Fundamental Differences Between Positive and Negative Tone Imaging

Chris A. Mack
FINLE Technologies, Plano, TX 75026

James E. Connors
GCA Tropel, Fairport, NY 14450

Abstract

The reasons that imaging is tone-dependent come from two fundamental concepts: the aerial images of complimentary mask patterns for partially coherent projection systems are not complimentary, and the exposure reaction is highly non-linear in the concentration of the soluble species. Complimentary mask patterns are simply patterns of opposite tone. If $m_p(x)$ describes a positive mask pattern, then its complimentary mask pattern, $m_n(x)$, is given by $m_n(x) = 1 - m_p(x)$. For incoherent imaging systems, complimentary mask patterns result in complimentary images; however, partially coherent imaging systems do not produce complimentary images. For a first order exposure reaction, the concentration of the photosensitive species is exponentially related to the exposure energy. However, the dependence of the concentration of developer-soluble species on exposure is different for positive and negative resist systems, resulting in different exposure properties. The net result is lithographic behavior which can vary significantly with resist tone.

I. Introduction

The wide availability of negative photoresists for deep-UV lithography has given the industry one of its first experiences with high-resolution negative tone imaging. As a result, workers in this area are beginning to discover that there are some fundamental differences between positive and negative tone imaging. In particular, it is now widely accepted that contacts have much greater depth-of-focus when imaged in positive photoresist rather than negative. Further, lithographers are beginning to realize that there are significant differences in the biasing properties of negative versus positive resists. The goal of this paper is to examine, on a fundamental level, the causes for certain tone-dependent lithographic properties. In doing so, we hope to provide a method for answering what may soon become a vitally important question: for a given desired resist feature, is there an optimum resist tone?

II. Imaging Fundamentals

Complimentary mask patterns are simply patterns of opposite tone. If $m_p(x)$ describes a positive mask pattern as a function of the spatial dimension x, then its complimentary mask pattern, $m_n(x)$, is given by $m_n(x) = 1 - m_p(x)$. Since mask patterns are essentially binary, the relationship between complimentary patterns is intuitively obvious. For example, a "positive contact" may be a chrome background with a 1 µm hole. The complimentary "negative contact" is simply a glass background with a 1 µm island of chrome. It is only natural to assume, not knowing otherwise, that complimentary mask patterns give rise to complimentary aerial images. This, however, is not true in general.

The relationship between positive and negative tone aerial images is a direct consequence of the linearity (or non-linearity) of the imaging process. Given a general imaging system S with an input mask pattern m resulting in an aerial image $S\{m\}$, the system is linear if it obeys the property

$$S\{m_1+m_2\} = S\{m_1\} + S\{m_2\} \qquad (1)$$

For complimentary mask patterns

$$S\{m_p\} = S\{1 - m_n\} = S\{1\} - S\{m_n\} = 1 - S\{m_n\} \qquad (2)$$

Thus, for linear imaging systems, complimentary mask patterns result in complimentary images.

Are steppers linear imaging systems? A projection system is linear in intensity for incoherent illumination only. For coherent illumination, the system is linear in electric field, but would not be linear in intensity. Partially coherent illumination results in a projection system which is not linear at all. Since all lithographic projection systems use partially coherent illumination, steppers are not linear imaging systems. Thus, complimentary mask patterns give rise to images which are not complimentary. Figure 1 shows aerial images resulting from two complimentary mask patterns (simulated with PROLITH/2, FINLE Technologies). It is easy to see that the images have significantly different shapes. Although the non-linearity of partially coherent imaging systems is well know in the field of optics, is it not well appreciated in the lithographic community and the effects of this non-linearity with respect to resist tone remain largely unexplored.

If the images from complimentary mask patterns are different, is one better than the other? To answer this question, one must first define what is meant by a "better" image. Since the complete shape of the aerial image (and how that shape changes through focus) is the driving force behind many characteristics of the lithographic process, it is impossible to define one metric of image quality which reflects all of the different aspects of lithographic quality. Instead, there are several ways of evaluating the quality of an image which relate to different measures of the quality of the lithographic process. One simple but important metric is the aerial image log-slope [1,2]. The log-slope, which is just the slope of the natural logarithm of the aerial image evaluated at the nominal line edge, is proportional to exposure latitude. The decrease in the log-slope with defocus describes how the exposure latitude decreases with focus and gives very valuable insight into the overall quality of the imaging process.

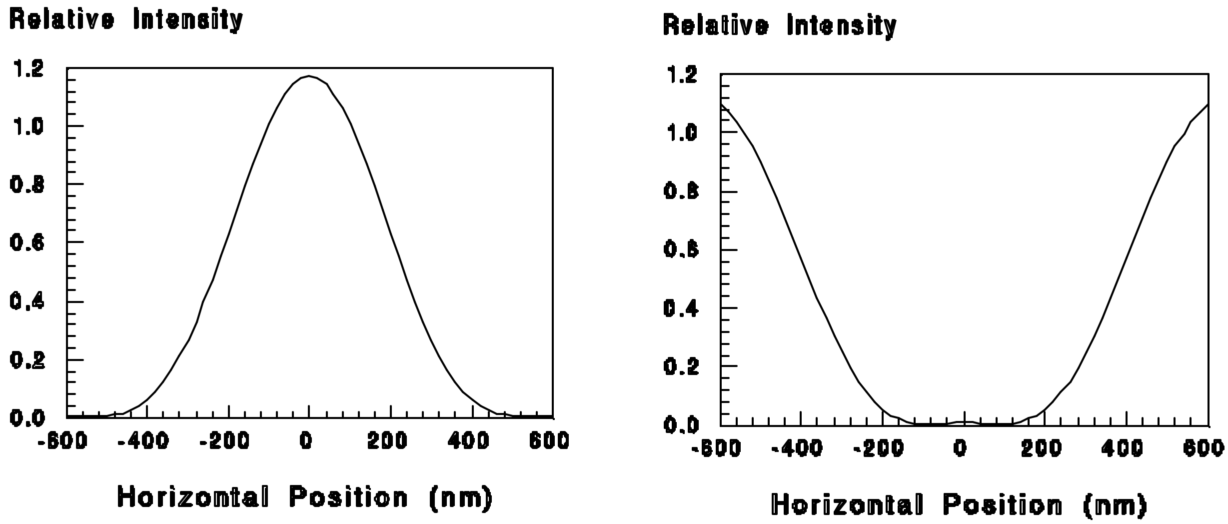

Figure 1. Aerial images for a space and line (i-line, NA = 0.5, σ =0.5, no defocus) show that partially coherent imaging produces non-complimentary images.

Figure 2 shows such a log-slope defocus curve for a small contact and its complimentary mask pattern, a small island. The difference is quite dramatic, with the island (which forms a contact in a negative resist) showing significantly worse depth-of-focus than the "positive" contact. Obviously, given the choice one would much rather image this contact in a positive photoresist than in a comparable negative resist due to the extreme differences in the aerial image responses to defocus. Thus, we have by way of example shown that one imaging tone may indeed be better than another. In fact, one can easily conclude that there could be an optimum tone for any desired resist feature, contacts being just one example. The subject of imaging contacts will be discussed in greater detail in a following section.

Although log-slope is a useful means of evaluating the exposure and focus behavior of an image, it is not the only metric by which image quality can be measured. One important aspect of a lithographic process is its ability to print isolated and densely packed lines at the same linewidth. Often, however, the *print bias* between isolated and dense lines is as large as 10% of the nominal linewidth. Figure 3a shows that the underlying reasons for this bias are the imaging properties of a diffraction limited lens. The image of an isolated line is wider than the image of a dense line. On the other hand, Figure 3b shows that the images of dense and isolated spaces are very similar in size. Thus, printing lines in a negative photoresist (which would use spaces on the mask) should result in dense and isolated lines in resist which do not exhibit any significant bias. If the print bias between dense and isolated lines is an important lithographic metric for a particular device level, then negative tone imaging is preferred.

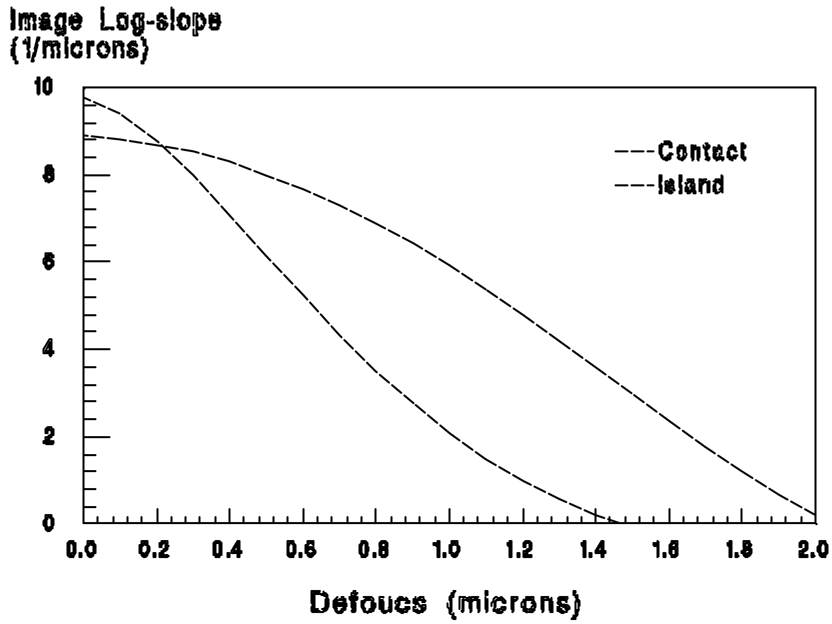

Figure 2. The log-slope defocus responses of a contact and an island on the mask, showing the benefit using positive resist when printing resist contact images (generated with PROLITH/2).

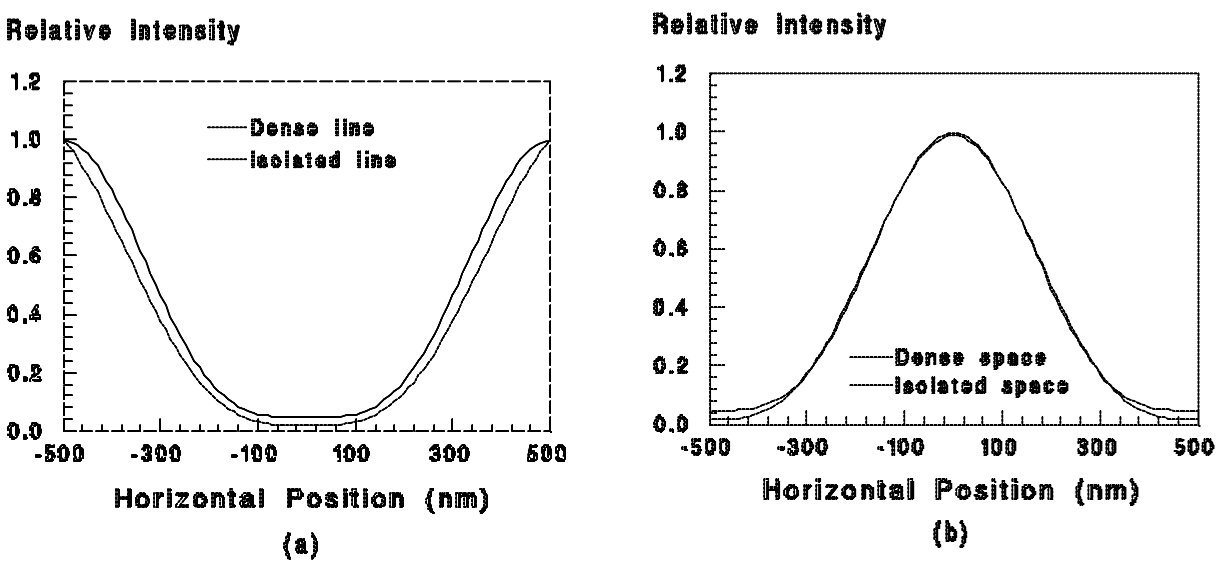

Figure 3. Ideal lens performance produces a bias between dense and isolated lines (a), but not between dense and isolated spaces (b).

Another important feature of photoresist response to focus and exposure is called the *isofocal bias*. Figure 4a shows a typical focus exposure matrix. At some exposure, called the isofocal exposure, the change in linewidth with focus is minimized (shown as the "flattest" curve in Figure 4a). The linewidth resulting from the isofocal exposure at best focus, however, may not be the desired linewidth. The difference between the isofocal linewidth and the nominal CD is called the isofocal bias. Obviously, it is desirable to have an isofocal bias of zero. Another way of looking at this same effect is with the focus-exposure process window, as shown in Figure 4b. This graph shows the focus and exposure values required to get a ±10% change in CD from the desired value. Values of focus and exposure which are within this window result in linewidths which are within specifications. The effect of a non-zero isofocal bias is to bend this window either up or down (depending on the sign of the bias) for out-of-focus conditions. The result is a reduction in the usable process window.

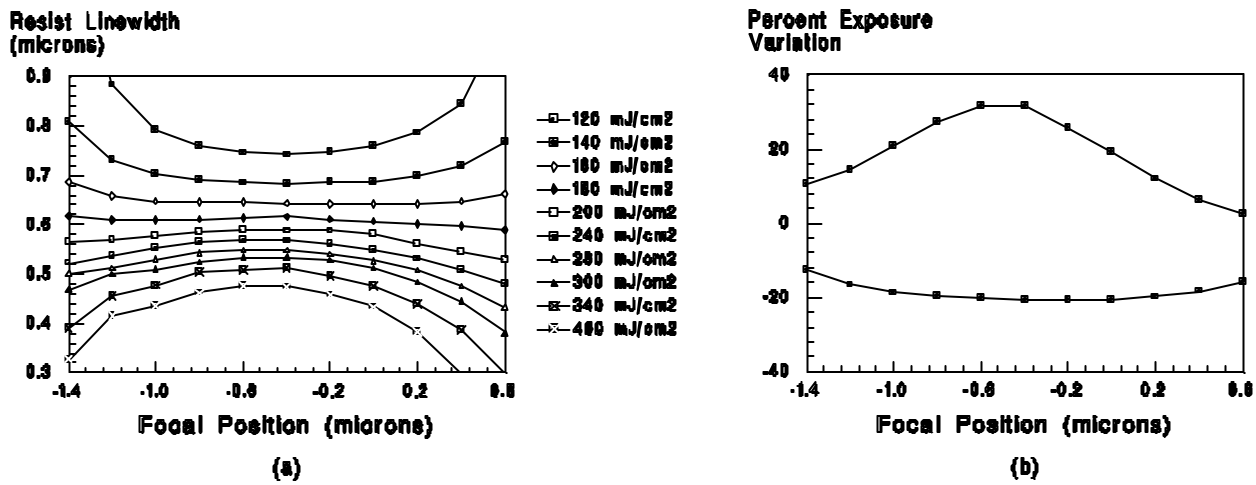

Figure 4. Typical focus-exposure linewidth data shown as (a) the Bossung curves, and (b) the focus-exposure process window (for a ±10% linewidth specification).

Do positive and negative tone imaging have different isofocal bias properties? Before answering this question, one must first determine the basic cause of isofocal bias. The behavior of linewidth through focus and exposure is determined by two things: (1) the shape of the aerial image and how it changes with focus, and (2) how this image interacts with the photoresist. Figure 5 shows a typical aerial image (equal lines and spaces in this case) both in and out of focus. An important feature of these images is the point at which they cross, sometimes called the *aerial image isofocal point*. As shown, the image isofocal point is not at the mask edge, but is located in the clear region of the mask. As an example, let us consider the implications of this crossing point for a positive photoresist.

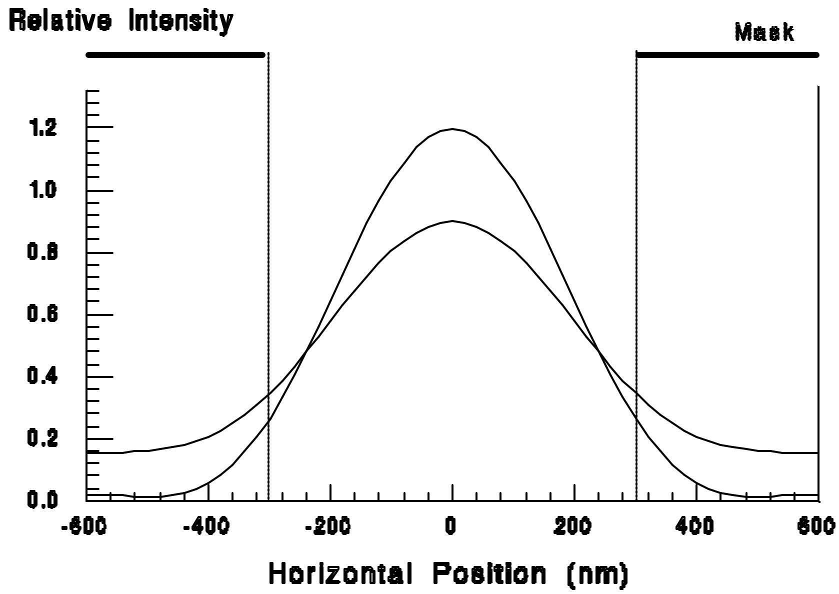

Figure 5. Aerial image for an array of equal lines and spaces in and out of focus. In this case, the image isofocal point is under the clear area of the mask.

The dissolution of a high contrast resist can be thought to be segmented into vertical followed by horizontal development paths [3]. The rate of the vertical development is determined by the peak intensity of the aerial image. Thus, the effect of defocus, which reduces the peak intensity, is to slow down the vertical development rate. The horizontal development rate, on the other hand, is determined by the intensity of the aerial image near the nominal line edge. For the images shown in Figure 5 the intensity at the mask edge increases as the image goes out of focus, thus increasing the horizontal development rate. What will be the effect on linewidth? In this case, the effect of defocus will be to decrease the vertical development rate and increase the horizontal rate. The effect on linewidth will depend on which of these two development rates is more significant (i.e., it will depend on the exact dissolution properties of the resist). However, it is conceivable that a resist system may have properties at a certain exposure energy such that the decrease in the vertical development rate cancels the increase in the horizontal rate leaving the linewidth unchanged. When this happens, the system is at its isofocal bias.

If the image isofocal point is in the clear region of the mask, then it is possible for a positive resist to have zero isofocal bias, but if the isofocal point is under the chrome, a positive resist can never have zero isofocal bias. Similarly, a negative resist can have a zero isofocal bias when the image isofocal point is under the dark area of the mask, but will never have zero isofocal bias when the image isofocal point is under the clear area of the mask. Thus, by looking for the image isofocal point, one can determine the optimum resist tone when isofocal bias is the criterion. Table I shows the position of the isofocal point for a variety of mask patterns and the subsequent "best" resist tone from the point of view of isofocal bias.

Table I - Isofocal Points of Various Images ($\sigma = 0.5$)

Mask Feature	Position of Image Isofocal Point	Optimum Resist Tone (isofocal bias criterion)
Isolated Lines	clear area	positive
Equal Lines/Spaces ($>0.55\lambda/NA$)	clear area	positive
Equal Lines/Spaces ($<0.55\lambda/NA$)	dark area	negative
Isolated Space ($>0.6\lambda/NA$)	clear area	positive
Isolated Space ($<0.6\lambda/NA$)	dark area	negative
Island	clear area	positive
Contact ($>1.0\lambda/NA$)	clear area	positive
Contact ($<1.0\lambda/NA$)	dark area	negative

Note that for most production size features ($>0.6\lambda/NA$), a positive resist gives the potential for zero isofocal bias, with the exception of contacts less than $1.0\lambda/NA$. Since the only feature that a negative resist performs well on in terms of isofocal bias (a small contact on the mask which prints as an island in photoresist) is not usually of interest in IC devices, the positive resist is the clear winner from this perspective.

III. Exposure Differences

The above discussion shows that the aerial images used to expose positive and negative resists to obtain a given resist feature are fundamentally different. But is that the only fundamental difference between imaging tones? If a positive and negative resist were exposed with complimentary images, would they result in identical imaging properties? Consider a positive and negative resist, each with first order exposure kinetics. For the negative resist, the result of exposure is to decrease the concentration of some soluble species S_n. The spatial distribution $S_n(x)$, called the latent image, which results from a spatial exposure by the negative image $I_n(x)$, is given by

$$S_n(x) = exp(-cE_nI_n(x)) \qquad (3)$$

where c is the exposure rate constant, E_n is the exposure energy, and S_n is relative to the initial concentration of soluble species. Similarly, exposure of a positive resist with energy E_p and positive image $I_p(x)$ results in the creation of the soluble species given by

$$S_p(x) = 1 - exp(-cE_pI_p(x)) \tag{4}$$

If the positive and negative images are complimentary, then $I_n(x) = 1 - I_p(x)$. If it is possible to pick the exposure energies E_p and E_n such that the two latent images are identical, then one could say that the resists can be made to behave identically, independent of tone, for complimentary images. In equation form,

$$S_n(x) = exp(-cE_n\{1-I_p(x)\}) = 1 - exp(-cE_pI_p(x)) = S_p(x) \tag{5}$$

After some inspection, one can see that the only solution to equation (5) is the trivial solution of zero and infinite exposure energies for E_p and E_n. Thus, even for complimentary images it is not possible to produce identical latent images in positive and negative photoresist. The fundamental reason is again one of non-linearity, this time that of the exposure relations given by equations (3) and (4).

IV. An Example - Printing Contacts

By now the fundamental differences between imaging with positive and negative photoresists should be apparent. But what are the lithographic consequences of these differences? As an example we consider imaging high resolution contacts, one of the more difficult layers in IC manufacturing. To show lithographic results, the lithography simulator PROLITH/2 will be used. Square contacts are two-dimensional mask features resulting in three-dimensional photoresist patterns. However, one common feature of small square contacts is that print as circles. Thus, the natural coordinate system for calculating such images is the cylindrical coordinate system (z, r, and θ). Further, for images which are circularly symmetric there is no θ dependence of the image, and thus no θ dependence of the photoresist pattern. For such cases, the two-dimensional aerial image can be represented by a one-dimensional cross-section and the three-dimensional photoresist image can be computed as a two-dimensional cross-section (in the same manner as long lines and spaces are computed).

Figure 6 shows two cross-sectional views, horizontal and diagonal, of the images from square contacts of various sizes for i-line radiation with NA=0.5 and σ=0.5 at best focus. For a circularly symmetric image, the two cross-sections should be identical. As can be seen, the images are essentially circular for contacts less than 1.0λ/NA in size. Thus, for high resolution contacts, the use of a two-dimensional photoresist model with a one-dimensional cross-section of the image of a contact will yield accurate results. The ability to simulate contacts in this fashion has been added to PROLITH/2 and will be used in the following analysis.

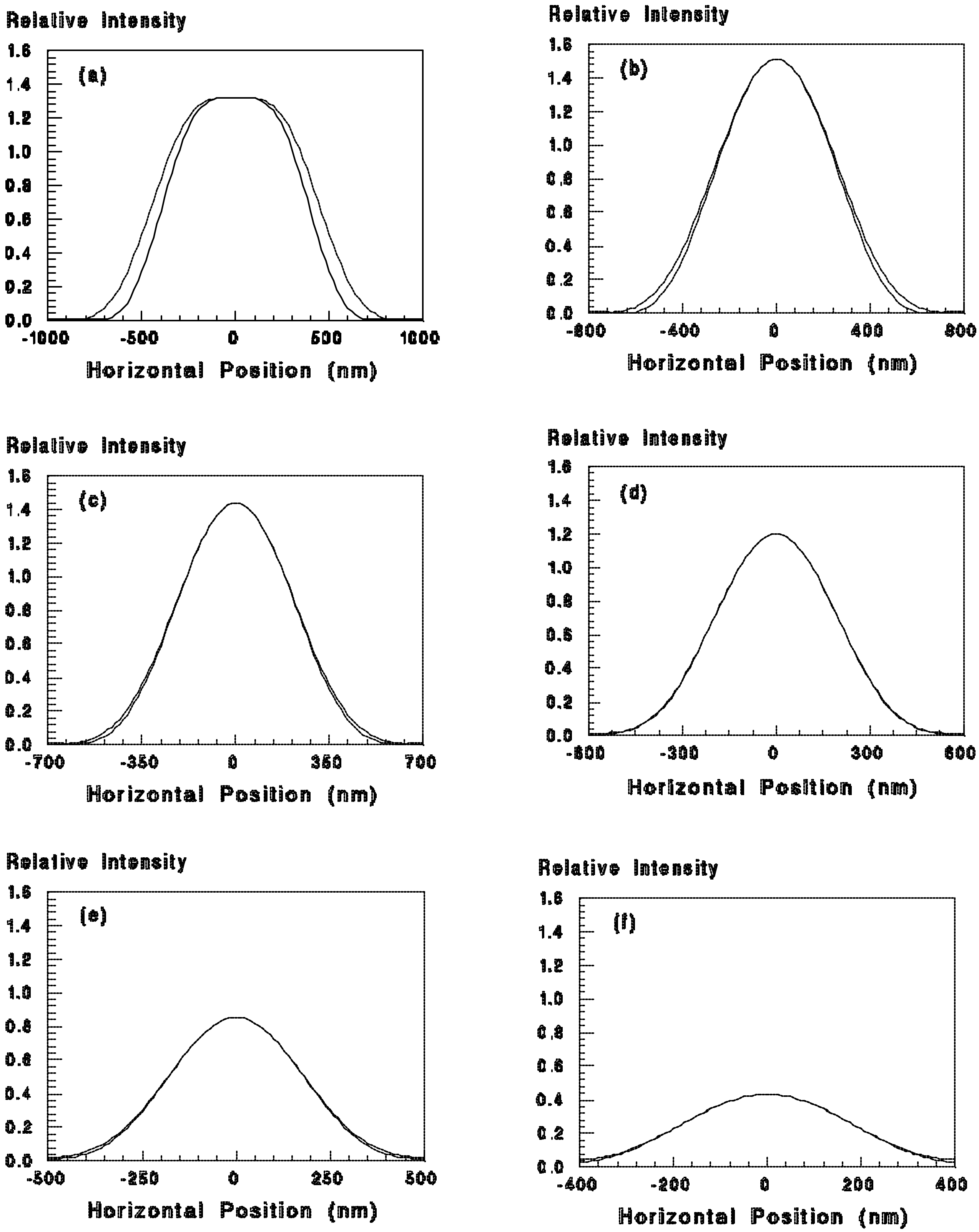

Figure 6. Aerial images of contacts (i-line, NA=0.5, s=0.5, in focus) for (a) 1.0 mm, (b) 0.8 mm, (c) 0.7 mm, (d) 0.6 mm, (e) 0.5 mm, and (f) 0.4 μm sizes. Solid line shows a horizontal cross-section, dashed line is a diagonal cross-section.

Figure 2 showed the problem with imaging contacts in negative photoresist. To emphasize this point, Figure 7 shows the aerial images through focus of small contacts and islands. Of particular interest is the intensity of the image at the isofocal point, a very low 0.2 for the contacts and a very high 0.6 for the islands. For even a defocus of 0.75 μm, the island gives an unacceptable aerial image due to the high intensity in the dark area. The result is a very shallow depth-of-focus for the negative contacts. Figure 8 compares the resulting process windows when printing contacts in positive and negative resists with comparable parameters. Obviously, the positive contacts give a dramatically larger process window. Note also that the process window bends upward for the positive contacts, indicative of a significant isofocal bias. Biasing the mask would straighten out the process window slightly and result in even greater process latitude.

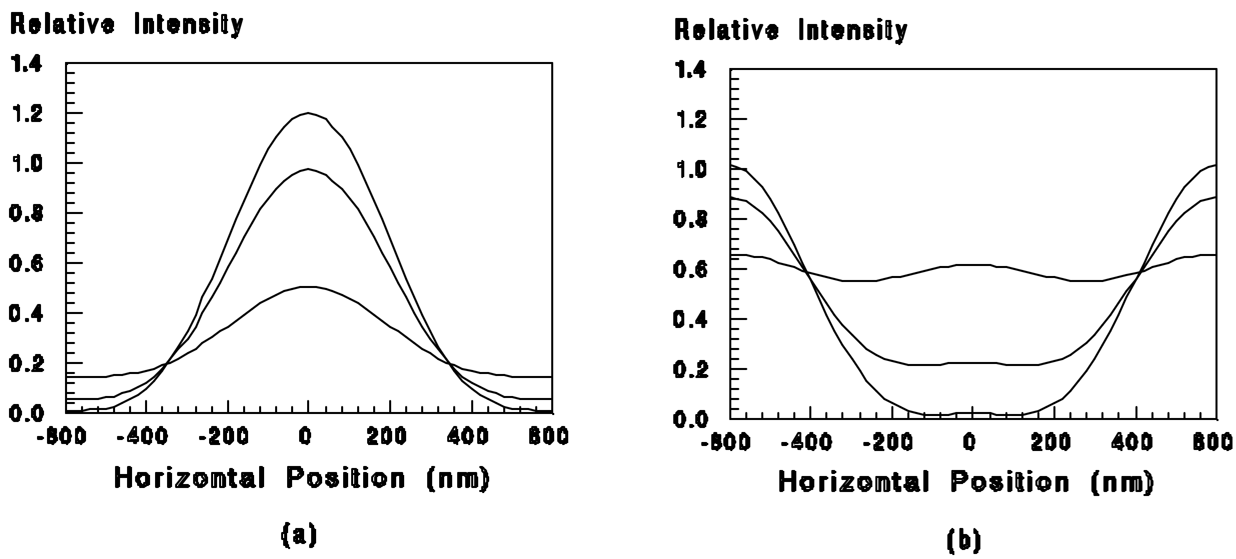

Figure 7. Aerial images for arrays of 0.6 μm features of (a) contacts and (b) islands with i-line, NA = 0.5, σ = 0.5, and defocus values of 0, 0.75, and 1.5 μm.

V. Conclusions

The properties of imaging in positive versus negative photoresist are fundamentally different on two levels. First, for partially coherent illumination, complimentary mask patterns do not result in complimentary images. The most striking example is the difference in the imaging of contacts versus islands. Second, the exposure process is also non-linear, causing further differences in the behavior of positive and negative tone imaging. As a result, changing the tone of the imaging results in significant lithographic differences in the behavior of the imaging and brings forward an important conclusion: for any mask pattern there is an optimum resist tone to image that pattern. The definition of optimum, however, depends on what metric of lithographic quality is used. The size of the process window, the magnitude of the isofocal bias, and the print bias between isolated and dense lines all depend on resist tone. Given the availability of equally desirable positive and negative photoresist materials, the ability to chose the optimum tone could play an important role in future process optimization efforts.

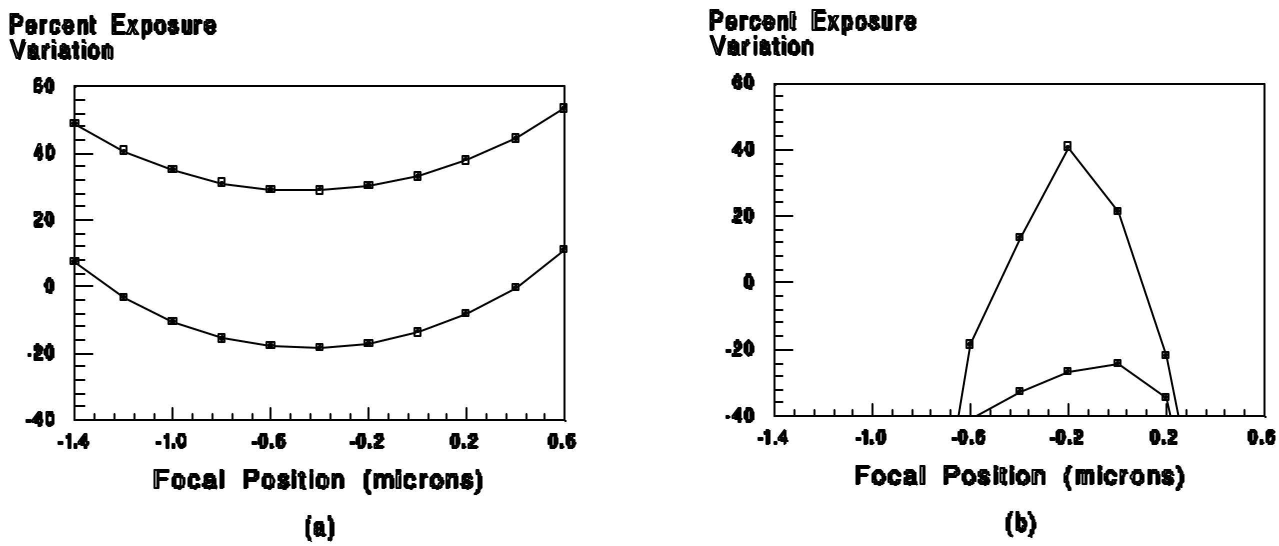

Figure 8. Focus-exposure process window for 0.6 μm contact resist features image in (a) positive and (b) negative photoresist.

Acknowledgements

The authors would like to thank SEMATECH and the many workers there for the support received during the early phases of this project.

References

1. H. J. Levenson and W. H. Arnold, "Focus: The Critical Parameter for Submicron Lithography," *Jour. Vac. Sci. Tech.*, Vol. B5, No. 1 (Jan/Feb 1987) pp. 293-298.

2. C. A. Mack, "Understanding Focus Effects in Submicron Optical Lithography," *Optical/Laser Microlith., Proc.*, SPIE Vol. 922 (1988) pp. 135-148, and *Optical Eng.*, Vol. 27, No. 12 (Dec. 1988) pp. 1093-1100.

3. C. A. Mack, A. Stephanakis, R. Hershel, "Lumped Parameter Model of the Photolitho-graphic Process," *Kodak Microelectronics Seminar, Proc.,* (1986) pp. 228-238.