A New Interferometric Phase-Shifting Technique for Sub-half-micron Laser Microlithography

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ABSTRACT

This paper reports recent progress in achieving sub-half-micron feature sizes with UV laser illumination based on a novel interferometric phase shifting (IPS) technique. In the IPS arrangement, the intensity and amount of phase shift of the shifted beam can be controlled continuously and independently using the same mask. Consequently the method can be considered as a convenient general testbed for practical phase shifting concepts such as strong, weak and attenuated phase shifting. Recent measurements of the lithographic performance of a new concept are reported where phase shifting is combined with off-axis illumination. Experimental as well as simulation data are used to demonstrate this new method. A lithography simulator, Depict from Technology Modeling Associates, Inc. and a related Integrated CAD Framework which is being developed at Rice University was used to simulate and evaluate the performance of the IPS scheme.

Keywords: microlithography, phase shifting, off-axis illumination, depth of focus

1. INTRODUCTION

Advanced microlithography will be necessary in order to achieve the smaller size features required for the fabrication of future high density integrated circuits. From the relationship, $W = k_1(\lambda/NA)$ it is obvious that a smaller linewidth (W) can result from either a reduction of the illumination wavelength (λ) or a imaging system with high numerical aperture (NA). Since the depth of focus (DOF) scales with $1/NA^2$, images obtained with a high NA projecting lens have small DOF. The problem of reduced DOF becomes increasingly important as the surface of the fabricated wafer becomes more and more non-planar as process steps increase. Therefore it is important to find a technique which simultaneously improves both spatial resolution and DOF.

Phase shifting techniques[1] increase the resolution and the DOF by a factor of about 1.5. However, the doubling of spatial frequency[2] causes fundamental design problems in the mask. Multiple focal plane exposures[3,4] increase the DOF by a factor of about 4, while the resolution limit is unchanged This technique is suited for contact holes but not as much for line-space (L/S) or isolated line patterns.

Off-axis illumination[1] offers an increase of resolution by a factor of about 1.2 and an increase of DOF by a factor of about 1.4. The absence of spatial frequency doubling simplifies the design of the mask. The main problem with off-axis illumination is that the 0-order of diffraction (amplitude=1/2) is stronger than the +1-order (amplitude=$1/\pi$) for a L/S pattern. Therefore the image contrast is decreased to 90.6%. The contrast here is defined as $C = (I_{max} - I_{min})/(I_{max} + I_{min})$. By using an attenuated phase shifting mask (PSM) with a transmission of 4.9%, the intensities can be equalized.[3]

In a previous paper we have reported progress in achieving sub-half-micron feature sizes with UV laser illumination based on a novel interferometric phase shifting (IPS) technique.[5] This technique is based on a chrome reflection type mask which is used as both a reflective and transmission mask irradiated from the front as well as the back sides. The reflected and transmitted beams are projected onto the target wafer. The optical paths of the beams are chosen so that the phase of the two beams is different by an odd multiple of π radians at the surface of the wafer thus achieving an interferometric phase shifting effect.

In this paper, we report recent measurements of the lithographic performance of another new concept where phase shifting is combined with off-axis illumination. This new method allows us to obtain arbitrary intensities and phases for the phase shifted beams. This results in a simultaneous increase of DOF and spatial resolution. The new experimental set-up is described in section 2 and the results are reported in section 3.

Section 4 describes a related Integrated CAD Framework which we have developed. This set of CAD tools links layout geometry editors, such as Magic[6] to lithographic simulators. This framework has been used to evaluate the new scheme, combining off-axis illumination with phase-shifting.

2. EXPERIMENTAL SET-UP

Figure 1 shows the experimental arrangement used. The mask was a patterned evaporated, reflective chrome layer on fused silica substrate, forming a line and space pattern, with a spatial frequency of 16μm.

An Ar^+ laser beam was split into two parts and used to illuminate both the front and back surface of the mask. The intensity and the phase of the back illumination was controlled by a variable attenuator and a piezo-controlled linear translator respectively. A microscope objective (Nikon, magnification(M) = $20X$, $NA = 0.4$) was used to image the mask onto the photoresist. The mask to objective distance was adjusted to the manufacturer specified microscope tube length to ensure nominal magnification ratio and high image quality.

The off-axis illumination angle of the mask was 1°. The first order diffraction angle was 0.7°. Thus, the microscope objective, which has a numerical aperture of $0.4/20 = 0.02$ on the mask side, accepts only the 0 and +1 order beams propagating at a relative angle of 1.7° while all other diffraction orders are rejected (see inset of figure 1).

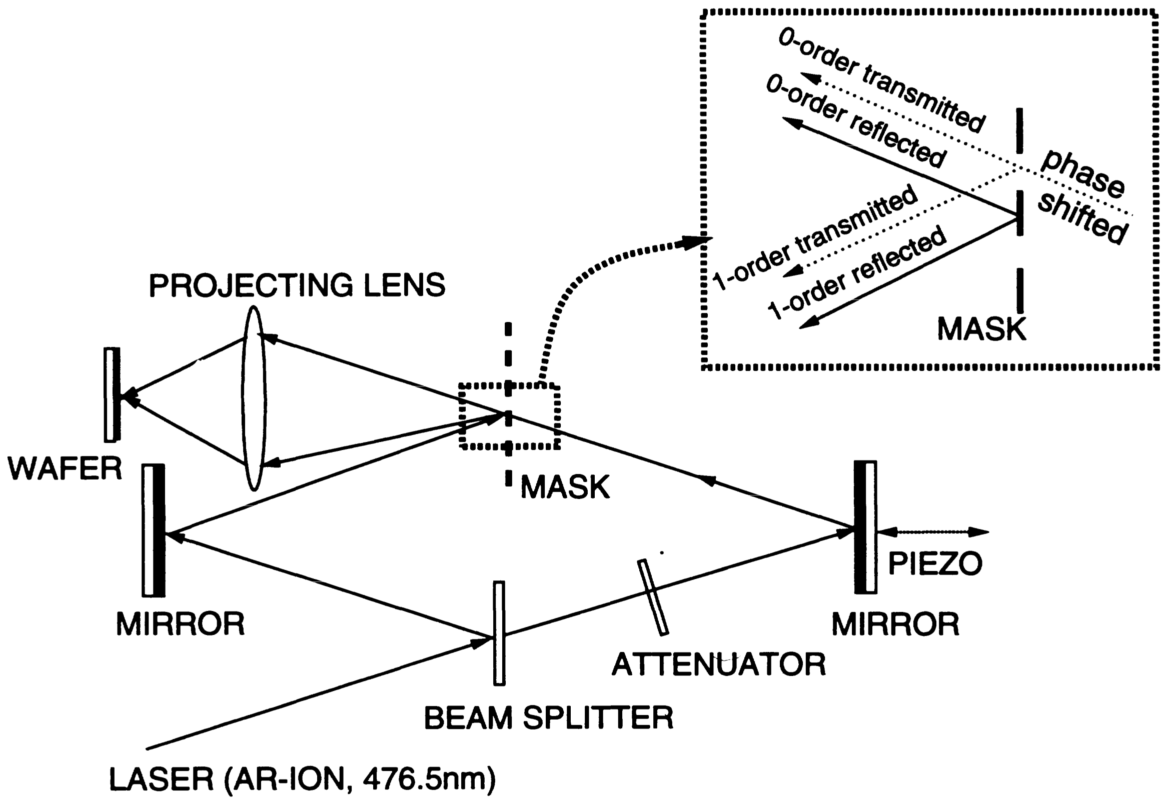

Figure 1: The experimental set up

3. RESULTS

A series of experiments were carried out to test the feasibility of the scheme combining off-axis illumination with interferometric phase shifting. This section, presents CCD camera images of the pattern generated by this new scheme as well as AFM photographs of patterns printed on photoresist.

3.1 Intensity images

The image of the mask formed by the microscope objective using an Ar^+ laser (476.5nm, 20mW) was observed and analyzed with a CCD camera (COHU 4800). In order to do this, the target wafer with the photoresist was removed and the plane of the photoresist was imaged into the CCD array with two microscope objectives in tandem (Olympus M=20X, NA=0.5 and M=40X, NA=0.65). Special care was taken to avoid any optical degradation of the image. The imaging lens could also be translated along the optical axis in order to measure the depth of focus.

A beam profile software was used to produce a two dimensional intensity distribution of the CCD camera image. The two dimensional intensity distribution was later analyzed to obtain the one-dimensional intensity profiles shown in Figure 2.1b, 2.2b, 2.3b and 2.4b.

This off-axis illumination with interferometric phase shifting scheme was simulated using the photolithography simulator Depict within the Integrated CAD Framework. The CAD framework allows the modeling of a phase shift mask layout using the layout editor Magic (see section 4 for more details). The results of this simulation are presented along with the intensity profiles of the CCD camera images in figure 2.

Figure 2.1b shows the CCD image of the mask when the back illumination is blocked. The intensity ratio of the beam diffracted into the zero and first order for an equal lines-and-space pattern[7] is known to be $1 : (2/\pi)^2$, resulting in a image contrast of $C = 90.6\%$. However, if we take into consideration that the reflectivity of the chrome layer[8] is $R = 0.7$ and the Fresnel-reflection at the surface of the mask substrate is 0.032, the calculated contrast drops to 67.7%. The measured value of the visibility of the pattern shown in figure 2.1b is 68.7%, which agrees very closely with this calculated value.

Figure 2.2b shows the image of the mask when the reflected beam in the front is blocked and only the transmitted beam is intercepted by the imaging microscope objective. A careful comparison of figures 2.1b and 2.2b shows (see the vertical dotted lines) that this image is spatially shifted by half of a period of the pattern (see inset in figure 1). This means that there is no transmission from the back side when there is reflection from the front side of the mask.

Figure 2.3b shows the interference pattern when both the beams are used and the phase of the transmitted image was shifted by π with respect to the reflected image, using the piezo-controlled translator. The electric fields are subtracted and consequently the contrast of the image is improved. The intensity of the transmitted beam was adjusted, using the attenuator shown in figure 1 so that the peak intensity of the transmitted pattern was equal to the minimum intensity of the reflected pattern (see figure 2.1b and 2.2b), thus obtaining 100% modulation depth of the image.

When the phase shift between the transmitted and reflected beams is set to 0 or multiples of 2π, the electric fields of the two beams are added and the visibility decreases (figure 2.4b). 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 illumination schemes.

Figure 2 shows that the intensity profiles obtained from both simulation and the experiments agree closely.

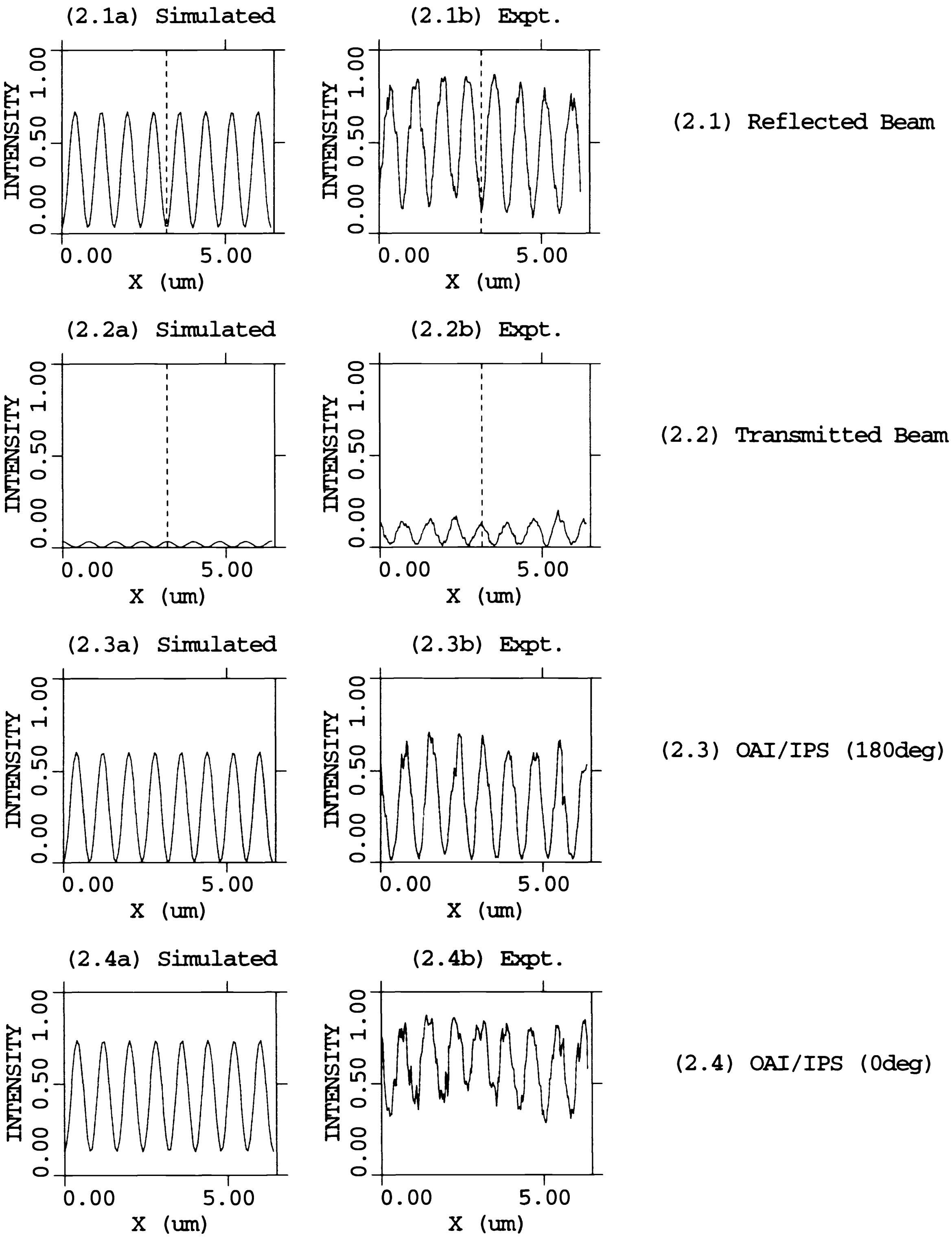

Figure 2: Intensity profiles for off-axis illumination (OAI) with interferometric phase shifting (IPS). Feature size is 0.40μm

Figure 3 shows the defocus-contrast plot from a Depict simulation of our scheme. As expected, we obtain a very large DOF with this scheme. Experimentally, we found that the contrast stays quite high (> 90%) for almost 10μ of defocus in one direction. This is quite large and results from the combined effect of off-axis illumination and interferometric phase shifting techniques.

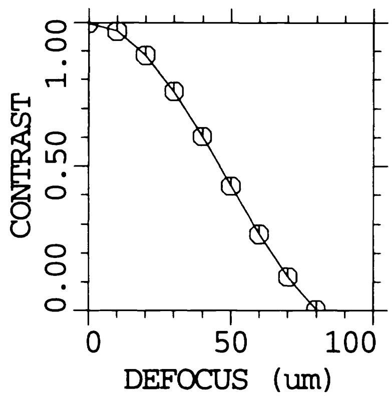

Figure 3: Defocus-contrast plot (Depict simulation)

3.2 Exposed pattern

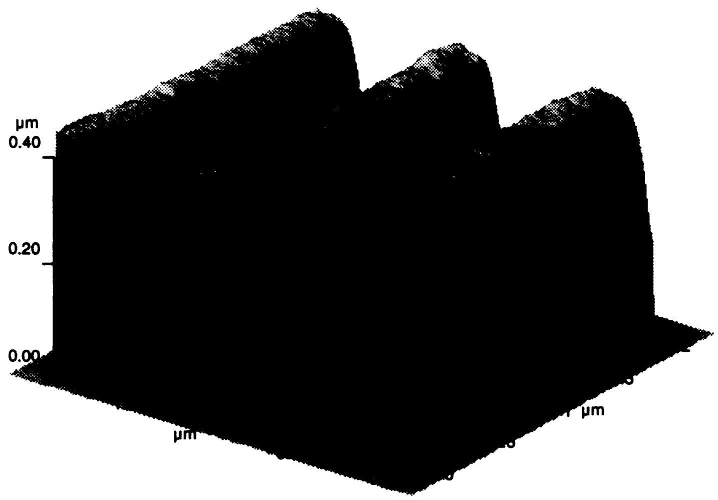

Figure 4: AFM photograph of patterns produced on photoresist

Line and space patterns were also written in a Shipley photoresist using this new scheme, with the Ar^+ laser (457.9nm,100mW). A 0.5μ thick photoresist layer was deposited on a 1 inch silica wafer by spinning the wafer at 5000 rpm. A beam with an energy density of 40 mJ/cm^2 was used to expose the wafer. Development time was 60 seconds with a Shipley MF 320 developer. An atomic force microscope (Park Scientific Instruments) image of an exposed photoresist pattern is shown in figure 4.

4. AN INTEGRATED CAD FRAMEWORK

The lithography simulator, Depict,[9] within an Integrated CAD Framework, was used to evaluate the performance of the new scheme. This set of CAD tools links layout geometry editors, such as Magic to lithographic simulators such as Depict. This will help designers to construct more compact circuits, as they will be able to see the effect on simulated manufactured silicon.

The basic approach followed by the preliminary version of the Integrated CAD Framework is as follows: (1) the CIF (Caltech Intermediate Format), GDS-II or Magic layout is passed through a Filter which identifies areas in the layout that are more prone to problems arising out of photolithographic resolution tolerance, (2) the Filter creates the corresponding inputs for closer analysis with process simulators (Depict), for these critical areas, (3) the process simulator is run on the input provided by the Filter, (4) an Analyzer analyzes the simulator outputs (using pattern matching techniques) and decides whether the printed layout will match the designed mask for a particular set of process parameters, (5) the designer can make some corrections to the original layout based upon this analysis, (6) steps 1-5 can be repeated until the simulator and the designer find that the layout is acceptable. The whole Integrated CAD Framework is based on Magic and all the capabilities described are provided as additional commands to Magic.

4.1 Filter

Figure 5 shows a block diagram of the Filter module and its integration with Magic. The Conditional Design Rules are formulated to identify critical geometries like 'nested elbows' and 'open ends'. These rules appear as a part of the Magic technology file. The CDRC (Conditional Design Rules Checker) block identifies critical geometries based on these conditional rules. It then passes on the layout areas containing these geometries to the Depict Input module. This module prepares Depict input for these areas.

The Filter module is invoked from Magic using the **:drc check** command of Magic or as a part of Magic's continuous background design rule checker.[10] If a critical geometry is found, Magic places a label at the point from where the critical geometry is detected and generates the input files for Depict. The file names contain the cell name, the point from where the critical geometry is detected and the layer in which it is detected in order to identify a specific critical area. The CIF version of the critical areas is also saved.

4.2 Running Depict

Depict is run from within Magic using a new **:depict** command. This command invokes Depict using the inputs generated by the Depict module in Magic.

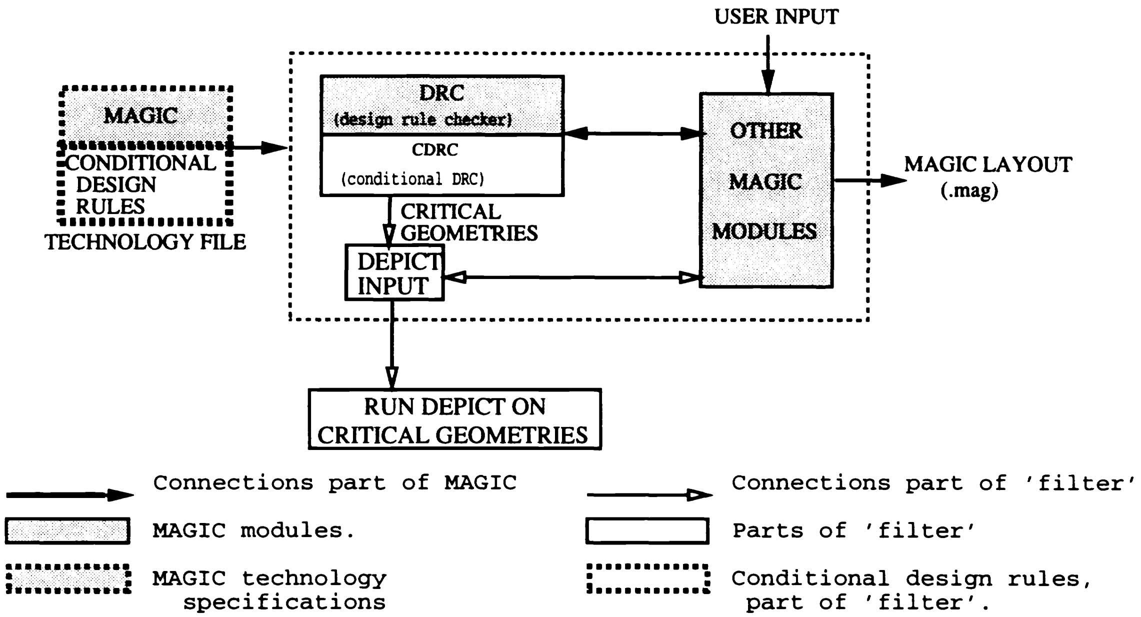

Figure 5: Integration of the Filter module with Magic

4.3 Analyzer

The following process simulations are done on the critical areas using Depict:
(An example of the output of the Analyzer is shown in the appendix (section 7)).

- Aerial Intensity : A 2D aerial intensity image of the mask is generated. The first figure in the top row of the Analyzer output shows this.
- 1D Aerial Intensity : A 1D aerial intensity image of the mask is generated along a cutline through the 2D mask (marked as line AA' on the 2D Aerial Intensity image).
- Etch : The structure along the same cutline is exposed, developed and etched for certain process parameters. The linewidth along the cutline and some process parameters are shown at the bottom right hand corner of the Analyzer output.
- Binary Aerial Intensity : The etched structure is analyzed to determine the minimum threshold intensity till which the printing is fine. This threshold is the intensity at the point on the cutline which marks the beginning of a space in a space-line mask pattern. This threshold is applied to the 2D Aerial Intensity image to get the Binary Aerial Intensity image. All points on the 2D Aerial intensity image that have an intensity value above the threshold are '1' and those below are '0'. The threshold intensity and the x value along the cutline AA' to which the threshold corresponds is shown below the etched structure.
- Binary mask : A binary image of the mask is obtained by marking all points inside the mask elements as '1' and all points outside as '0'.

The Binary Aerial Intensity and the Binary mask is then compared to find a percentage of match between the two. If the percentage match is above a threshold (say 80 percent), the Analyzer declares that the mask "passes" the analysis.

4.4 Magic representations of phase shift masks

While modeling and evaluating the IPS methods, using the Integrated CAD Framework, phase shifting masks are represented in Magic using the usual Magic layers. A single mask is represented by more than one Magic layer, each layer having different optical properties (transmission amplitude and phase). When the Filter converts such masks to Depict input format, it reads the optical properties for each layer (transmission amplitude and phase) from a file and places the information in the Depict input file.

5. CONCLUSIONS

A new high resolution photolithography scheme, which combines off-axis illumination with interferometric phase shifting was demonstrated. Using Ar^+ laser operating at 457.9nm, feature sizes of 0.4 μm were obtained with a DOF of 10μm. Because of the freedom to adjust the relative phase and amplitude of the two illuminating beams, the modulation depth could be improved to almost 100%. This freedom of adjustment makes this scheme a very useful test bed for studying various phase shift and off-axis illumination schemes.

6. ACKNOWLEDGEMENTS

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7. APPENDIX

Figure 6 shows an example of the output of the analyzer for a feature size of 0.49μm using light of wavelength 248nm and the MICROPOSIT SNR200[11] photoresist. The Integrated CAD tool selected the "elbows" from a larger layout and calculated its aerial intensity image (a). The Analyzer then calculated a threshold intensity from the etch simulation (c) and applied it to the aerial intensity image to get an image of the printed feature (d).

Figure 7 shows the analyzer output for the simulation of the new scheme combining off-axis illumination with interferometric phase shifting. The linewidth was 0.4μ and it was printed using a wavelength of 435.8nm on AZ1350J photoresist. The optical co-efficients used for AZ1350J were taken from the Depict library.

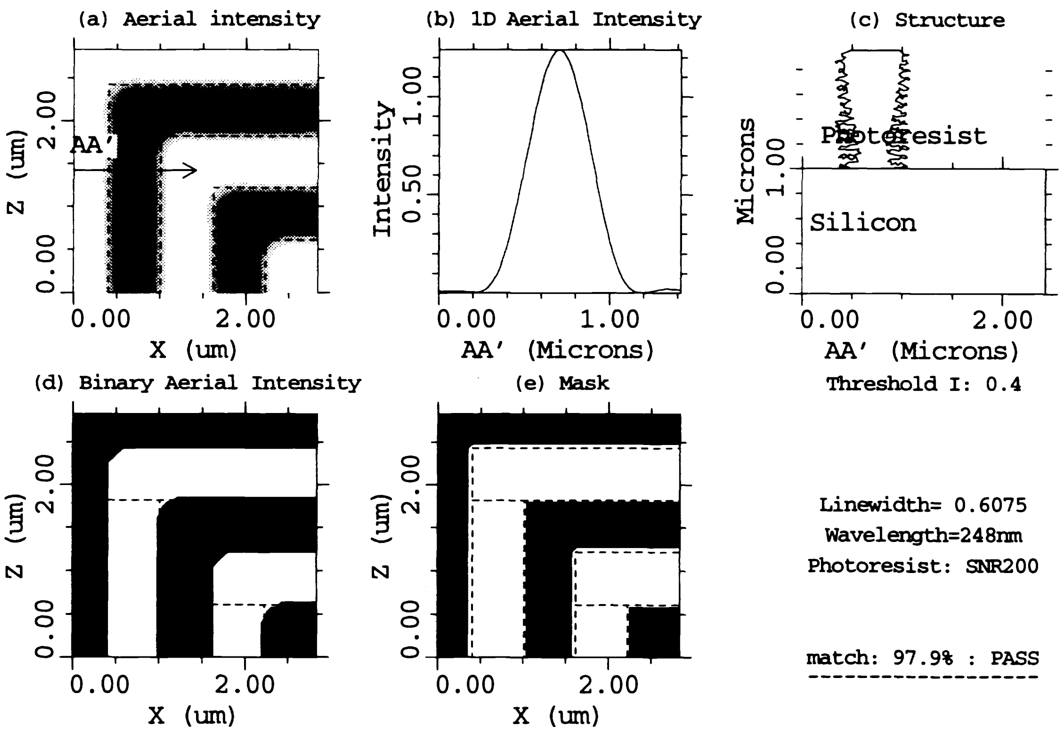

Figure 6: An example of the output of the Analyzer

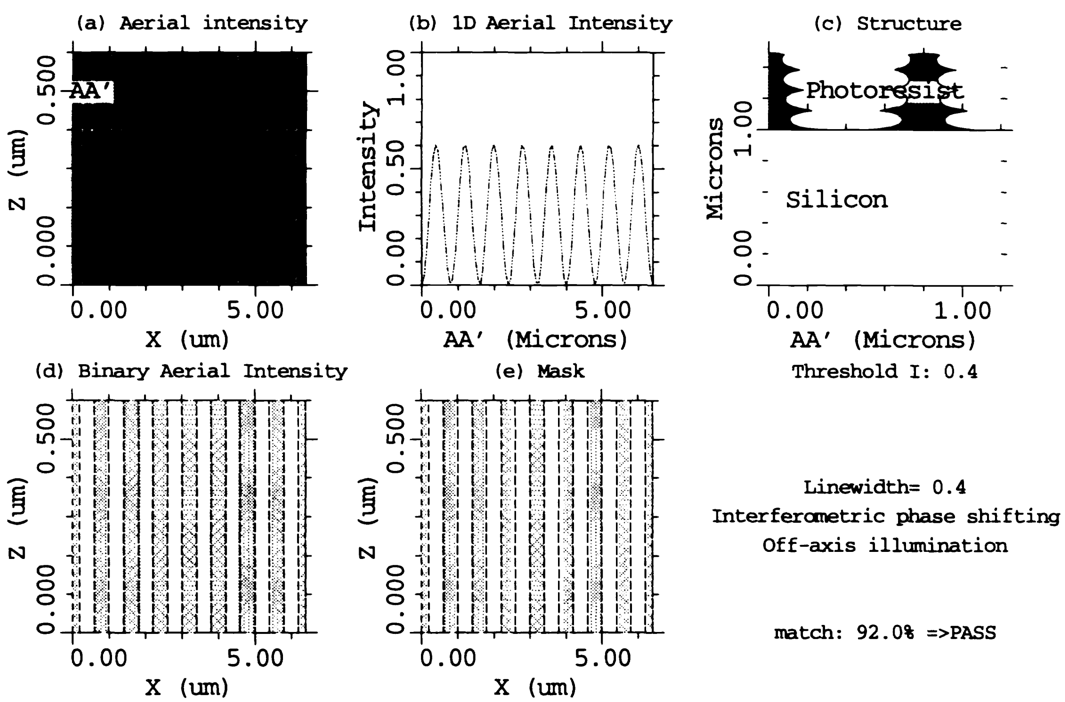

Figure 7: Analyzer output for OAI/IPS

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