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Phase Contrast Lithography

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Abstract

This paper analyzes theoretically the potential for a novel approach to lithographic imaging: Phase Contrast Lithography. In this approach, a unique chromeless phase shifting mask is combined with a specific phase filter at the pupil plane to produce high contrast images projected onto the wafer. Like the phase contrast microscope, the pupil filter is designed to phase-shift the zero order diffracted light by some angle. The design of the chromeless mask is purposely kept simple using essentially the same design information as for a conventional chrome/glass mask. Initial analysis of the Phase Contrast Lithography technique reveals some problems, especially proximity effects.

I. Introduction

The phase contrast microscope, first proposed by Fritz Zernike in the early 1930s, uses spatial filtering to produce high contrast images of transparent samples. The concept of the phase contrast microscope is quite simple: phase shift the zero order light diffracted from the sample by 90° to produce an image whose intensity is linearly proportional to the phase of the object. However, as with most aspects of optics, this simple linearity holds true only over limited ranges and an accurate analysis of the imaging behavior of a phase contrast microscope is not trivial.

Is the phase contrast imaging technique applicable to lithography? This paper will analyze theoretically the potential for a novel approach to lithographic imaging: Phase Contrast Lithography (PCL). In this approach, a unique chromeless phase shifting mask is combined with a specific phase filter at the pupil plane to produce high contrast images projected onto the wafer. Like the phase contrast microscope, the pupil filter is designed to phase-shift the zero order diffracted light by some angle. The design of the chromeless mask will be optimized for best image quality.

II. Historical Review

A conventional microscope has trouble imaging transparent samples (for example, a biological specimen) due, quite obviously, to a lack of contrast in the sample. Several techniques became known to address this problem, but in the early 1930s Fritz Zernike proposed a technique which produced an image whose intensity was linearly proportional to the phase of the object (and thus the object's

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thickness) [1]. Zernike's invention of the *phase contrast microscope* revolutionized the field of biological microscopy and is one of the earliest examples of spatial filtering techniques in optical imaging. (Not coincidentally, the phase contrast microscopy is the optical analogy of FM radio broadcasting, which was invented the following year.) The following is a simple description of the behavior of a phase contrast imaging system (following the descriptions given by Goodman [2] and Born and Wolf [3]).

Consider a transparent object whose electric field transmission is given by

$$t(x,y) = e^{i\phi(x,y)} = 1 + i\phi(x,y) - \frac{\phi^2(x,y)}{2} - \ldots \qquad (1)$$

If the magnitude of the phase of the object (which is proportional to the object's thickness) is much less than 1 radian, the second and higher orders of ϕ can be neglected. If a conventional imaging system with coherent illumination is considered to be near-ideal and the finite extent of the aperture can be neglected (i.e., a high numerical aperture system), the electric field and the intensity of the resulting image will be approximately

$$E(x,y) \cong 1 + i\phi(x,y) \qquad (2)$$

$$I(x,y) \cong 1 + \phi^2(x,y) \qquad (3)$$

Since the phase of the object is added to the dc component of the light in quadrature, the resulting image intensity has a strong dc component (bright background) with a small modulation proportional to the square of the phase.

Zernike recognized that the modulation of phase will be diffracted away from the center of the entrance pupil of the imaging system, whereas the dc component of the light will pass through the center of the lens. He then proposed a phase filter which would shift the phase of the dc light by 90° but leave the diffracted phase modulation alone. This filter is easily constructed as a glass plate with a small dot of glass in the center of proper thickness to give a 90° phase shift. As a result, the dc component of the electric field would be in-phase with $\phi(x,y)$ giving

$$E(x,y) \cong i(1 + \phi(x,y)) \qquad (4)$$

$$I(x,y) \cong 1 + 2\phi(x,y) \qquad (5)$$

Thus, using Zernike's spatial filter the resulting image has an intensity which is linearly proportional to the phase of the object (the contrast of the image is determined by the phase of the object, thus the term *phase contrast*) for small phase variations.

In lithography, we desire images which are binary (0 and 1 intensity values). Looking at equation (5), it appears that if the object were binary with phases of -0.5 and +0.5 the resulting image would exhibit very good contrast. This conclusion is somewhat misleading, however, because a phase of 0.5 is large enough to make the assumption of small phase less than accurate. To investigate the potential of phase contrast techniques for lithography, a more thorough analysis is required.

III. Phase Contrast Lithography Design

When designing a new lithography system, as with any design, the first step is to list the goals and constraints of the design. The goal in lithography is to create images with as close to binary intensity values as possible, with one of those binary values equal to zero. Of course, the image should keep its binary qualities over a wide range of feature sizes and shapes down to as small a size as possible. There are always many practical constraints in any design process, but in this case I wish to impose a very important constraint: the mask pattern used in this lithography system will be constrained to be a binary phase mask using essentially the same CAD mask design as would be used for a conventional lithography system.

Let us represent the mask design information as the binary function *m(x,y).* In a conventional imaging system, the 0 and 1 values for *m(x,y)* would represent chrome and glass, respectively. Thus, the transmittance of the conventional binary mask is simply *m(x,y).* A phase-only binary mask would have a phase shift given by the presence or lack of a shifter material on the mask plate. The resulting phase shift of the mask would be given by

$$\phi(x,y) = \phi_0\, m(x,y) \tag{6}$$

where ϕ_0 is the phase of the shifter material used. Equation (6) represents a mathematical statement of the design constraint imposed on this problem. The resulting electric field transmittance of the mask would then be given by

$$t(x,y) = e^{i\phi(x,y)} = 1 + i\phi(x,y) - \frac{\phi^2(x,y)}{2} - \ldots \tag{7}$$

Since *m(x,y)* is purely binary, raising *m* to any power is simply *m*. Thus, the Taylor's series expansion of the exponential can be written as

$$e^{i\phi(x,y)} = 1 + i\phi(x,y) - \frac{\phi^2(x,y)}{2} - \ldots = 1 + m(x,y)\left(i\phi_0 - \frac{\phi_0^2}{2} - \ldots \right)$$

$$t(x,y) = 1 + m(x,y)\left(e^{i\phi_0} - 1 \right) \tag{8}$$

The diffraction pattern which results from this mask can be determined by taking the Fourier transform of the mask transmittance. Letting $T(f_x,f_y)$ represent the Fourier transform of $t(x,y)$ and $M(f_x,f_y)$ the Fourier transform of $m(x,y)$, then the electric field distribution of the diffraction pattern is given by

$$T(f_x,f_y) = \delta(f_x,f_y) + M(f_x,f_y)\left(e^{i\phi_0} - 1\right) \tag{9}$$

where $\delta(f_x,f_y)$ is a delta function at the center of the aperture. We must know define a filter at the pupil plane, using as our model the phase contrast filter of Zernike. Let us define a filter with electric field transmittance of F that is transparent, but with a small phase-shifting dot in the center. Letting ϕ_f be the phase shift of the central dot,

$$F(f_x,f_y) = 1 + \left(e^{i\phi_f} - 1\right) circ\left(\frac{\sqrt{f_x^2 + f_y^2}}{f_0}\right) \tag{10}$$

where *circ* is the standard circle function (1 inside the circle, 0 outside) and f_0 is the radius of the circle (i.e., the radius of the phase-shifting dot).

The light entering the lens will be the product of the diffraction pattern, the filter and the pupil function of the lens. We shall now make three simplifying assumptions (two of which will be removed later). Let us assume that the pupil is very big such that the entire diffraction pattern is captured. Further, let us assume that our phase dot radius is very small and that coherent illumination is used. Finally, we will assume that the mask pattern of interest is an isolated feature such that $M(0,0)$ is not a delta function (this occurs when $m(x,y)$ is an isolated value of 1, for example). Because the phase dot is very small, it will have a negligible effect on the diffraction pattern unless there is a delta function passing through the dot. Since we have assumed that $M(f_x,f_y)$ does not contain a delta function at the origin, the product of the filter and the diffraction pattern will be

$$TF = e^{i\phi_f}\,\delta(f_x,f_y) + M(f_x,f_y)\left(e^{i\phi_0} - 1\right) \tag{11}$$

Because of our assumption of a pupil of infinite extent, the resulting electric field image is simply the inverse Fourier transform of equation (11).

$$E(x,y) = e^{i\phi_f} + m(x,y)\left(e^{i\phi_0} - 1\right) \tag{12}$$

Calculating the intensity of the aerial image from equation (12) gives

$$I(x,y) = 1 + 2m(x,y)\left[1 + \cos(\phi_f - \phi_0) - \cos(\phi_0) - \cos(\phi_f)\right] \tag{13}$$

(Note that this result is very similar to one given by Born and Wolf [3].)

Recalling our goal of making the aerial image binary, what would it take to make equation (13) give a binary aerial image? Obviously, when *m(x,y)* is zero, the resulting aerial image intensity will be one. Thus, to make the intensity go to zero when *m(x,y)* is one, the term in the square brackets must become -1/2. Examining this term in brackets reveals that there are only two possible combinations of angles which satisfy this condition:

$$\phi_f = 60^o \; and \; \phi_0 = -60^o, \quad or \quad \phi_f = -60^o \; and \; \phi_0 = 60^o \tag{14}$$

Thus, using what I shall call the 60/60 design of a 60° phase shifter on the mask and a -60° phase shifter at the center of the lens pupil, the resulting aerial image would be

$$I(x,y) = 1 - m(x,y) \tag{15}$$

From a design perspective, if a standard mask layout is used, then the 60° shifter material on the mask would represent the equivalent of chrome and the unshifted material would represent glass.

Before analyzing this imaging system further, it is interesting to note the differences between the 60/60 phase contrast design for lithography and the conventional 90° phase contrast design for microscopy. One might have expected, from an analogy to the phase contrast microscope, that a 90/90 design would work for lithography. However, as was pointed out earlier, these angles violate the assumption of a small phase angle on the object. Further, the design goals for microscopy and lithography are quite different. In microscopy, a linearly varying intensity is desirable, whereas in lithography a highly non-linear intensity is needed.

IV. Analysis of the 60/60 Design for Phase Contrast Lithography

In order to investigate the behavior of the 60/60 PCL design, the assumptions used in the derivation of this design will be eliminated. First, how does the 60/60 PCL compare to conventional imaging when the finite extent of the aperture is considered? Consider a binary chrome mask with pattern *1-m(x,y)*. The electric field image resulting from this mask pattern will be given by

$$E_C(x,y) = \mathcal{F}^{-1}\left\{\left(\delta(f_x,f_y) - M(f_x,f_y)\right)P(f_x,f_y)\right\} = 1 - \mathcal{F}^{-1}\left\{M(f_x,f_y)P(f_x,f_y)\right\} \tag{16}$$

or,

$$\mathcal{F}^{-1}\left\{M(f_x,f_y)P(f_x,f_y)\right\} = 1 - E_C(x,y) \tag{17}$$

where $P(f_x,f_y)$ is the pupil function and may include defocus and aberrations. Considering now our PCL system, multiplying equation (11) by the lens pupil function will give the electric field distribution entering the objective lens.

$$TFP = e^{i\phi_f}\,\delta(f_x,f_y) + M(f_x,f_y)\left(e^{i\phi_0}-1\right)P(f_x,f_y) \tag{18}$$

Taking the inverse transform gives the electric field of the aerial image.

$$E(x,y) = e^{i\phi_f} + \left(e^{i\phi_0}-1\right)\mathcal{F}^{-1}\left\{M(f_x,f_y)P(f_x,f_y)\right\} \tag{19}$$

Using equation (17) and plugging in the values of 60° and -60° for ϕ_0 and ϕ_f respectively,

$$E(x,y) = 0.5 - i\tfrac{\sqrt{3}}{2} + \left(0.5 + i\tfrac{\sqrt{3}}{2} - 1\right)\left(1 - E_C(x,y)\right) \tag{20}$$

$$E(x,y) = \left(0.5 - i\tfrac{\sqrt{3}}{2}\right)E_C(x,y) \tag{21}$$

$$I(x,y) = I_C(x,y) \tag{22}$$

Thus, the aerial image from the 60/60 PCL design is the same as the conventional image even when the finite extent of the aperture is included.

Of course, the analysis still assumes coherent illumination (so that a very small phase dot can be used as the filter) and an isolated line feature such that $M(0,0)$ is not a delta function. Let us now consider the case of a mask pattern where the Fourier transform of $m(x,y)$ results in a delta function at the origin (such as equal lines and spaces or an isolated value of 0 resulting in an isolated space in the image). For such a case, we can write $M(f_x,f_y)$ and the diffraction pattern $T(f_x,f_y)$ as

$$M(f_x,f_y) = K\delta(f_x,f_y) + M(f_x,f_y) - K\delta(f_x,f_y) \tag{23}$$

$$T(f_x,f_y) = \left[1 + K\left(e^{i\phi_0}-1\right)\right]\delta(f_x,f_y) + \left(M(f_x,f_y) - K\delta(f_x,f_y)\right)\left(e^{i\phi_0}-1\right) \tag{24}$$

where K is the amplitude of the zero order term of $M(f_x,f_y)$ and the first term on the right hand side of equation (24) represents that portion of the diffraction pattern passing through the center of the lens. Thus, our phase contrast filter will shift the phase of only this term.

$$TF = e^{i\phi_f}\left[1 + K\left(e^{i\phi_0}-1\right)\right]\delta(f_x,f_y) + \left(M(f_x,f_y) - K\delta(f_x,f_y)\right)\left(e^{i\phi_0}-1\right)$$

$$TF = e^{i\phi_f}\,\delta(f_x,f_y) + \left(e^{i\phi_0}-1\right)M(f_x,f_y) + K\left(e^{i\phi_0}-1\right)\left(e^{i\phi_f}-1\right)\delta(f_x,f_y) \tag{25}$$

We are now ready to inverse transform this equation to determine the electric field aerial image. This is made easier by recognizing the similarity of equation (25) to equation (11). For the case of the 60/60 design, equation (11) inverse transformed to give us equation (21). Thus, the electric field image resulting from equation (25) will be

$$E(x,y)=\left(0.5-i\frac{\sqrt{3}}{2}\right)E_C(x,y)+K \qquad (26)$$

Note that equation (26) is the most general imaging equation for the 60/60 PCL design. For the case of a series of lines and spaces, K becomes the duty cycle, $K = w/p$ where w is the width of the line and p is the pitch. Thus, for an isolated line $K=0$ and equation (26) reverts to the earlier result of equation (21).

Equation (26) introduces a serious problem with the 60/60 PCL design. The PCL image differs from the conventional image (this in itself may or may not be bad), and the difference is duty cycle dependent. To illustrate the problem, Figure 1a shows aerial images calculated for a conventional imaging system with coherent illumination for varying duty cycle. Figure 1b shows the same patterns for the 60/60 PCL imaging system as calculated from equation (26). It is obvious that the images from a conventional lithography system show a significant proximity effect - the image changes as the pitch changes. In this case, the isolated line (i.e., the largest pitch) has an image which is wider than the equal line/space image. However, in the 60/60 PCL case the proximity effect is much worse. The equal line/space image will print much smaller than the isolated line. Further, the proximity effect for conventional imaging dies off when the pitch is greater than four times the width. For the PCL case the proximity effect extends much further.

The final issue to be addressed in considering the 60/60 design as a possible lithographic imaging technique is the use of realistic illumination. Since the -60° pupil filter must be large enough to shift the entire zero order of the diffraction pattern, the size of the phase dot must equal the size of the partial coherence. This presents the problem that for large or isolated features the higher diffraction orders may also overlap the phase dot. The results in these cases are hard to predict and must be carefully investigated.

V. Conclusions and Further Work

A new approach to optical lithographic imaging has been introduced and, due to its similarity to the phase contrast microscope, has been named Phase Contrast Lithography. The basic concept is to use a chromeless phase mask with a pattern identical (or nearly so) to a conventional chrome mask pattern. In combination with this simple mask a radially symmetric pupil filter with a phase shifter at the very center is used. By applying first principles, the use of a 60° phase shift on the mask in combination with a -60° phase shift at the center of the pupil plane was shown to give reasonable imaging characteristics. This approach is called the 60/60 PCL design.

The 60/60 PCL design is not without its problems. In particular, the proximity effect is much worse for the initial PCL design than for conventional imaging. Also, isolated spaces do not image well. And finally, the question of whether this new lithographic approach offers advantages over conventional imaging has yet to be addressed. By varying the phase of the mask and the phase of the filter off of the 60/60 design, there are in effect two new "knobs" which can be turned in order to optimize the imaging system for a given feature. Thus, future work will address the faults of the 60/60 PCL design and show where this approach may give benefits over conventional imaging. Also, it is quite common in phase contrast microscopy to include absorption in the central phase shifting dot, and to use annular illumination to improve resolution. Both of these techniques will be investigated in the context of the 60/60 PCL design in the future.

References

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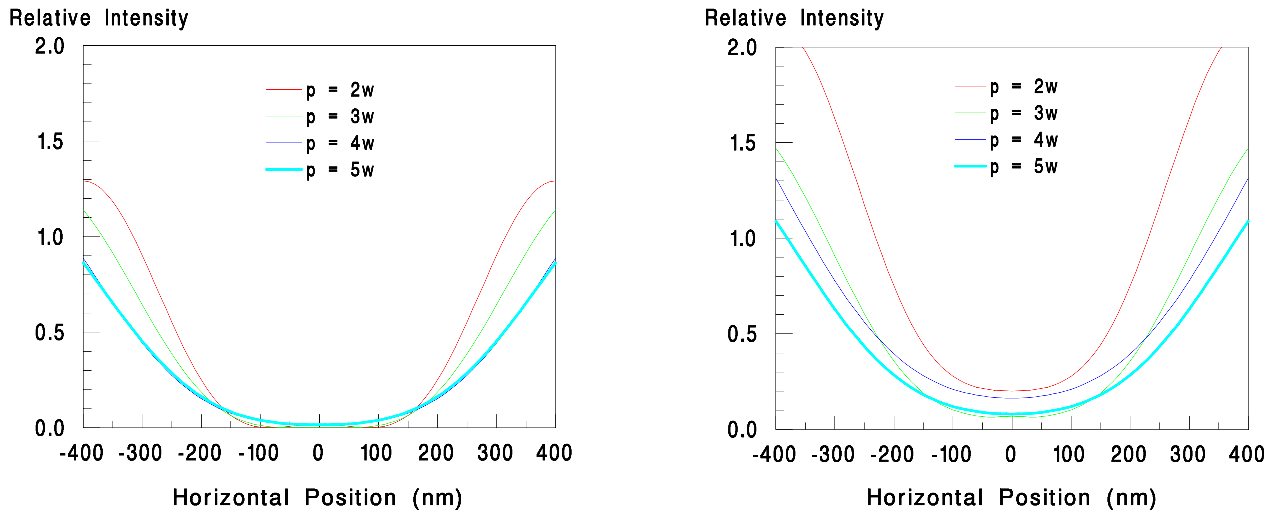

(a) (b)

Figure 1. Proximity effect for printing lines using (a) conventional imaging, and (b) the 60/60 PCL design. The pitch is varied from twice the width of the line to five times the width of the line (*w* = 0.4µm, NA = 0.5, λ = 365 nm, coherent illumination, no defocus). Simulations were performed using IMAGEPRO/2 from FINLE Technologies.