reduction of the illumination wavelength λ or a larger imaging system numerical aperture, NA. The desire for shorter wavelength will lead to the increasing use of excimer lasers (KrF and ArF) as high brightness UV illumination sources. Achieving a larger numerical aperture is a challenge to the lens maker's art and is one of the major driving forces leading to the high cost of modern photolithographic steppers. The depth of focus (DOF) is given by

$$DOF = k_2 \frac{\lambda}{NA^2}. \tag{2}$$

Decreasing λ and increasing the NA cause a serious degradation to the depth of focus, and consequently the final image at the wafer. In particular, the inverse square relationship between DOF and NA is a serious problem. A smaller DOF requires a more stable and controlled, and hence costlier stepper. The problem of reduced DOF becomes increasingly important as the surface of the fabricated wafer becomes increasingly non-planer as process steps increase.

An alternate approach to decreased d_w and increased DOF is to attempt to alter the optical system coefficients k_1 and k_2. One technique that has been shown to significantly improve both resolution limit and depth of field of the photolithographic image is that of phase shifting[1-3]. By appropriate manipulation, the electric field adjacent regions of the photolithographic image can be made to be 180° out of phase with one another. The assures that when these images overlap (due to diffraction) there will be some place where the two images exactly cancel one another, resulting in near 100% contrast. The desired phase shift is usually accomplished by making some regions of the photolithographic mask optically thicker than in other regions. This is achieved by either etching regions of the mask, or by adding an additional layer to the mask, and then etching it away from unwanted regions. The finished mask, and the resultant image at the silicon wafer surface are shown schematically in figure 1.

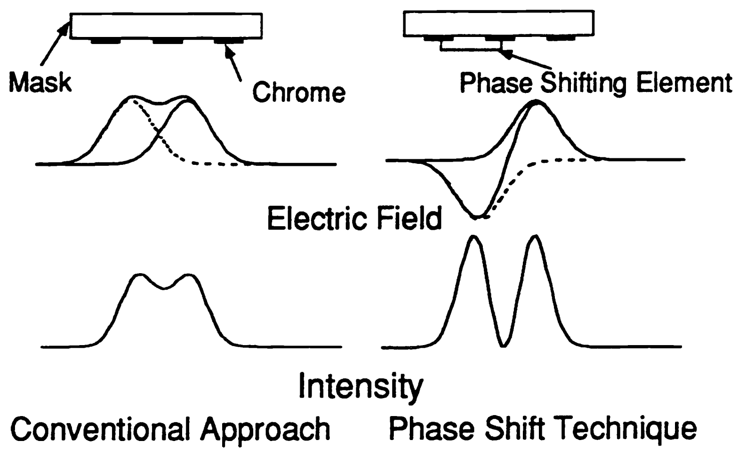

Figure 1. Comparison of conventional and phase-shift masking.

Besides the alternating phase-shift regions shown above, phase-shift regions can be placed at the rim of larger structures to enhance the contrast of their image. More recently, chromless phase shift masks [4], as well as masks which achieve the desired phase shift effect by propagating some of the light through lossy regions in the mask have been studied [5, 6].

While any of these approaches to phase shifting have shown significant promise, and offer distinct advantages over conventional photolithography, extending the phase shifting technique to shorter wavelengths (deep and ultra UV) will be difficult. This is because the required tolerances for the appropriate phase shift material become tighter as the wavelength is decreased. Also, it becomes much harder to find appropriate phase shifting materials which do not absorb strongly in the UV.

In a recent paper [7] we reported progress on a novel phase-shifting technique which does not require special phase shifting regions built into to the mask. By using a reflective chrome mask in a laser-based interferometric scheme, the desired phase shift can be achieved. As outlined in figure 2, light from a laser is divided into two beams by a beam splitter. One beam passes through the mask in the conventional way, while the other is reflected off of the back of the mask. The two beams are then imaged onto the wafer surface. The optical path lengths of the two beams are adjusted so that their relative phase is 180° apart, so as to achieve the desired phase-shift effect.

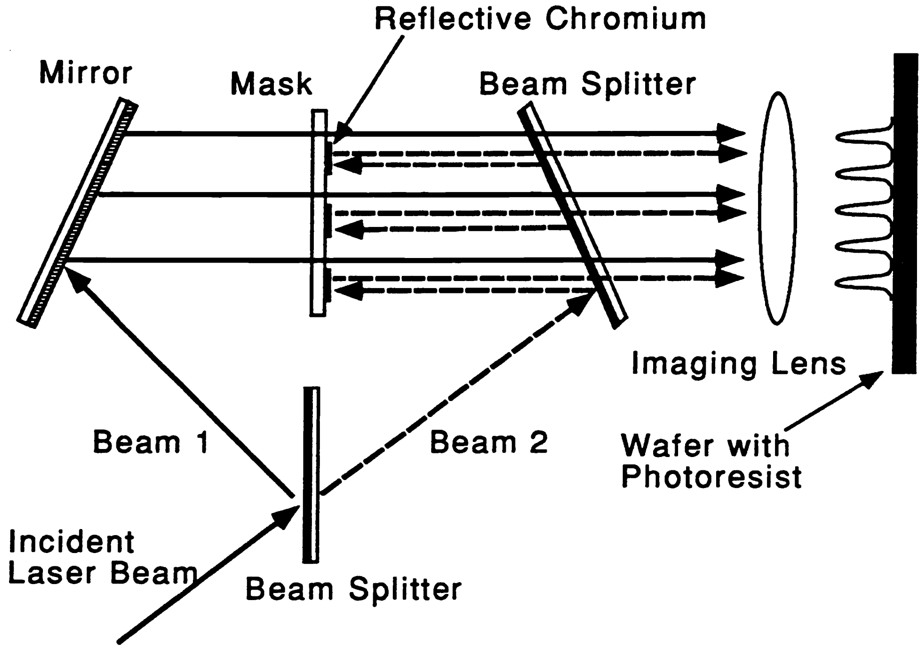

Figure 2. Interferometric Phase-Shift Technique

With this technique, we were able to write line and space patterns with a linewidth of less than 0.3 μm using a frequency tripled Nd:YAG laser at 355 nm as the illumination source. Both CCD camera imaging as well as computer simulations demonstrated the effectiveness of this new scheme. One of the unique features of this approach is that both the amplitude and the phase of the two incident images are independently adjustable, which is not the case for most other phase shifting techniques.

In this paper we report on recent investigations where the interferometric technique described above is combined with off-axis illumination. The ability to independently control the amplitude of the two out-of-phase beams is especially helpful in this application. Improved resolution as well as greater depth of focus result from applying this new imaging scheme. We also report on an Integrated CAD Framework which we have developed, which link layout editors such as MAGIC [8] to lithographic process simulators such as DEPICT [9]

Phase shifting can increase the depth of focus by about 50%. Off-axis illumination can add an additional 40% of depth of focus [10]. However since off-axis illumination uses the +1 diffracted beam (amplitude $\frac{1}{\pi}$) instead of the principal or zero order beam (amplitude $\frac{1}{2}$) the image contrast is reduced by about 5%. The additional use of an attenuated phase shift mask with a transmission of about 5% can compensate for this however, and the equalized intensity can bring the image contrast back to 100% [11].

2. EXPERIMENTAL ARRANGEMENT

The experimental set-up used in these experiments is shown in figure 3.

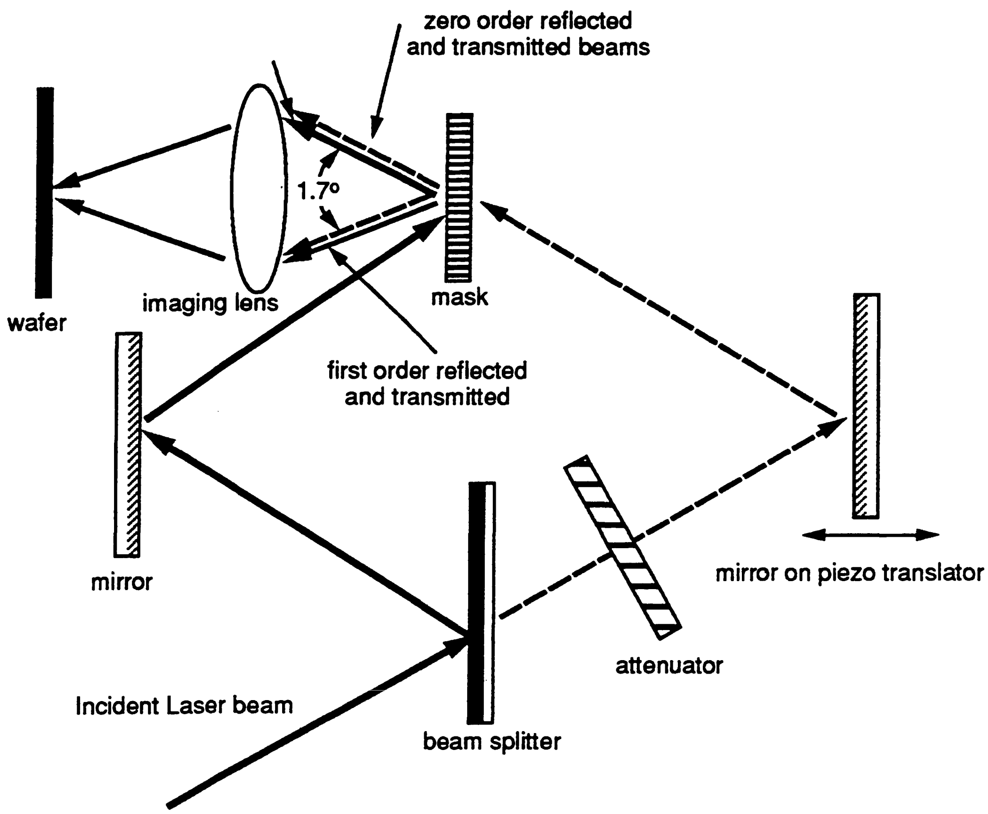

Figure 3. Experimental set-up for off-axis phase shift experiment (The angles of the beams have been greatly exaggerated for clarity.)

The incoming laser beam is split in two beams with a beam splitter. One beam is directed to the front of the mask at an angle of 1° from the normal, where it is reflected and diffracted. The other beam is attenuated and brought to the back of the mask at an angle about 1°. The first order diffraction from the grating is about - 0.7° with respect to the normal of the mask. Thus, as is shown in the figure, the two zero order reflected and transmitted beams and the two first order reflected and transmitted beams leave the mask at a relative angle of about 1.7°. The imaging lens (an Olympus 20X NA. = 0.4 microscope objective) is large enough to just intercept these two pairs of beams, but rejects all other diffraction orders. The mirror controlling the back illumination is mounted on a piezo-electric translator, so that the phase of its beam can be adjusted. In the experiments reported here, the illuminating laser beam was the 442 nm line from an He-Cd laser.

In order that experimental data could be compared to simulation, a Integrated CAD Framework was utilized to import layout information into the photolithography simulator DEPICT [9]. The Framework allows a designer to pass layout information (in either MAGIC, CIF or GDS-2 format) through a filter which identifies areas in the layout that may be prone to photolithographic problems, such a tightly packed elbows, or single lines emerging from a more densely packed region. The filter produces input for DEPICT of these regions so that process options and/or layout changes can be evaluated. The CAD framework was used to compare experimental results from the off-axis phase shift technique with simulation results.

3. EXPERIMENTAL RESULTS

The performance of the new scheme was evaluated by two different methods. In the first, the image which was created by the lens was enlarged using two microscope objectives (20X NA=0.5 and 20X NA=0.65 Olympus optics) and then projected onto a COHU 4800 CCD camera. The expansion optics were carefully aligned so as to minimize the possible degradation of the image. The imaging lens could be translated along the optical axis in order to measure the depth of focus. The second method of evaluation consisted of making actual patterns in photoresist and then observing them using either a scanning electron microscope or an atomic force microscope.

The experimental results using the CCD camera, along with simulation results are shown in figure 4. Figure 4.1b shows the results obtained with only the front of the mask illuminated. The simulation (4.1a) predicts a contrast ratio C

$$C = \frac{I_{max} - I_{min}}{I_{max} + I_{min}} \tag{3}$$

of about 90% taking into account the zero and first order diffracted beams from an equal lines-and-space pattern. However, the simulator assumes perfect reflectivity for the chromium layer, and ignores the dielectric reflection from the clear regions of the mask. Taking these into account (chromium reflectivity $R_{chrome} = 0.7$ and mask reflectivity $R_{mask} = 0.032$) the predicted image contrast would decrease to about 67%, as compared to the 68% measured in this experiment.

Figure 4.3 shows calculated (4.3a) and measured (4,3b) results when both beams are used. The piezo translator was adjusted to get optimum (180^o) phase shift between the two beams and the attenuator was adjusted to bring the contrast to essentially 100%. Under these conditions, the image from the rear illumination just cancels out the "trough" illumination from the front, reflected beam, bringing the minimum almost to zero.

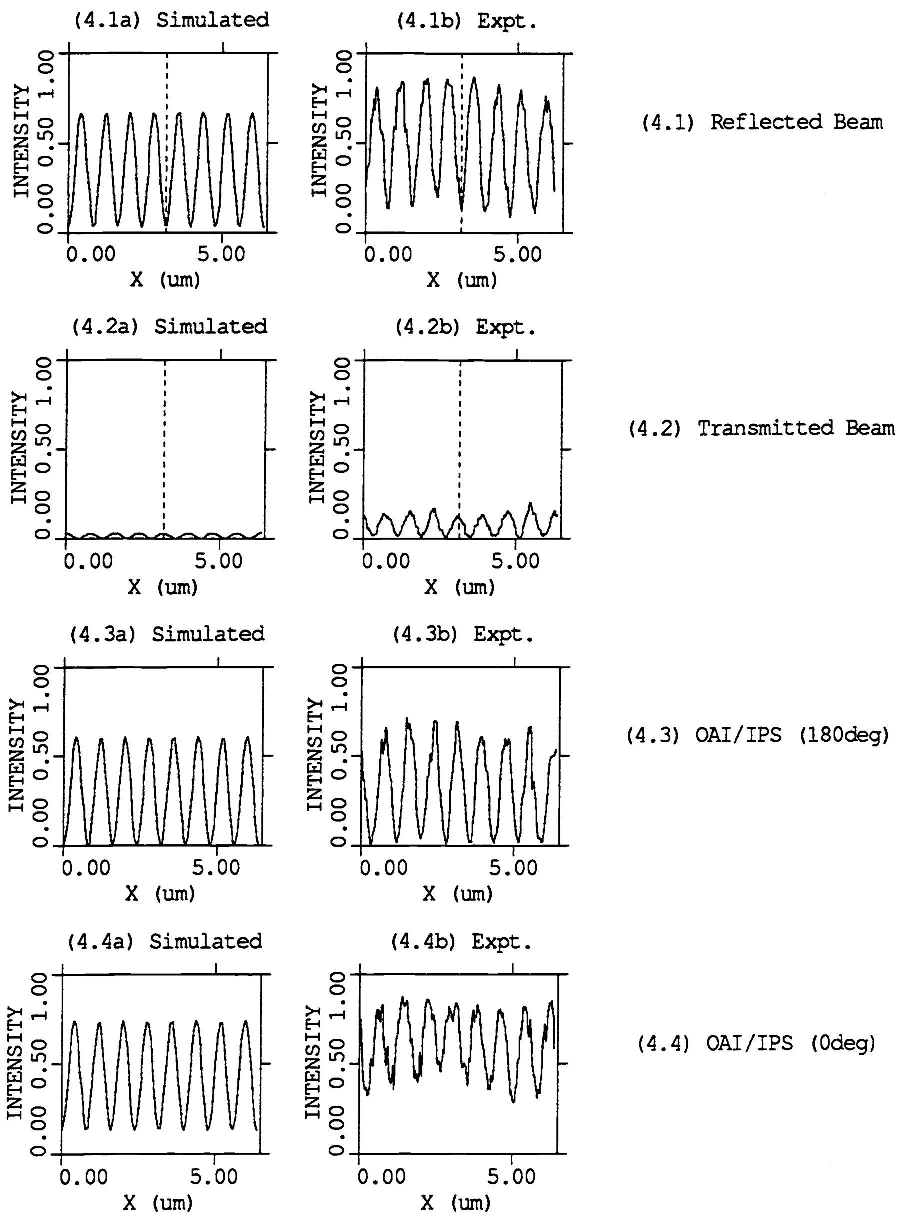

Figure 4. Intensity profiles for off-axis, interferometric phase shift image formation.

When the piezo was then adjusted for 0^o phase shift, the pattern seen in 4.4b results. Here the light from the two beams add in the troughs, and the contrast decreases to 69%. This data demonstrates one of the strengths of this new approach in that various imaging schemes can be tested and manipulated in order to judge their effectiveness. It provides a test bed facility for examining various phase shift and off axis exposure schemes.

Wafers were also coated with Shipley 1813 photoresist and exposed using this new technique. Although the photoresist is not optimized for the 442 nm region, there was still sufficient sensitivity that a pattern could be written. An atomic force microscope image of an exposed photoresist pattern is shown in figure 5. Note that a feature size somewhat less than 400 nm was obtained, even though the illumination wavelength was somewhat more than that. Thus, by combining phase shift techniques with off-axis illumination, features less than 85% of the illuminating wavelength were reproduced.

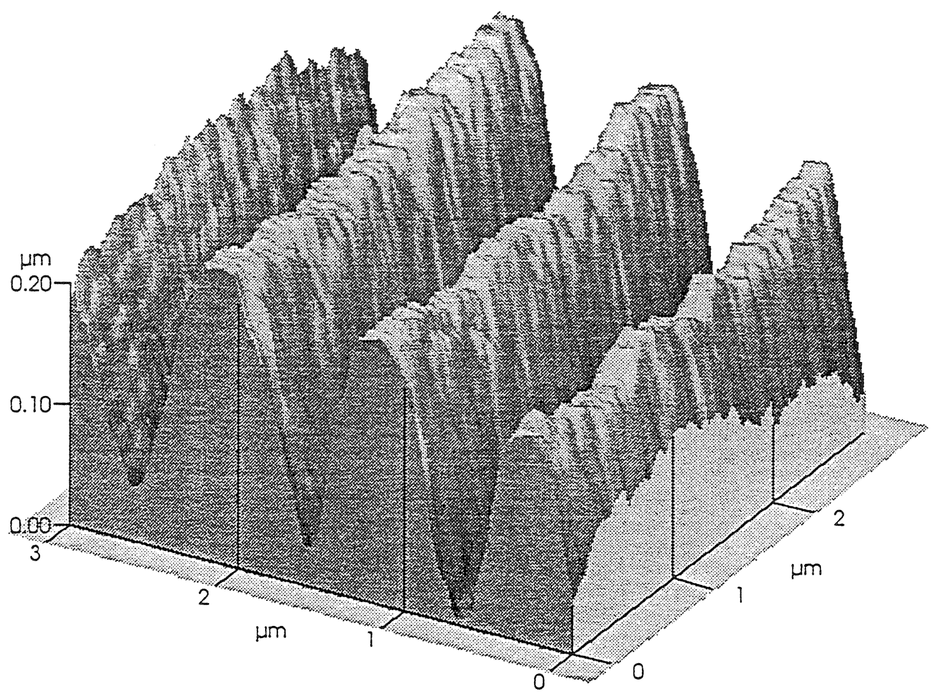

Figure 5. AFM image of pattern written in photoresist with off-axis phase shift method

The effect on contrast by defocusing the image was also studied. Because of the combined effect of the off-axis mask illumination and the coherence of the illumination, the depth of focus was at least 20 μm. In fact, so long as the wafer was positioned such that the overlap of the two beams occured at the surface, images with 100% contrast could be achieved.

4. CONCLUSIONS

A new and unique off-axis phase-shift photolithographic technique has been demonstrated and characterized. Feature sizes of less than 85% of the illuminating wavelength with a depth of focus of almost 20 λ were observed. Because of the freedom to adjust the relative phase and amplitude of the two illuminating beams, the modulation depth of the image of a lines-and-spaces pattern could be brought to nearly 100%. This freedom of adjustment makes this scheme a very useful test bed for studying various phase shift and off-axis illumination schemes.

5. ACKNOWLEDGEMENTS

This work was supported in part by the National Science Foundation under grant DDM-9202639. The authors would also like the thank Technology Modeling Associates for the DEPICT simulator used in this work.

1. M. D. Levenson and N. S. Visnawathan, "Improving Resolution in photolithography with phase-shifting mask", *IEEE Trans. Elec. Devices* , ED-29, pp. 1828-1836, 1982.

2. D. J. Ehrlich and J. Y. Tsao, Laser Microfabrication, (Academic Press, 1989)

3. B. J. Lin, "Phase-shifting maks gain and edge", *IEEE Circuits and Devices* , 2, pp. 28-35, 1993.

4. K. Toh, G. Dao, R. Singh and H. Gaw, "A chromless phase-shifted mask: a mew approach to phase-shifting masks", *Proceedings of 10th Annual Symposium on Microlithography,* Vol. SPIE, pp. 74-86, 1990.

5. M. Nakajima, N. Yoshioka, J. Miyzaki, H. Kusunose, K. Hosono, H. Morimoto, Y. Watakabe and K. Tsukamoto, "Attenuated phase-shit mask with a single layer absorptive shifter of CrO, CrON, MoSiO and MoSiON film", *Proceedings of Optical/Laser Microlithography VII,* Vol. 2197, SPIE, pp. 111-121, San Jose, CA, 1994.

6. A. Wong, C. Pierrat, P. Vasdev and A. Neureuther, "Phase-shifter edge effect on attenuated phase-shifting mask image quality.", *Proceedings of Optical/Laser Microlithography VII,* Vol. 2197, SPIE, pp. 122-129, San Jose, CA, 1994.

7. M. Kido, G. Szabo, J. Cavallaro, W. Wilson and F. Tittel, "A new phase shifting method for high resolution microlithography", *Proceedings of Optical/Laser Microlithography VII,* Vol. 2197, SPIE, pp. 835-843, San Jose, CA, 1994.

8. G. S. Taylor, J. Ousterhout, G. Hamachi, R. Mayo and W. S. Scott, "Magic: A VLSI layout system", *Proceedings of 21st Design Automation Conference,* Vol. pp. 152-159, 1984.

9. R. Pack and D. Bernard, DEPICT-2 applications for VLSI technology, (Technology Modelling Associates, Palo Alto CA, 1990),

10. P. Luehrmann, P. v. Oorschot, H. Jasper, S. Stalnaker, B. Brainerd, R. Rolfson and L. Karklin, "0.35 μm lithography using off-axis illumination", *Proceedings of Optical/Laser Microlithography,* Vol. 1927, SPIE, pp. 103-124, 1993.

11. H. Fukuda, A. Imai, T. Terasawa and S. Okazaki, "New approach to resolution limit and advanced image formation techniques in optical lithography", *IEEE Trans. Electron Devices* , ED-38, pp. 67-75, 1991.