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Enhanced Microlithography Using Combined Phase Shifting and Off-axis Illumination

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Off-axis illumination is a promising optical microlithography technique which can be used to improve the image quality of line-space patterns. With this method the image is produced by the zero and first order diffracted beams. Due to the intensity difference between these two order diffracted beams the contrast of the image cannot be unity. This paper demonstrates the optical enhancement that can be achieved by a combination of interferometric phase shifting and off-axis illumination. In such an arrangement the mask is illuminated symmetrically from both the front and back sides, and not two but in fact four – (two zero and two first) – order beams produce the image. We show experimentally that the contrast of the image can be improved if the phase difference between the reflected and transmitted beams is π, and the intensity of the transmitted beam is about 13% of the reflected beam. This improved quality image with feature sizes of 0.4 μm was recorded in a photoresist using an Ar^+ ion laser operating at 457.9 nm.

KEYWORDS: phase shifting technique, submicron microlithography, off-axis illumination, interference

1. Introduction

High quality, high resolution imaging is important for many applications in optics. One of the most important uses is optical lithography for the fabrication of integrated circuits. Continued development of optical lithography is essential in the microelectronics industry.$^{1)}$ Simultaneous improvement of the resolvable linewidth (W) and the depth of focus (DOF) is an important issue. The resolution of a diffraction-limited optical system is given by

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

where λ is the wavelength, NA is the numerical aperture of the imaging system and k_1 is the Rayleigh's coefficient for resolution. The value of k_1 depends on the imaging technology and process control. This equation shows that the resolution can be improved by using a shorter wavelength illumination source or by increasing the value of NA. However, since the depth of focus (DOF) of an optical system is

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

(where k_2 is the Rayleigh's coefficient for DOF), images that are obtained with a high NA projecting lens have a small DOF. The value of k_2 is determined by both the diffraction and aberration of the imaging system. Unlike the conventional on-axis approach, only the first two diffraction orders enter the imaging system, which has the effect of significantly improving k_2. A smaller DOF requires a more stable and controlled, and hence costlier exposure tool. The problem of reduced DOF is of growing importance as the surface of the fabricated wafer becomes increasingly non-planar. An alternate approach to reduce the resolvable linewidth and increase DOF is to modify the optical system coefficients k_1 and k_2. These techniques are based on the manipulation of the mask (phase shifting), illumination (off-axis), exposure (multiple focal plane exposure), or the resist (surface imaging).

One of the critical images often used in the layout of integrated circuits is the line-space pattern used for buses and other multi-bit pathways. Phase shifting techniques$^{2)}$ can increase the resolution by a factor of about 1.5. However, the doubling of spatial frequency causes fundamental design problems in the mask.$^{3)}$ Multiple focal plane exposure increases the depth of focus by a factor of about 4, while the resolution limit remains unchanged.$^{4)}$ This technique is well suited for the imaging of contact holes but does not offer advantages for imaging line-space patterns. Off-axis illumination$^{2)}$ offers an increase in resolution by a factor of about 1.2 and an increase in DOF by a factor of about 1.4. The absence of spatial frequency doubling simplifies the design of the mask. One of the problems in using off-axis illumination is that the amplitude of the zero and first order diffraction beams is not equal, thus leading to a certain loss in the contrast of the imaged line-space pattern.$^{5)}$ In this paper we show experimentally, that by superimposing a phase shifted interference pattern onto the main interference pattern the contrast of the image can be significantly improved. The experimental method of superimposing the interference pattern is the same as was used in earlier work on interferometric phase shifting.$^{6-9)}$

2. Experimental Setup

Figure 1 shows the experimental arrangement. The output from a continuous wave laser operating at 457.9 nm was split into two beams and used to illuminate both the front and back surfaces of the mask. The mask was a patterned evaporated, reflective chrome layer on a fused silica substrate, forming a line-space pattern, with a spatial frequency of 16 μm (see Fig. 2). The intensity and the phase of the back illumination was controlled by a

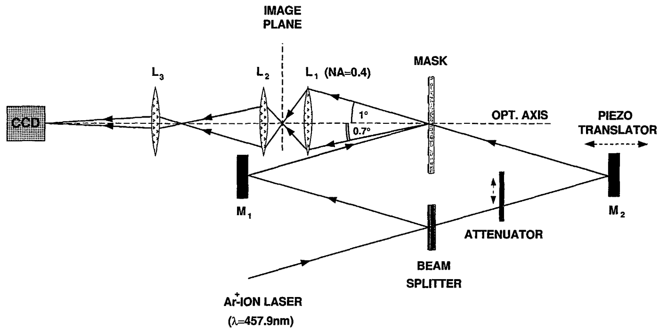

Fig. 1. Experimental scheme for off-axis illumination combined with interferometric phase shifting. The mask is illuminated symmetrically both from the back and front sides with a beam splitter and two (M_1, M_2) mirrors. The phase difference between the two beams and amplitude of the beam coming from the back can be adjusted by a piezo-controlled linear translator and a variable attenuator. Lens L_1 collects only the zero and first order diffracted beams, and produces an image of the mask on the image plane. The properties of the image could be studied by projecting it onto a CCD camera using two microscope objectives (L_2, L_3).

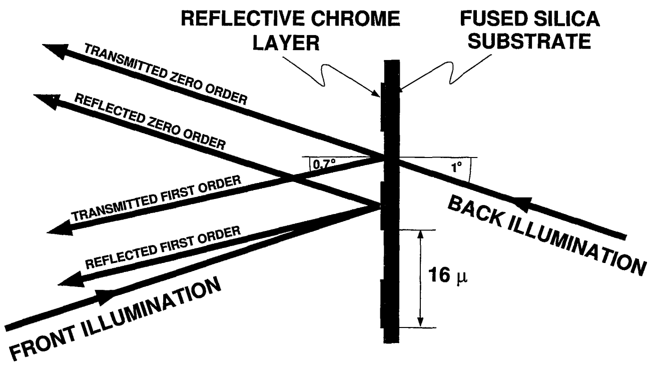

Fig. 2. Diffraction effects at the mask. Due to the symmetrical illumination, the transmitted and reflected zero order beams as well as the transmitted and reflected first order beams are collinear.

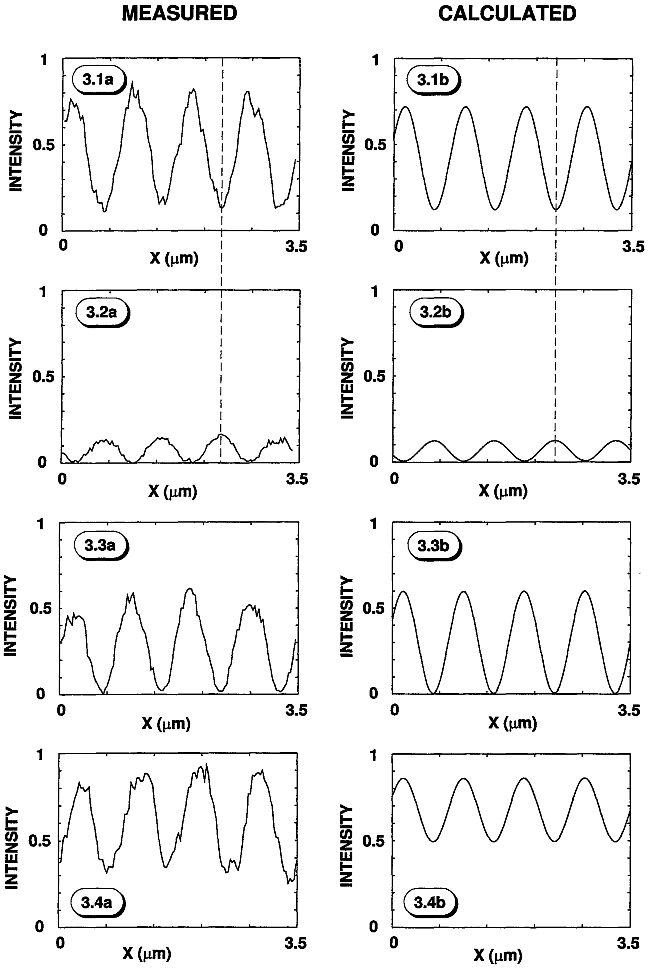

Fig. 3. Intensity pattern as observed by the CCD camera. Figures (a) show the measured and figures (b) show the calculated curves. 3.1: blocking the back illumination, 3.2: blocking the front illumination, 3.3: using both beams with 180° phase difference, 3.4: using both beams with 0° phase difference on the surface of the mask.

variable attenuator and a piezo-controlled linear translator, respectively. A microscope objective (L_1: magnification $(M) = 20X$, $NA = 0.4$) produced the image. The mask to objective distance was adjusted to the manufacturer microscope tube length to ensure a nominal magnification ratio and high image quality.

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

The image of the line-space pattern formed by lens L_1 was magnified by means of two microscope objectives L_2 and L_3 in tandem ($M = 20X$, $NA = 0.5$ and $M = 40X$, $NA = 0.65$). The imaging lens L_2 was mounted on a precision translator allowing a direct measurement of the depth of focus of the image. The magnified image was projected onto a CCD camera by lenses L_2 and L_3, which were only used for image diagnostics. During photoresist exposure, the resist was placed directly in the image plane of lens L_1, as discussed below.

3. CCD Measurement of the Image

Since the path difference between the two beams which illuminated the mask was less than the coherence length of the illuminating laser ($\approx$ 50 mm), the image was produced by coherent beams. A calculation was performed to predict the intensity distribution in the image plane. In this calculation the electric fields of the diffracted order beams (see Fig. 2) were added, under appropriate phase and amplitude conditions. The intensity was represented by the time average value of the square of the sum of the electric fields. A comparison of the calculated and measured intensity distributions is depicted in Fig. 3.

Figure 3.1a shows the CCD image of the line-space pattern when the back illumination reflected from mirror M_2 was blocked. The intensity ratio of the beam diffracted into the zero and first orders for an ideal equal line-space pattern is known[10] to be $1 : (2/\pi)^2$, resulting in an image contrast of

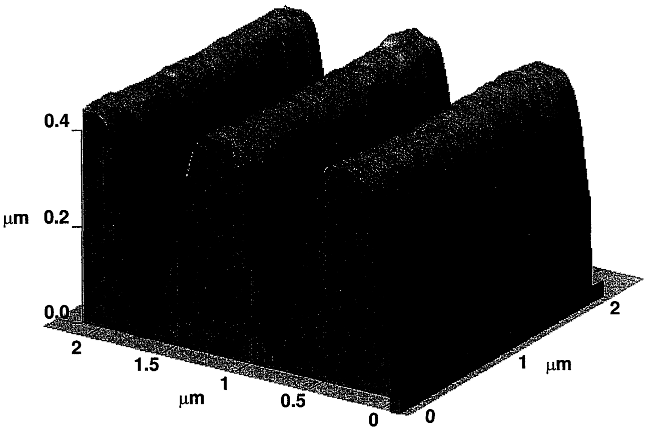

Fig. 4. AFM photograph of the line-space pattern produced on photoresist.

$$C = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}} = \frac{\left(1+\frac{2}{\pi}\right)^2 - \left(1-\frac{2}{\pi}\right)^2}{\left(1+\frac{2}{\pi}\right)^2 + \left(1-\frac{2}{\pi}\right)^2} = 90.6\% \qquad (3)$$

However, if we take into consideration that the reflectivity of the chrome layer R_{Cr} is not 1 but 0.71 and the Fresnel reflection at the transmitting surface of the mask is not 0 but $R_{\mathrm{Sub}} = 0.032$, then the calculated contrast decreases to about 70.5%. The measured value of the pattern visibility as shown in Fig. 3.1a is 68.7%, which agrees very closely with the calculated value. Figure 3.2a shows the image of the mask when the reflected beam in the front is blocked, and only the transmitted beams are intercepted by the imaging microscope lens L_1. A careful comparison of Figs. 3.1a and 3.2a shows (see vertical dotted lines), that these images are spatially shifted by half the period of the pattern. This means that there is no transmission from the back side, when there is a reflection from the front side of the mask (see Fig. 2).

Figure 3.3a depicts the interference pattern, when both beams were used and the phase of the transmitted image was shifted by π with respect to the reflected image, by adjusting mirror M_2 using the piezo-controlled translator. The intensity of the transmitted beam was adjusted with the attenuator shown in Fig. 1 so that the peak intensity of the transmitted pattern would be equal to the minimum intensity of the reflected pattern (see Figs. 3.1a and 3.2a). In this case it means that the intensity of the back illumination is about 13% of the intensity of the front illumination. Due to the π phase shift of the patterns, the electric fields are subtracted resulting in a nearly 100% modulation depth of the image. Due to the high spatial coherence of the illuminating laser beam, a high image contrast results in approximately 5 μm defocus in both directions.

When the phase shift between the transmitted and reflected images is set to 0 or multiples of 2π, the electric fields of the two beams are added and the visibility decreases (depicted in Fig. 3.4a).

4. Recording of Images in Photoresist

The image of the line-space pattern was recorded in an experimental Shipley XP 94314 photoresist using the off-axis phase shifting scheme. An about 0.5 μm thick photoresist layer was deposited on a 1 inch diameter silica wafer. A beam with an energy density of 40 mJ/cm^2 was used to expose the resist. The development time was 60 seconds with a Shipley MF 320 developer. An atomic force microscope (Park Scientific Instruments) image of the exposed photoresist is shown in Fig. 4. A significant fraction of the sidewall slope seen here is due to the resolving power of the AFM microscope tip. The minimum feature sizes of the line-space pattern in the image plane can be calculated knowing the period of the line-space pattern on the mask and the magnification of objective L_1. The calculated 0.4 μm value agrees with the period of the exposed pattern.

5. Conclusion

A new high resolution photolithography scheme combining both off-axis illumination with interferometric phase shifting was demonstrated. Feature sizes of 0.4 μm were obtained with a *DOF* of 10 μm (± 5 μm) using laser illumination at 457.9 nm and a microscope objective with *NA* = 0.4. This large *DOF* results from the combined effect of the interferometric phase shifting technique and off-axis illumination. Because of the ability to adjust the relative phase and amplitude of the two illuminating beams, a modulation depth of almost 100% can be achieved. This freedom of adjustment makes this scheme a useful test bed for studying various phase shifting schemes combined with off-axis illumination.

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1) K. H. Brown: Proc. SPIE **2440** (1995) 33.
2) P. Luehrmann, P. van Oorschot, H. Jasper, S. Stalnaker, S. Brainerd, B. Rolfson and L. Karklin: Proc. SPIE **1927** (1993) 103.
3) M.D. Levenson, N. S. Viswanathan and R. A. Simpson: IEEE Trans. Electron Devices **29** (1982) 1828.
4) H. Fukuda, A. Imai, T. Terasawa and S. Okazaki: IEEE Trans. Electron Devices **38** (1991) 67.
5) T. Ogawa, M. Uematsu, F. Uesawa, M. Kimura, H. Shimizu and T. Oda: Proc. SPIE **2440** (1995) 772.
6) M. Kido, G. Szabó, J. R. Cavallaro, W. L. Wilson and F. K. Tittel: Proc. SPIE **2197** (1994) 835.
7) F.K. Tittel, J. R. Cavallaro, M. Kido, M. C. Smayling, G. Szabó and W. L. Wilson: Proc. SPIE **2502** (1994) 617.
8) M. Kido, G. Szabó, J. R. Cavallaro, W. L. Wilson, M. C. Smayling and F. K. Tittel: Jpn. J. Appl. Phys. **34** (1995) 4269.
9) M. Erdélyi, C. Sengupta, Zs. Bor, J. R. Cavallaro, M. Kido, M. C. Smayling, F. K. Tittel, W. L. Wilson and G. Szabó: Proc. SPIE **2240** (1995) 827.
10) M. Born and E. Wolf: *Principles of Optics* (Pergamon Press, 1980) 6th ed., p. 405.