Interferometric Lithography Optical System Utilizing a 442nm HeCd Laser

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Abstract **- An interferometric optical lithography system utilizing a 442nm Helium Cadmium (HeCd) laser source has been developed. The HeCd laser was passed through a 2μm diffraction grating etched into a phase shift quartz mask to generate two mutually coherent light beams. The ±1st diffraction orders were collected and interfered at angles ranging from 0 to 90° with respect to the substrate normal. Incident angles of 13, 26, 34, and 47° were implemented to produce corresponding pitches of 1.0, 0.5, 0.4 and 0.3μm, respectively. The smallest line width that was fabricated approached 0.10μm. In order to synthesize the behavior of conventional projection lithography one of the incident light beams was pulsed to adjust the intensity of that beam for variable transmissions producing a range of duty ratios. Images were acquired from scanning electron micrographs (SEM's) for each of the cases analyzed.**

1. INTRODUCTION

Optical lithography is approaching hard limits in the creation of patterns for next generation IC's and there is a concern whether this optical techniques will continue to be used. Advancements have enabled optical lithography as the favored technique for the production of shrinking line widths to facilitate the high density of devices that will be required in future microprocessor technology. One method of overcoming the perceived limits of optical technology is the implementation of interferometric lithography. Interferometric lithography is an emerging tool for the patterning of materials for the semiconductor industry that uniformly produces regular arrays of extremely small features, approaching quarter wavelength. It is an effective means of generating periodic patterns because it affords well-defined illumination and high contrast over a range of spatial frequencies.[1]

Interferometric lithography has the ability to produce highly coherent repeating patterns. These patterns maintain a high contrast over a large depth of focus and resolution is constrained only by diffraction and the coherency of the source. Another benefit of interferometric lithography is its ability to be implemented inexpensively and with minimum complexity since there is limited use of masks and refractive components.[2]

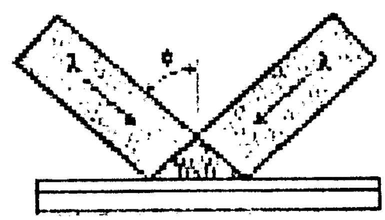

FIG. 1. Two equal wavelength light beams interfering on a resist-coated substrate at angle ϕ.[4]

The simplest method of implementing an interferometric lithography system centers on the interference of two mutually coherent light beams of wavelength λ. The beams interfere at the surface of a substrate coated with photosensitive material at an angle θ with respect to the substrate normal. The interference of the light beams produces a sinusoidal intensity distribution with period P (line/space) specified by:

$$P = \frac{\lambda}{2\sin(\theta)} \tag{1}$$

The minimum resolvable line width decreases as the angle of incidence θ increases, therefore the minimum period that can be imaged with wavelength λ is $\lambda/2$ as θ approaches 90°. A spatial resolution of this size "far exceeds the ability of conventional projection lithography when utilizing the same wavelength".[3-4]

The depth of the optical field of the interferometric lithography system is determined by the beam diameter, the angle of beam intersection, and is typically large (centimeter range). The depth of focus (DOF) is the latitude of an optical system to continue to produce high-resolution features in the presence of focal variation.

The NA of interferometric lithography systems is equivalent to the sin (θ); therefore the DOF can be expressed as a function of that angle by:

$$DOF = \frac{\lambda}{NA^2} = \frac{\lambda}{\sin^2(\theta)} \qquad (2)$$

The depth of focus in an interferometric lithography system can be considered to be infinite since the system eliminates the use of optical components such as masks and lenses, which induce optical aberrations. Simple adjustments can be made to the incident angle θ that will allow variation of the period over a wide range enabling studies to be conducted that would be impacted by changes in pitch. Complete control over aerial image contrast is also possible by unbalancing the intensity of the interfering light beams.[3]

2. EXPERIMENTATION AND RESULTS

A. Optical System Design

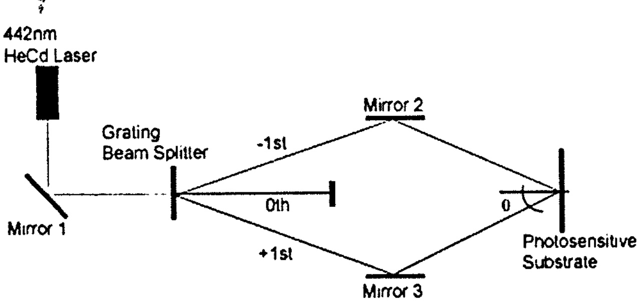

FIG. 2. Interferometric optical system design.

A model 100 Omnichrome series 39x Helium Cadmium laser (λ=442nm) provided the illumination for the interferometric lithography system. The laser source was passed through a 2μm diffraction grating that generated a coherent diffraction pattern (see appendix – Phase Shift Diffraction Grating). The ±1st diffraction orders were collected with rotating plane mirrors and were interfered at the substrate surface exposing a repeating pattern into the photoresist. Adjusting the distance from mirrors 1 and 2 to the imaging plane varied the angle θ. The ±1st diffraction orders were aligned to the 0th order to ensure that each θ, between the diffraction orders and the substrate normal, and the optical path lengths were equal. During photoresist exposure an IL500 research radiometer was placed in the path of the 0th order to prevent it from interfering with the ±1st orders and also to monitor the intensity of the laser beam. The use of the radiometer to monitor the light intensity helped determine the optimal exposure time within the laser's firing period.

A distance of 84mm separated the deflecting mirrors, while the distance to the imaging plane was variable to accompany changes in the desired pitch value. The distance between the phase shift grating and the deflecting mirrors was held constant at 185mm.

B. Pushing the Minimum Line width

The smallest pitch that is attainable with a simple interferometric lithography system is on the order of λ/2, where λ is the exposing wavelength. The minimal possible pitch can be extracted by examining equation 1 where the pitch is minimized when the sine of the angle θ is maximized. As θ approaches 90° the pitch nears λ/2. A duty ratio of 1:1 will present line widths on the order of λ/4, for an exposing wavelength of 442nm the minimum line width is nearing 100nm.

FIG. 3. Line widths approaching 100nm, 20kx (left) and 10kx (right) magnifications.

Figure 3 illustrates the minimum line width achievable with the simple interferometric optical system built for this project. The 1:1 duty ratio is maintained well, however a moderate level of line edge roughness (LER) is apparent for such a fine line width. The loss in resolution can be attributed to factors not limited to speckle or vibrations in the optical system.

C. Generation of Variable Pitches

The interferometric system affords the ability to generate a wide range of pitches for a given wavelength. Varying the angle produced pitches ranging from 0.30μm to 1.0μm, as outlined in table 1. An adjustment to the distance between the deflecting mirrors and the imaging plane was necessary as a result of the angle modification.

Table 1: Imaging distances for pitch variation

Pitch (μm)	1:1 CD (μm)	Angle θ	Imaging Dist. (mm)
0.30	0.15	14	39
0.40	0.20	34	63
0.50	0.25	26	85
1.0	0.50	13	185

Exposing times of 8, 10, 15, and 20 seconds were sampled to determine the time period that produced the optimal patterns. The 10-second exposure time was found to produce the line widths with the highest contrast.

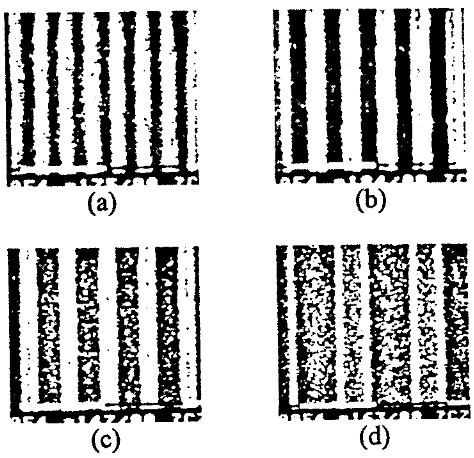

FIG. 4. Variable pitches using interferometric lithography.
(a) 0.30μm (b) 0.40μm (c) 0.50μm (d) 1.0μm

The optical system exhibited the ability to produce variable pitches. Line widths were uniformly patterned with a line:space duty ratio of 1:1. The reduction in the effective line width was also accompanied by a slight degradation in contrast. Feature integrity was maintained with traces of line edge roughness that can be credited to the lack of an optimized resist process, vibrations and stray light in the optical system.

D. Single Beam Attenuation

Techniques exist to utilize interferometric lithography to synthesize the functions of conventional projection photolithography. One such technique involves the intensity attenuation of one of the ±1st diffraction orders being interfered. A portion of the second beam is left uninterfered when the intensity of the first beam is reduced, as shown in figure 5. The uninterfered segment is background noise that closely resembles the 0th order.

FIG. 5. Attenuation of the +1st order while a portion of the −1st order is left uninterfered in the frequency domain.

The 0th order is typically used in conventional projection lithography to manipulate the bias of the sinusoidal intensity pattern. Figure 6 demonstrates how the 0th order bias determines the shape of the waveform. The waveform with lower 0th order amplitude bears a smaller space width and a larger line width than the waveform with a larger 0th order bias.

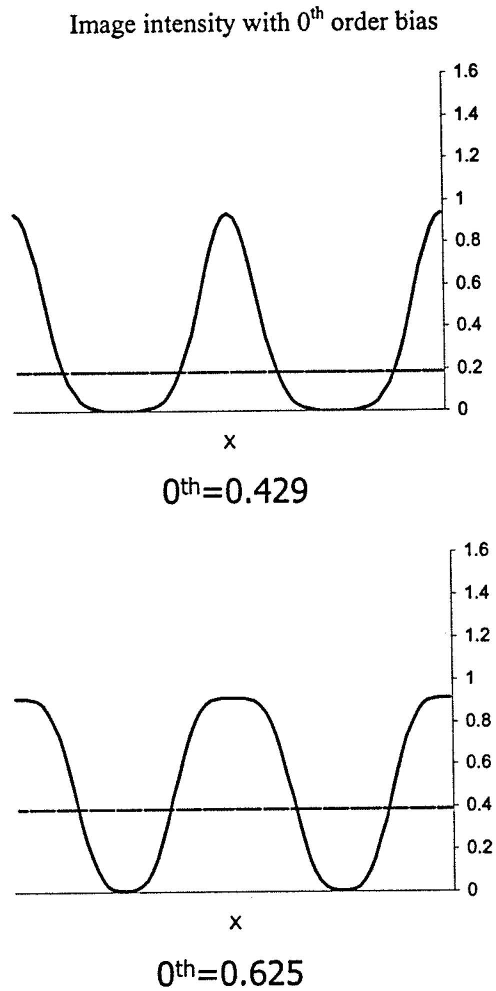

FIG. 6. Image intensity graphs demonstrating the effect the zero order bias has on the shape of the waveform.

The interferometric lithography system can be altered to produce varying duty ratios by manipulating the level of the 0th order intensity through the attenuation of a single beam. The fourier transform amplitude of the attenuated beam is given by equation 3 and the fourier transform amplitude of the unattenuated beam is given by equation 4, where s is the space width and p is the pitch (sin c = sinc). The transmission is extracted by taking the ratio of the attenuated beam over the unattenuated beam, equation 6.

$$A_{+1st} = \left(\frac{s}{p}\right)\sin c\left(\frac{s}{p}\right) \quad (4)$$

$$A_{0th,-1st} = \frac{s}{p} + \left(\frac{s}{p}\right)\sin c\left(\frac{s}{p}\right) \quad (5)$$

$$T = \frac{\left(\frac{s}{p}\right)\sin c\left(\frac{s}{p}\right)}{\frac{s}{p} + \left(\frac{s}{p}\right)\sin c\left(\frac{s}{p}\right)} \quad (6)$$

The ability to synthesize the function of projection lithography comes with a tradeoff in the loss of contrast for duty ratios deviating from 1:1. The loss in contrast occurs due to increase in background noise from the 0th order bias. Figure eight pictures the optimal contrast value at a 1:1 line to space ratio and a reduction in contrast as the duty ratio increases and decreases from that point.

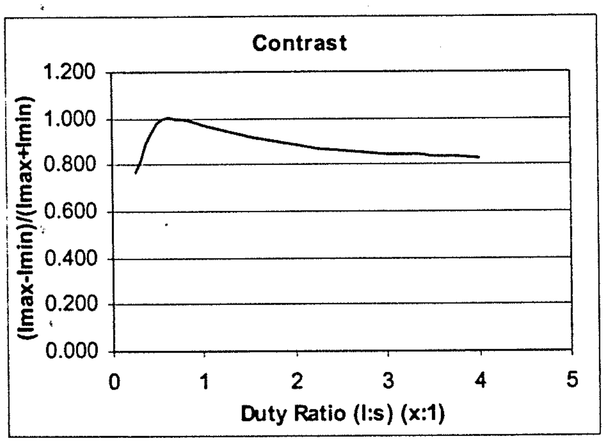

FIG. 7. A reduction in contrast occurs for duty ratios deviating from 1:1.

Single beam attenuation was accomplished by pulsing one of the interfered beams at a transmission appropriate to the desired duty ratio. The transmission - duty ratio pairings are listed in table 2. Discs were constructed with a percentage of the area removed proportional to each transmission value. The discs were mounted onto a motor and spun at a high enough speed to be a non-factor, pulsing the light beam with the proper transmission.

Table 2: Correlation of Transmission to Duty Ratio

Duty Ratio l:s	Pitch	0th	1st	Trans.
1:0.4	1.4	0.286	0.249	0.50
1:1	2	0.500	0.318	0.40
1:2	2.9	0.655	0.281	0.30
1:2.65	3.65	0.726	0.241	0.25
1:3.7	4.7	0.787	0.197	0.20

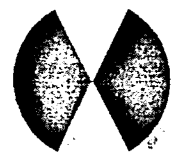

FIG. 8. Sample of fabricated disc used to pulse the light, pictured 30% transmission disc.

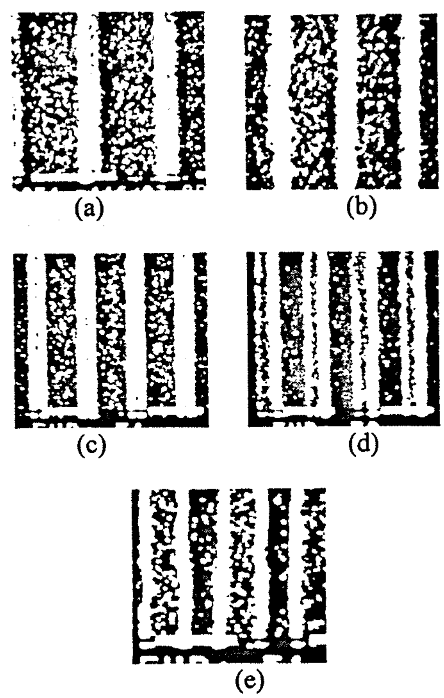

FIG. 9. Variable transmissions produced the desired duty ratios.
(a) 20% (b) 25% (c) 30% (d) 40% (e) 50%

Transmissions of 20, 25, 30, 40, and 50% were implemented to produce a designated duty ratio. The 40% transmission generated a duty ratio most similar to a 1:1 duty ratio. For transmissions deviating from 40% line edge roughness and image defocus were apparent. These image aberrations can be correlated to the contrast loss due to duty ratios differing from 1:1. The image integrity was optimal for transmissions near 40%.

3. DISCUSSION AND CONCLUSIONS

An optical system utilizing a 442nm Helium Cadmium (HeCd) laser source has been successfully developed that exhibits the basic characteristics of a simple interferometric lithography system. A 2μm diffraction grating etched into a phase shift quartz mask was used to generate the two mutually coherent light beams to be interfered at the substrate surface. The angle of interference was varied with values ranging from 0 to 90° with respect to the substrate normal.

Incident angles of 13, 26, 34, and 47° were implemented to produce corresponding pitches of 1.0, 0.5, 0.4 and 0.3μm, respectively. Line widths approaching 100nm were fabricated by pushing the incident angle near 90°. Scanning electron images exhibited moderate loss of resolution and line edge roughness as the line width was decreased.

It was shown that a simple interferometric lithography system could be utilized to synthesize the behavior of a conventional photolithography system with minimal cost and complexity to researchers. To exhibit this property one of the incident light beams was pulsed to adjust the intensity of that beam for transmissions of 20, 25, 30, 40, and 50% while the other remained unaffected for the exposure time. Each transmission value produced a corresponding duty ratio.

4. APPENDIX

A. Substrate Preparation and Processing

The substrates used were bare 6" silicon wafers. Resist processing was conducted on the SSI-150 Wafertrack. The wafers were vapor primed with HMDS, to promote adhesion, at 140°C for 60 seconds and then cooled to 25°C. A 2:1 (solvent to resist) mixture of ethyl lactate and OIR620-10 was hand coated to a thickness of 200nm and soft baked at 90°C for 60 seconds. OIR620-10 is a positive photoresist from Arch Chemicals, Lot# Q1K01RLI exp. November 1, 2002. In order to be mounted onto the optical system the photoresist coated wafers were broken into 1-inch wide and 1 ½ inch long samples. Following exposure the samples were developed, hard baked, and coated with gold for image retrieval in the scanning electron microscope (Philips 525 SEM).

B. Phase Shift Diffraction Grating

A diffraction grating is a repetitive array of diffracting elements that have the effect of producing periodic alterations in phase and amplitude. When the diffraction grating is illuminated with the laser source a series of intensity spots are generated called diffraction orders. The intensity of each successive diffraction order is dependent upon the level of interference between individual wave fronts that pass through each of the diffraction grating slits.[5]

A binary, chrome on quartz, mask was manufactured with a 2μm diffraction grating. The chrome thickness was 950A. The open quartz regions were dry etched to a depth of 4675A with plasma composed of 70sccm of CHF_3 and 10sccm O_2 gases. The etch time was 11 minutes and 30 seconds. Following the quartz etch; the chrome was completely removed leaving a chromeless 2μm phase shift diffraction grating.

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Frank C. Cropanese, originally from Brooklyn, New York, received a B.S. in Microelectronic Engineering from the Rochester Institute of Technology in 2002. He attained 18 months of co-op experience at Intel Corporation in Phoenix, Az. He will be continuing his studies in the RIT Microelectronics graduate program in the Fall of 2002.