Focus effects in submicron optical lithography, optical and photoresist effects

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Abstract

This paper gives a review of previous work [1-3] describing a new method to characterize the effects of defocus on an optical lithographic process. The interaction of the aerial image with the photoresist is described mathematically in order to determine the features of the image which are important in determining lithographic performance. The slope of the log-image is determined to be an appropriate metric of aerial image quality. By calculating this log-slope as a function of defocus, rigorous definitions of both depth-of-focus (DOF) and resolution are given. The DOF, for a given feature size, can be defined as the amount of defocus for which the log-slope of the aerial image remains above some minimum value. The minimum value of the log-slope which gives acceptable process latitude is determined by the properties of the photoresist process. The primary parameter lithography model PROLITH [4] is used to investigate how various process parameters change the response of the lithographic system to focus. The results are compared to the log-slope defocus curve to determine the minimum acceptable log-slope for the modeled system. Finally, experimental linewidth data was collected as a function of focus and exposure using electrical linewidth measurement techniques. This data is compared with both the modeled data and the log-slope analysis.

Introduction

In the age of submicron optical lithography, focus has become a critical process parameter. Each decrease in minimum feature size is accompanied by a corresponding decrease in depth-of-focus (DOF). Sources of focus errors, however, are not being reduced in proportion to the DOF. Thus, the effects of focus on the practical resolution capabilities of a lithographic tool are becoming increasingly important.

In describing the resolution and depth-of-focus of a lithographic system, it is common to apply the Rayleigh criteria. The Rayleigh criterion for the minimum resolvable feature size is

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

where λ is the exposure wavelength, NA is the numerical aperture of the objective lens, and k_1 is a process dependent constant. Typically, k_1 is in the range of 0.4 to 0.9. Similarly, the Rayleigh depth-of-focus is given by

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

where k_2 is another process dependent constant. Values of k_2 typically quoted are in the range of 0.5 to 1.0.

It is common to use the Rayleigh criteria to estimate resolution and DOF. These equations, however, are better interpreted as scaling equations where k_1 and k_2 are the scaled resolution and DOF, respectively. In a previous paper [1] alternate definitions of resolution and DOF were given based on an understanding of the interactions of the aerial image with the photoresist process. Earlier studies [5,6] have shown that the photoresist responds to the slope of the logarithm of the aerial image. Thus, this quantity is used as a metric for aerial image quality. The effect of defocus is to decrease the slope of the log-image. A plot of log-image slope versus defocus can be used to define both resolution and DOF simultaneously (in fact, it is impossible to define them independently). The photoresist affects DOF by determining the minimum value of the log-slope which will yield acceptable results.

1. Log-slope as an image metric

In order to simplify the analysis of a lithographic process, it is highly desirable to separate the effects of the lithographic tool from the photoresist process. This can be done with reasonable accuracy only if the interaction of the tool (i.e., the aerial image) with the photoresist is known. A previous study [6] has characterized the effects of the aerial image on the photoresist with the following general results. An aerial image $I(x)$ exposes the photoresist to produce some chemical distribution $m(x)$ within the resist. This distribution is called the *latent image*. Many important properties of the lithographic process, such as exposure and development latitude, are a function of the gradient of the latent image, $\partial m/\partial x$. Larger gradients result in improved process latitude. It has been shown that the latent image gradient is related to the aerial image by [6]

$$\frac{\partial m}{\partial x} \propto \frac{\partial \ln I}{\partial x} \quad (3)$$

A second important lithographic parameter is the sidewall angle of the resist profile. There are two ways in which the aerial image affects sidewall angle. First, the latent image has a "sidewall" slope due to absorption. This slope is again directly proportional to the log-slope of the image [6]. Secondly, the very nature of the development rate process gives rise to a sloped sidewall since the top of the resist is under attack by the developer for a longer period of time than the bottom. Neglecting absorption, the slope is approximately given by [6]

$$\textit{resist slope} \approx \frac{r(0)}{r(x)} \quad (4)$$

where $r(0)$ is the development rate in the center of a space and $r(x)$ is the development rate at the line-edge (i.e., at the edge of the photoresist profile). This ratio of development rates should be maximized in order to maximize the resist slope. Further, this ratio is a function of the aerial image. A simple approximation gives [5]

$$\frac{r(0)}{r(x)} = f\left(\frac{I(0)}{I(x)}\right) \simeq \left[\frac{I(0)}{I(x)}\right]^{\gamma} \quad (5)$$

where γ is the photoresist contrast.

The above discussion gives two ways in which the aerial image and photoresist process interact. First, the slope of the log-image affects process latitude and sidewall angle. Second, the ratio $I(0)/I(x)$ also affects sidewall angle. Thus, there are two logical metrics by which to judge the quality of the aerial image:

$$\frac{\partial lnI}{\partial x} \quad and \quad \frac{I(center)}{I(edge)} \; . \qquad (6)$$

For small features, with linewidths below about 0.75λ/NA, the two metrics are equivalent [2].

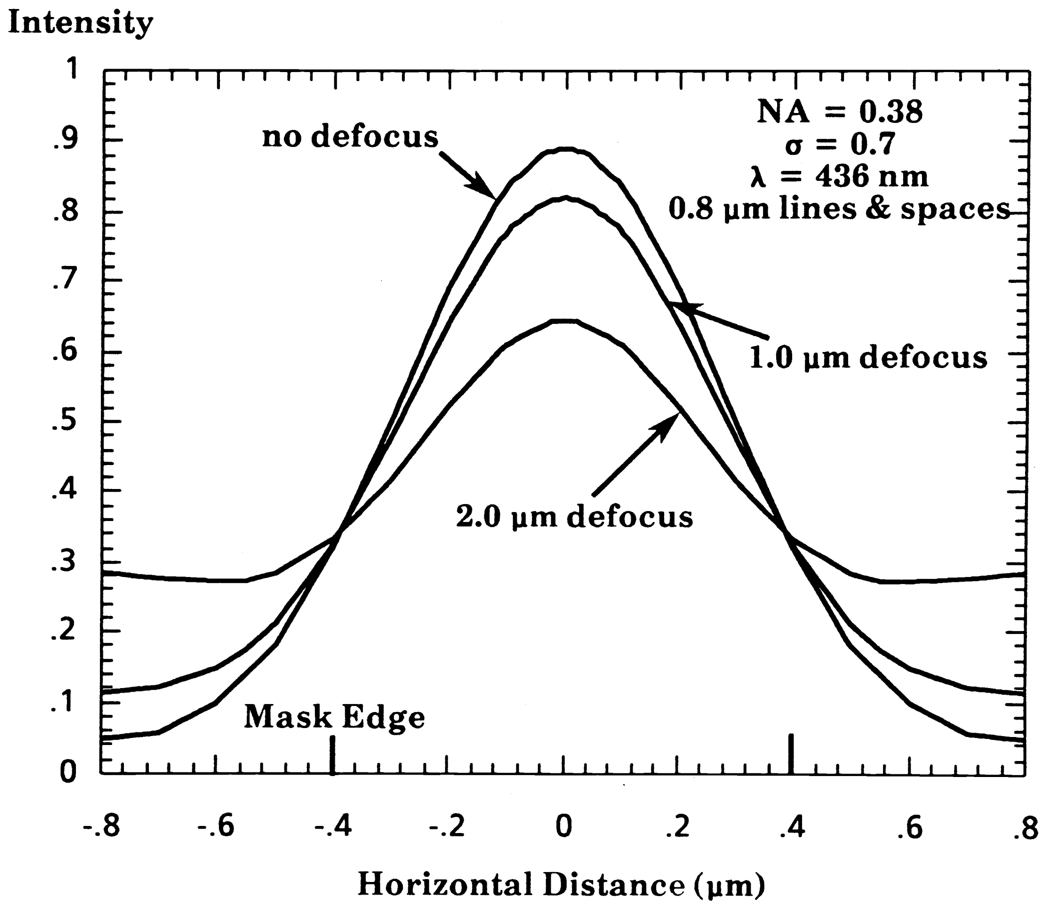

Figure 1 : The effect of defocus on the aerial image: 0, 1.0 μm, and 2.0 μm defocused aerial images were predicted using PROLITH.

Shown in Figure 1 is the well known effect of defocus on the aerial image. Both the edge slope of the image and the center intensity decrease with defocus, and the intensity at the mask edge remains nearly constant. To examine the behavior of the log-slope, the aerial images of Figure 1 were used to calculate the log-slope and plotted again in Figure 2. Clearly, the log-slope varies considerably with horizontal position x. To compare aerial images using the log-slope, one must pick an x-value to use. An obvious choice is the mask edge. Thus, all subsequent reference to the slope of the log-aerial image will be at the mask edge. Now the effect of defocus on the aerial image can be expressed by plotting log-slope as a function of defocus (Fig. 3).

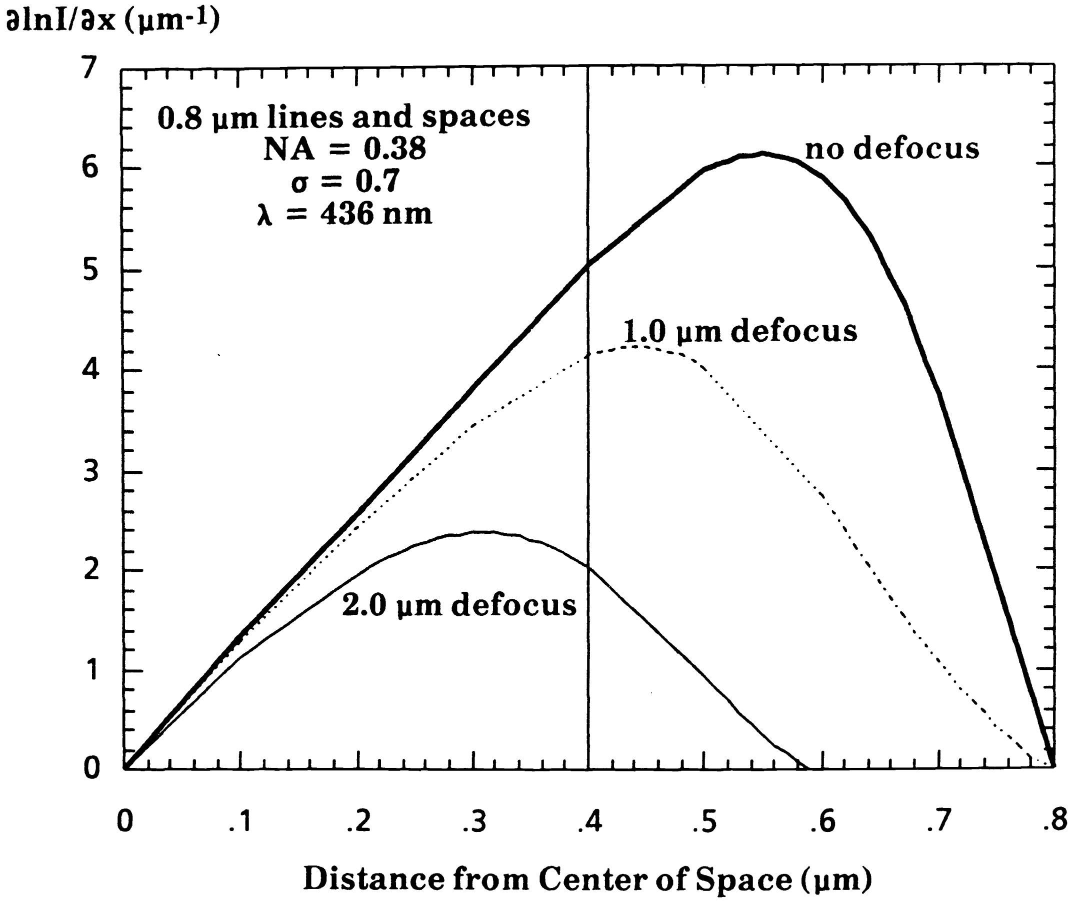

Figure 2 : Variation of the slope of the log-image with horizontal position. The mask edge is represented by the vertical line.

Some useful information can be obtained from a plot of log-slope versus defocus. As was previously discussed, both process latitude and sidewall slope vary directly with the log-slope of the image. Thus, minimum acceptable process latitude and sidewall slope specifications translate directly into a minimum acceptable value of the log-slope. The log-slope versus defocus curve can then be used to give a maximum defocus to keep the process within this specification. If, for example, the minimum acceptable log-slope of a given process was determined to be 4 μm^{-1}, the maximum defocus of 0.8 µm lines and spaces on a 0.38 NA g-line printer would be, from Figure 3, about ± 1.1 µm. This gives a practical definition of the depth-of-focus that separates the effects of the aerial image and the photoresist process. The printer determines the shape of the log-slope defocus curve, and the process determines the range of operation (i.e., the minimum log-slope value). If the minimum log-slope needed was 6 μm^{-1}, one would conclude from Figure 3 that this printer could not adequately resolve 0.8 µm lines and spaces. Thus, resolution can also be determined from a log-slope defocus curve.

To define resolution consider Figure 4, which shows the effect of feature size on the log-slope defocus curve. If, for example, a particular photoresist process requires a log-slope of 4.5 μm^{-1}, one can see that the 0.6 µm features will not be resolved, the 0.7 µm features will be resolved with a DOF of ± 0.4 µm, the 0.8 µm features will

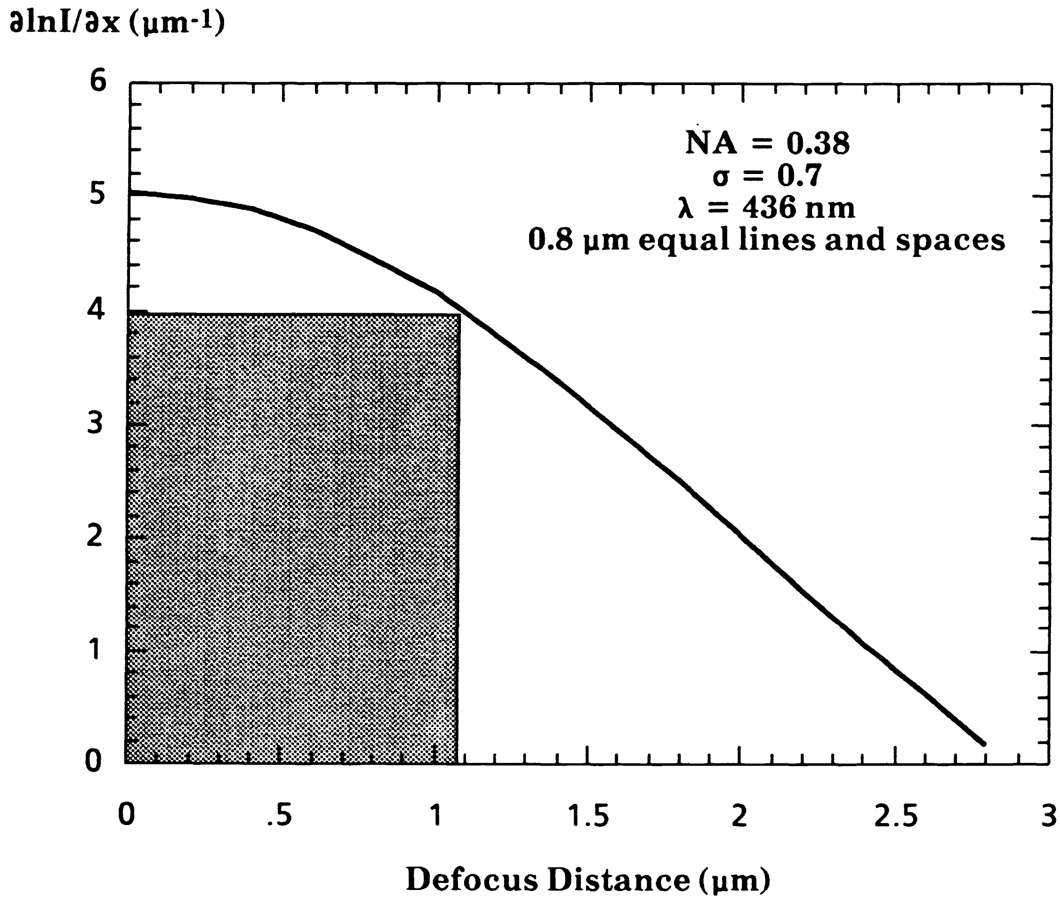

Figure 3 : The effect of feature size and focus on the edge slope of the log-aerial image. The resolution/depth-of-focus can be determined from these curves.

have a DOF of ±0.7 µm, and the 0.9 µm features will have a DOF of ±1.1 µm. Obviously, the DOF is extremely sensitive to feature size, a fact that is not evident in the common Rayleigh definition. Since DOF is a strong function of feature size, it is logical that resolution is a function of DOF. Thus, in the situation shown in Figure 4, if the minimum acceptable DOF is ±1 µm, the practical resolution is 0.9 µm lines and spaces. Resolution and depth-of-focus cannot be independently defined, but rather are interdependent.

The log-slope defocus curve can be used objectively to compare different printers. For example, there has been much discussion on the advantages of lower wavelength versus higher numerical aperture. It is common to compare a g-line, 0.42 NA system with an i-line, 0.35 NA system. Both have the same value of λ/NA (almost) and thus, according to the Rayleigh criterion, the same resolution. In terms of the log-slope curve, the same value of λ/NA corresponds to the same value of the log-slope of the image with no defocus (Figure 5). The practical resolution is defined as the smallest feature meeting a given log-slope specification over a given focus range. If a process requires a log-slope of 4.0 μm^{-1} and a focus budget of ±1 µm, Figure 5 shows that the i-line system will resolve a 0.6 µm feature, but the g-line system will not. Thus, the lower wavelength system has better practical resolution even though λ/NA is the same.

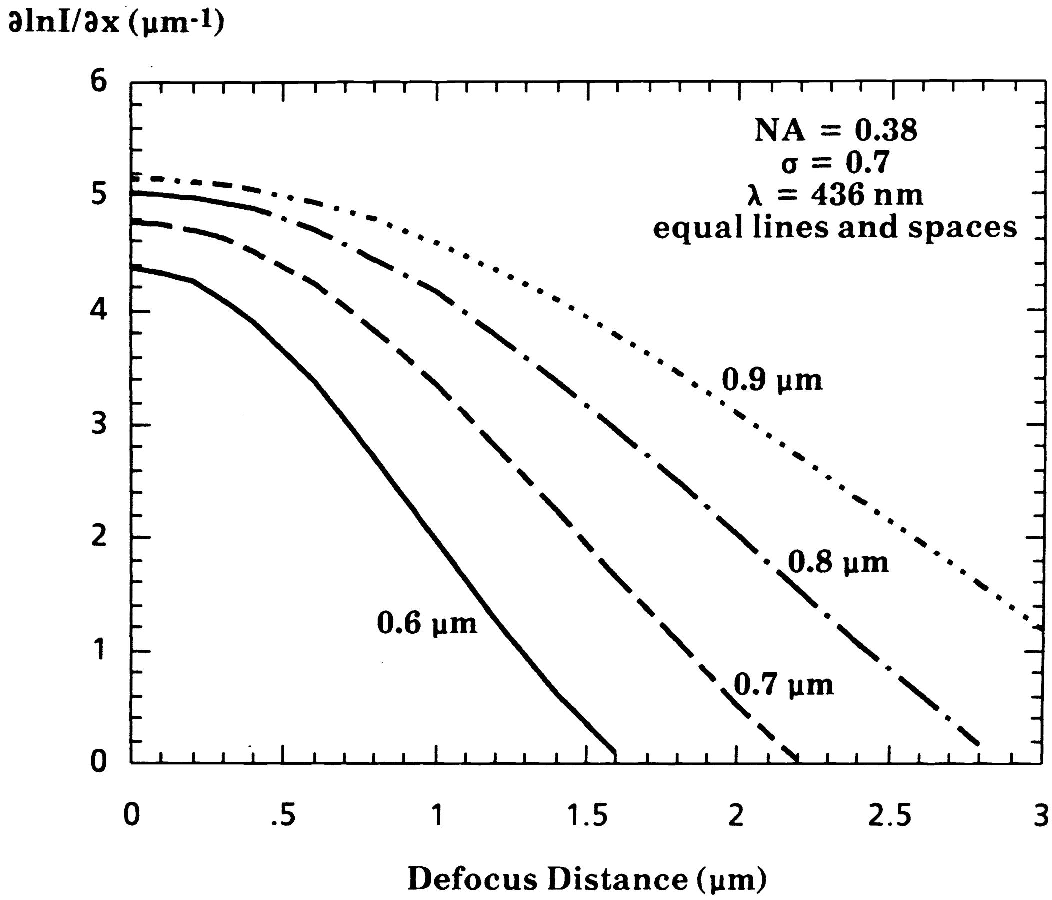

Figure 4 : The effect of feature size and focus on the edge slope of the log-aerial image. The resolution/depth-of-focus can be determined from these curves.

It is important to note that all of the aerial image calculations presented in this paper assume diffraction-limited lens performance, i.e., ideal lenses. Obviously the ideal lens does not exist and thus, real lenses have log-slope versus defocus curves that are degraded to some extent from the ideal curves shown here. To a first approximation, the aberrations in an optical system can be thought of as a "fixed defocus," where the degradation of the image is roughly equivalent to defocusing by a certain amount (this will be discussed to a greater extent in a later section). When comparing different lenses, as was done above, one must keep in mind that one lens may be further from ideal than the other.

2. PROLITH simulations of a focus-exposure matrix

A first step in investigating the usefulness of the log-slope is to compare the DOF predicted by the log-slope with that obtained using a complete lithography simulation package. The log-slope can easily predict how a change in an image parameter, such as numerical aperture, image flare, or fixed defocus, will affect DOF for a given log-slope specification. These same parameters can be varied in the lithography simulation program PROLITH, along with a variety of other non-image related parameters such as resist thickness and developer selectivity. Before determining the effects of these parameters on the DOF, a nominal baseline process will be studied in detail.

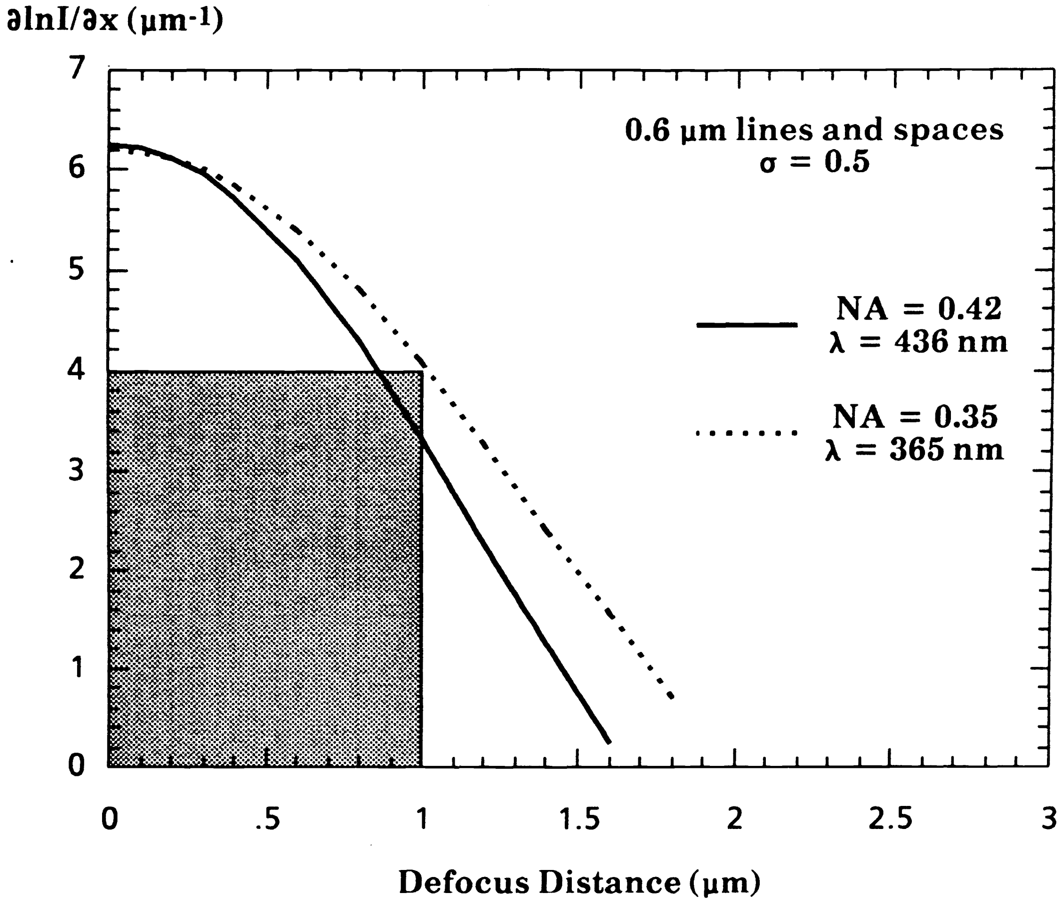

Figure 5 : Two printers with nominally the same resolution (i.e., the same λ/NA), in fact do not have the same practical resolution.

PROLITH Input Parameters

"Nominal Process"

Image Parameters:
- numerical aperture = 0.38
- partial coherence = 0.7
- wavelength = 436 nm
- linewidth = 0.8 μm
- pitch = 1.6 μm
- flare = 2%
- fixed defocus = 0.5 μm

Substrate Parameters:
- refractive index = 1.65-.02i

Photoresist Parameters:
- thickness = 1.0 μm
- A = 0.55 μm^{-1}
- B = 0.05 μm^{-1}
- C = 0.014 cm^2/mJ
- refractive index = 1.65

Development Parameters:
- development time = 45 sec
- R_{max} = 80 nm/s
- R_{min} = 1.0 nm/s
- m_{th} = 0.2
- n = 2.0

Figure 6 : PROLITH input parameters for the nominal process

Figure 6 shows the PROLITH input parameters for the nominal process. The only parameters not shown are the focus and exposure. These parameters were varied to generate a focus-exposure matrix of simulations which can be studied in the same way as a matrix of experimental data. The most common way of representing this type of data is a plot of linewidth versus focus for different exposure energies. In this case, linewidth is defined as the bottom width of the photoresist line and is determined by fitting the best straight line through the simulated photoresist profile. The result is shown in Figure 7. As can be seen, the resulting curves are not symmetric due to the effects of defocusing through the resist [1,2]. A focus position of zero means focusing on the top of the resist and negative defocus distances indicate focusing below the top surface of the resist by the value given. Much information can be obtained from Figure 7. The nominal exposure energy is about 115 mJ/cm^2. The best focus, defined as the minimum of the linewidth versus focus curve at the nominal exposure, is at about -0.2 µm. Higher exposure energies show less sensitivity to focus, unless the energy gets too high (as the 260 mJ/cm^2 curve shows).

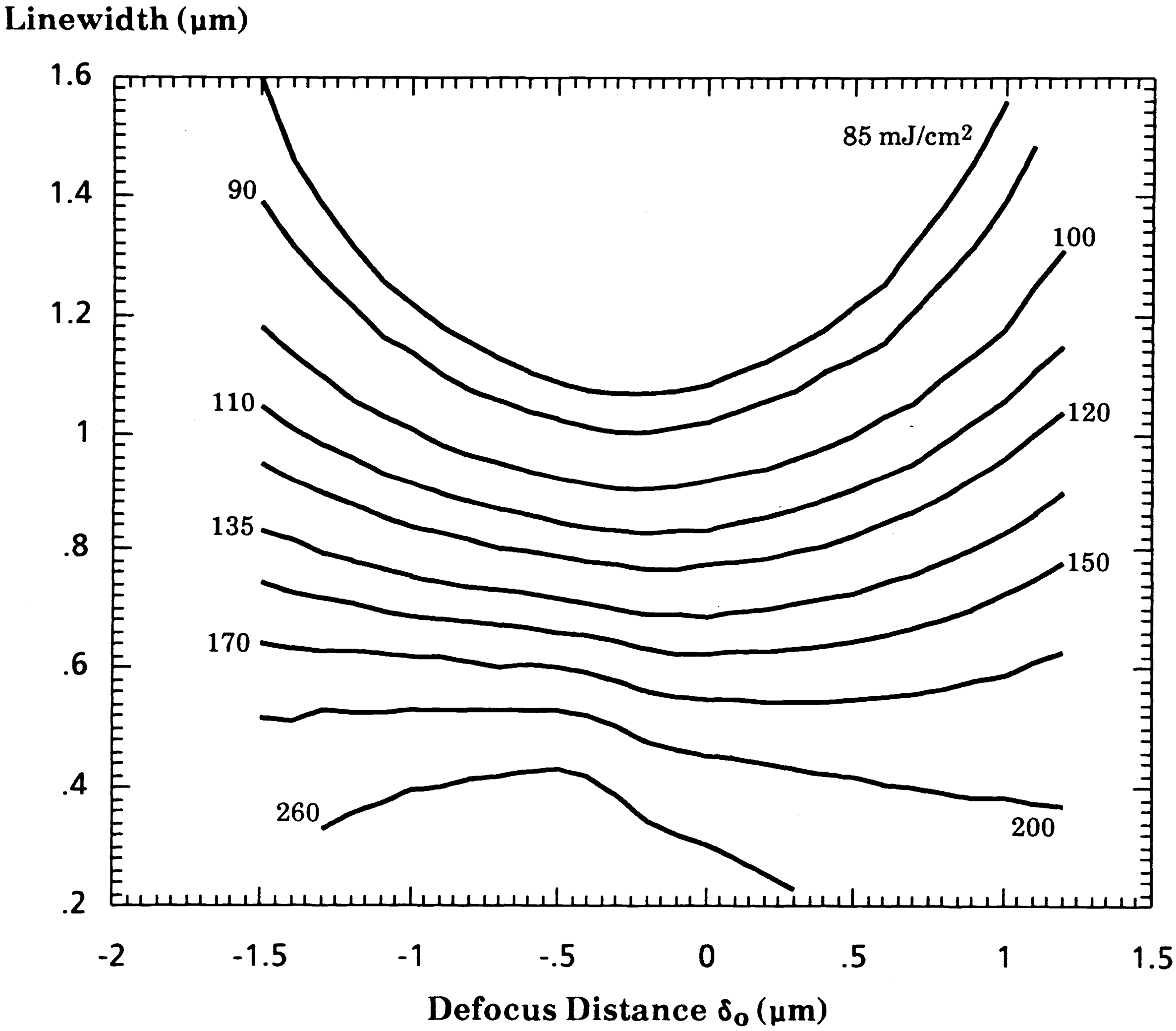

Figure 7 : Focus latitude as a function of exposure for the nominal process (as predicted by PROLITH).

The "process window" graph is a way to conveniently display the most important portions of the large amount of data found in Figure 7. Consider a 0.8 μm process with a linewidth specification of ±10% and a minimum sidewall angle specification of 70 degrees. From the data of Figure 7, one can determine the exposure energies required to give linewidths of 0.88 μm and 0.72 μm (the ±10% linewidths) as a function of focus. These energies are plotted as the solid lines of Figure 8. The exposure energy is expressed as the percent deviation from the nominal energy of 115 mJ/cm^2. The resulting graph shows a window of focus and exposure. Values of focus and exposure inside of the window result in linewidths which meet the given specification. Similarly, the 70 degree sidewall angle specification can be translated into two curves of exposure versus focus, shown as the dotted lines of Figure 8. Values of focus and exposure inside this window result in photoresist profiles which meet the 70 degree sidewall angle specification. Thus, Figure 8 conveniently shows the acceptable range of operation of focus and exposure for given specifications in the form of the focus-exposure process window.

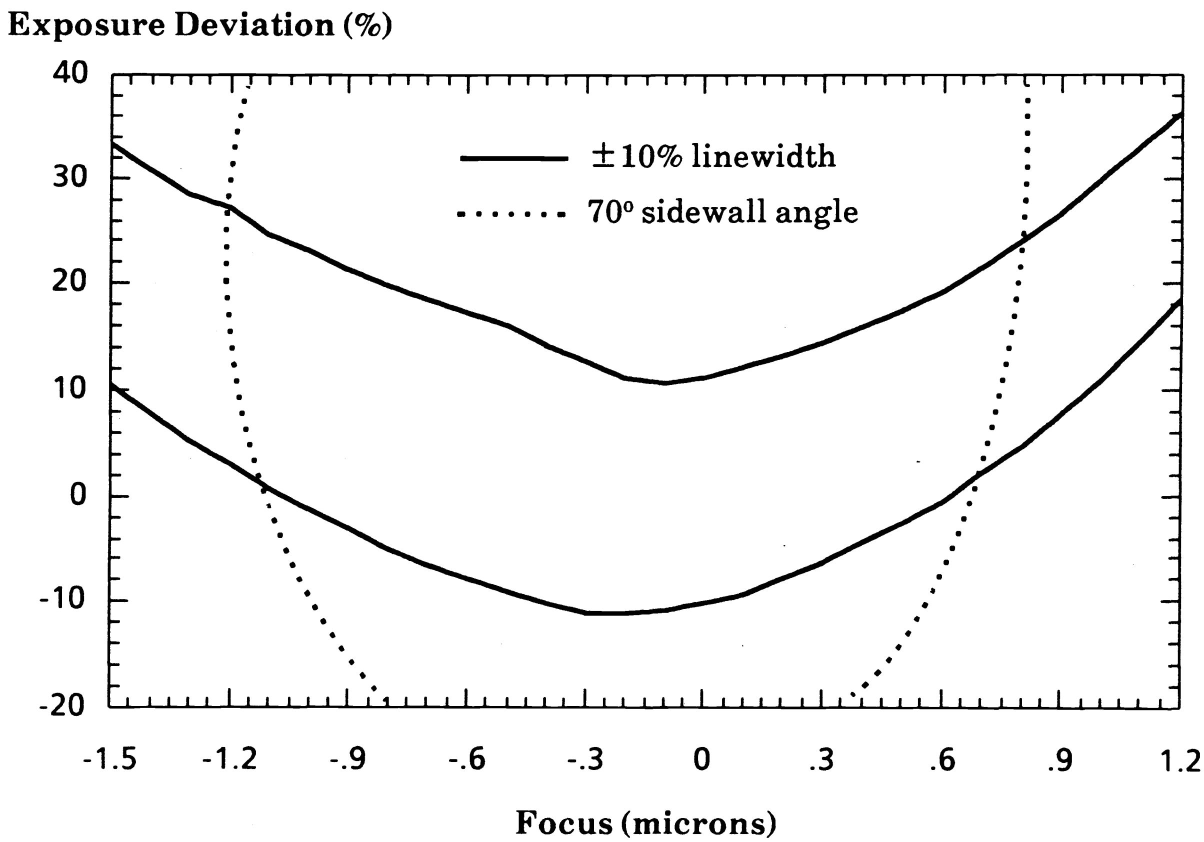

Figure 8 : Focus-Exposure process volume for the nominal process (as predicted by PROLITH).

Since the focus-exposure process window defines the acceptable range of focus and exposure, it seems natural that the depth-of-focus can be defined in some way using this process window. Although not unique, one possible way of defining DOF is the focus range (within the process window) at the nominal exposure. Specifically, the nominal focus is defined as the minimum of the lower 10% linewidth curve of Figure 8, and the nominal exposure is midway between the ±10% linewidth curves at the nominal focus. For the nominal process, the DOF is 1.69 microns. This somewhat arbitrary definition is used extensively in the next section.

3. PROLITH modeling results

In attempting to understand focus effects in submicron optical lithography, several important parameters were investigated and analyzed. PROLITH was used to simulate 0.8 μm equal lines and spaces on a non-reflective substrate as a function of *developer selectivity* and *photoresist thickness*. The results of these simulations were analyzed and the effects on DOF determined. Also simulated, for the standard process only, were 0.8 μm equal lines and spaces on a titanium layer. This was done in order to investigate the effect of a *reflective substrate,* and the associated standing waves, on DOF.

A. Developer selectivity

Developer selectivity, n, is proportional to photoresist contrast, γ [7]. Shown in Figure 9 is developer selectivity versus DOF at the nominal exposure. The result is to be expected. Increasing resist contrast results in an increase in DOF. Consequently, an interesting question arises: what happens to the DOF as the resist contrast goes to infinity? Obviously DOF will not go to infinity, so the curve in Figure 9 must level off for very high developer selectivities. The maximum DOF can be found from the log-slope defocus curve as the point where the log-slope goes to zero. Figure 3 shows a DOF limit of about 5.6 μm.

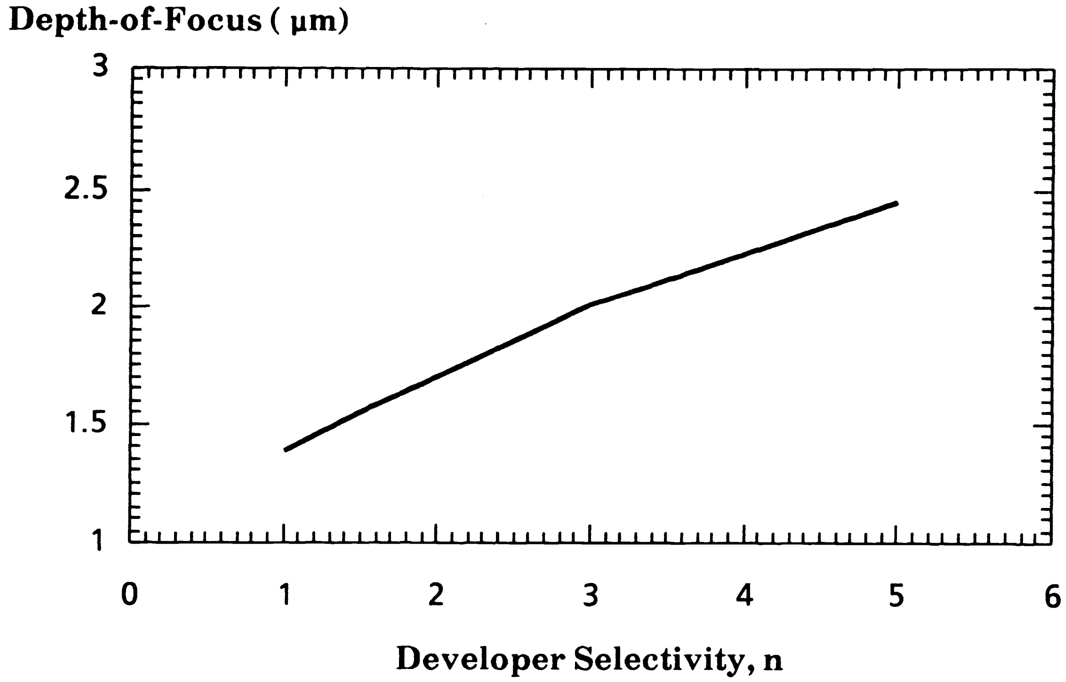

Figure 9 : Developer selectivity versus depth-of-focus at the nominal exposure (as predicted by PROLITH).

Figure 10 illustrates the focus-exposure process volume for a ±10% linewidth specification for developer selectivities of n = 1, 2, and 5 (where n = 1 corresponds to a low contrast photoresist and n = 5 corresponds to a high contrast photoresist). Examining the point of best focus, it is seen that the case of n = 5 exhibits the widest process volume while the case of n = 1 exhibits the smallest. This illustrates the fact that a higher contrast photoresist results in a better process latitude.

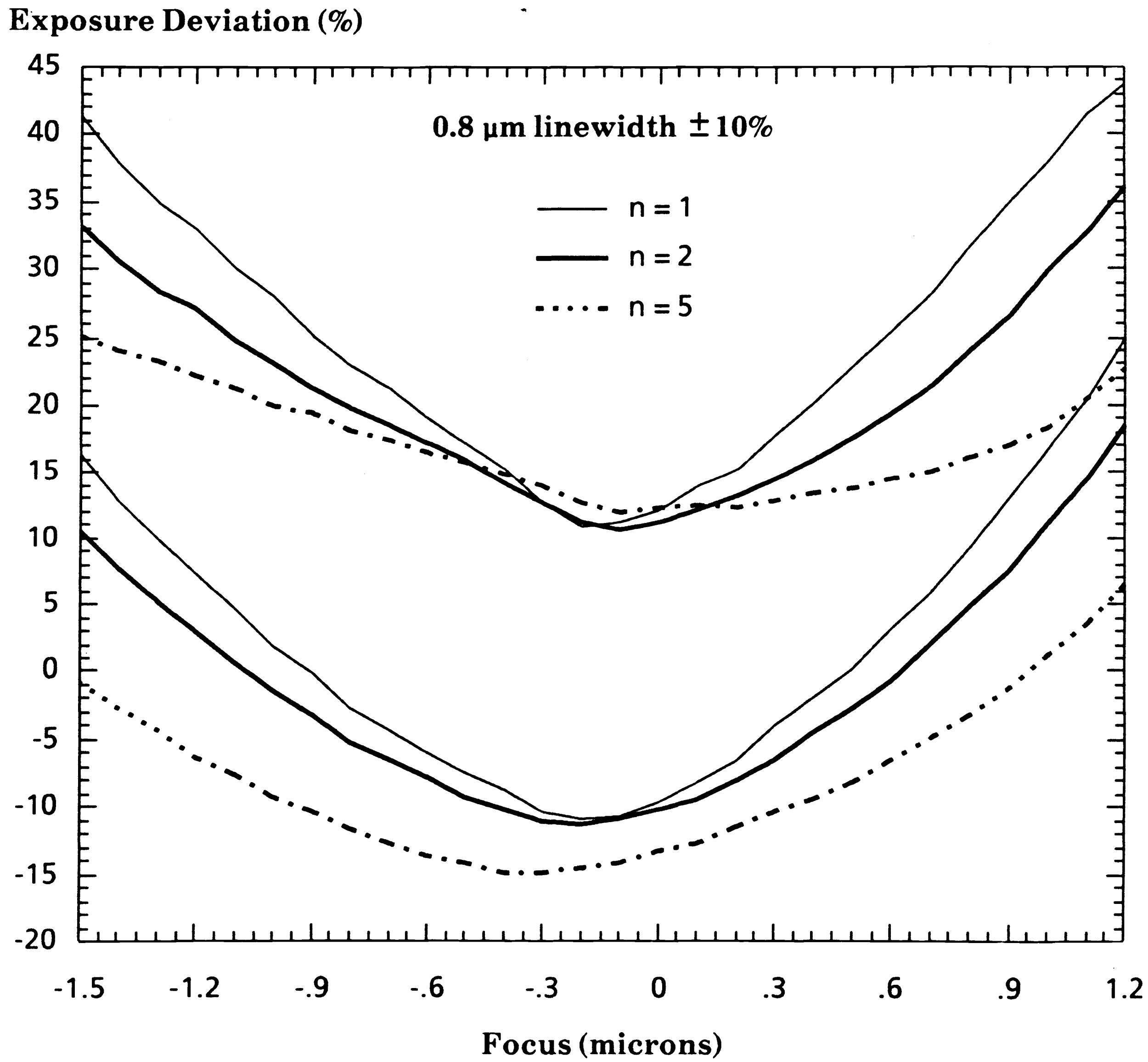

Figure 10 : Focus-exposure process windows for developer selectivities of n = 1, 2, and 5 (as predicted by PROLITH).

B. Photoresist thickness

The photoresist thickness has long been suspected as a factor contributing to loss of DOF. Figure 11 shows DOF versus resist thickness at the nominal exposure. The result is a dramatic improvement in DOF for thinner resists. The improvement is far more than would be expected if only the optical effect of defocus through the thickness of the resist were considered. Rather, the improvement in DOF with thin resists is due to an effective increase in resist contrast [5]. That is, a thinner layer of resist corresponds to a higher degree of contrast (which in turn corresponds to a higher developer selectivity). Note that the curve is relatively flat for thick resist layers. Increases in resist thickness at this point decrease the effective contrast slowly. Further, there appears to be no linear decrease in DOF with resist thickness due to an optical effect.

Shown in Figure 12 is the focus-exposure process volume for resist thicknesses of 0.5, 1.0, and 2.0 μm. This graph indicates, just as does the information included in Figure 11, that the thinner resist layers yield better DOF. Another interesting result shown in Figure 12 is that the deviation of the shape of the process volume for thinner resist layers is the same as for higher developer selectivities. This again confirms the proposition that thinner resists yield improved DOF due to an effective improvement in resist contrast.

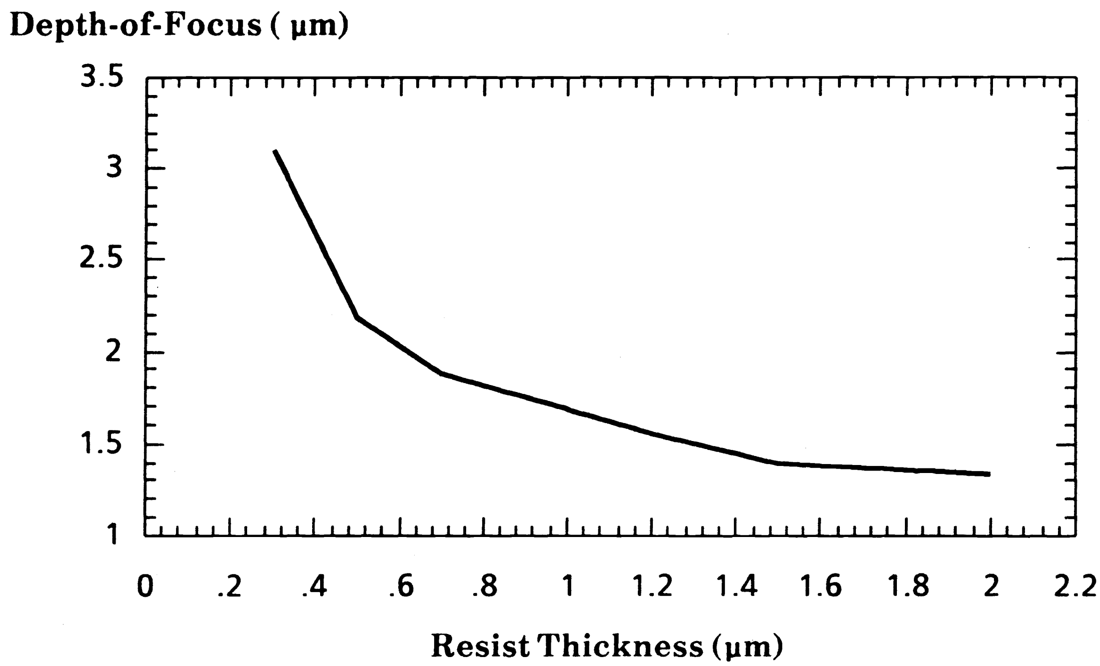

Figure 11 : Depth-of-focus versus resist thickness at the nominal exposure (as predicted by PROLITH).

C. Substrate reflectivity

The major effect of a reflecting substrate on the lithographic process is the formation of standing waves. These standing waves can dramatically alter the performance of a process. Figure 13 shows the focus-exposure process volume for the standard process on reflecting and non-reflecting substrates. Since experimental work was done on a thin titanium layer, titanium was chosen as the reflecting substrate. It is quite obvious that the case of a non-reflective substrate is far superior to that of a reflective substrate. The effect of standing waves is to significantly reduce the process volume [8].

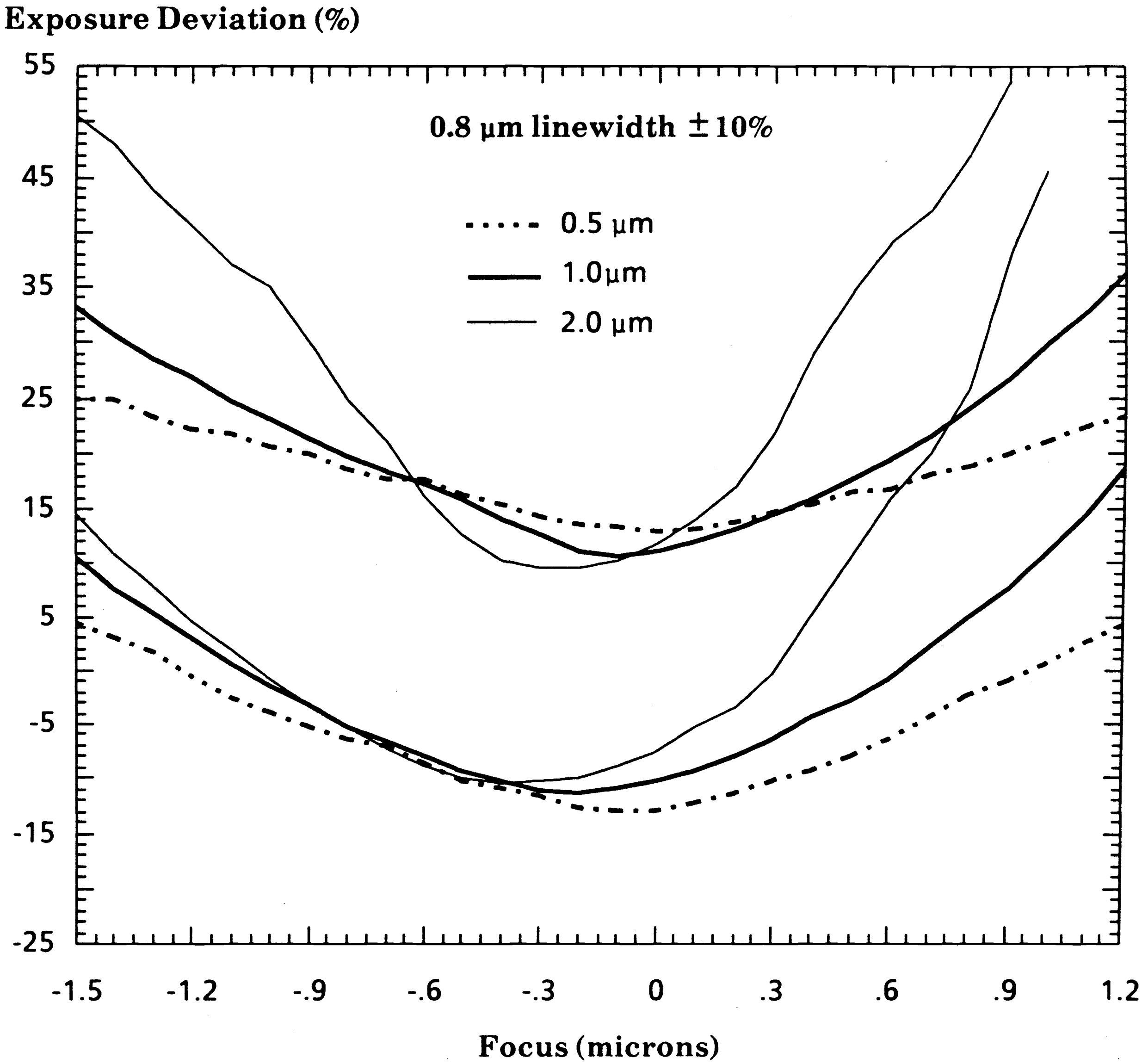

Figure 12 : Focus-exposure process volume for ± 10% linewidth for resist thicknesses of 0.5 μm, 1.0 μm, and 2.0 μm (as predicted by PROLITH).

4. Experimental results

As a final examination of defocus effects, PROLITH simulated data was compared to experimentally measured linewidth versus focus and exposure data. In the processing done for this work, silicon test wafers were used as the substrate material. First a 6.5 KÅ thermal oxide layer was grown. Next a thin (550Å) layer of titanium was sputter deposited onto the oxide. Aspect Systems' 812 positive photoresist was applied to the wafer surfaces using a spin coat technique followed by a prebake. The resulting photoresist film thickness was 1.1 μm. The wafers were next stepped through a series of focus-exposure matrices. The mask used to image the wafers contained a variety of feature sizes (i.e., 0.5 μm - 1.4 μm) in both the x-

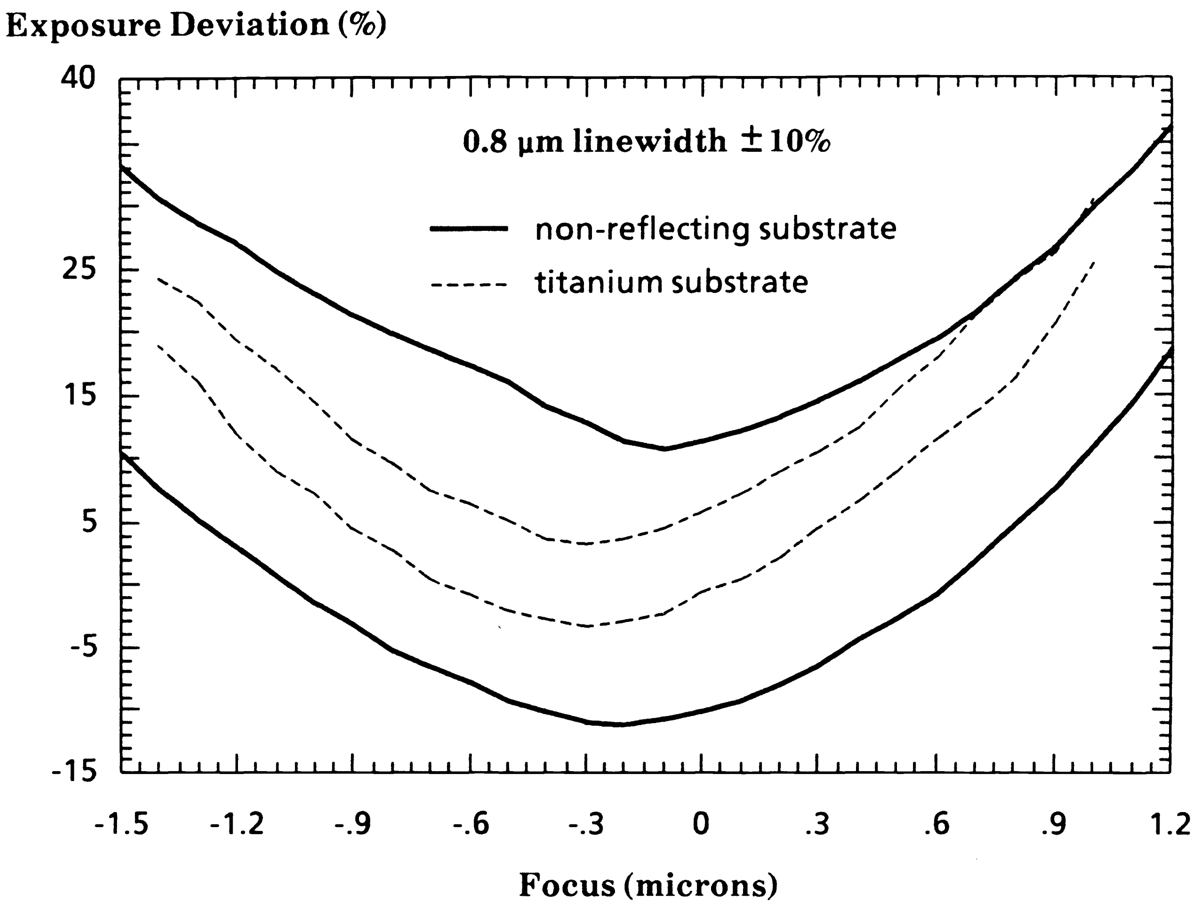

Figure 13 : Effect of substrate reflectivity on the focus-exposure process window (nominal process).

(horizontal) and y- (vertical) directions and of both the isolated and densely packed types. All imaging for this work was done on a GCA 6300 10:1 reduction stepper equipped with a g-line, 0.38 NA lens and a partial coherence of 0.7. Following the exposure step, the wafers received a 45 second spray development using Kodak 809 developer diluted one part to four parts water, a deep ultraviolet bake, and a postbake. Next the titanium was reactive ion etched and the remaining photoresist removed from the wafer surfaces using a 45 minute plasma strip.

Upon process completion, 1.0 μm linewidths were electrically probed using a Prometrix LithoMap EM1 system. The linewidth data obtained from the electrical measurements resulted in plots of linewidth as a function of focal position and exposure time (i.e., focus-exposure matrices). The experimental data obtained for 1.0 μm equal lines and spaces is shown in Figure 14. The focal position is given in GCA units, each unit being equal to 0.25 μm. The total DOF for this process is on the order of 0.5 μm.

A reasonably good match of simulated and experimental data was obtained using a developer selectivity of 3.0 and a large fixed defocus of 1.5 μm (Figure 15). The larger than anticipated fixed defocus was required to duplicate the rather poor focus response shown by the experimental data. As mentioned previously, the aerial image model used in PROLITH assumes diffraction-limited performance by the

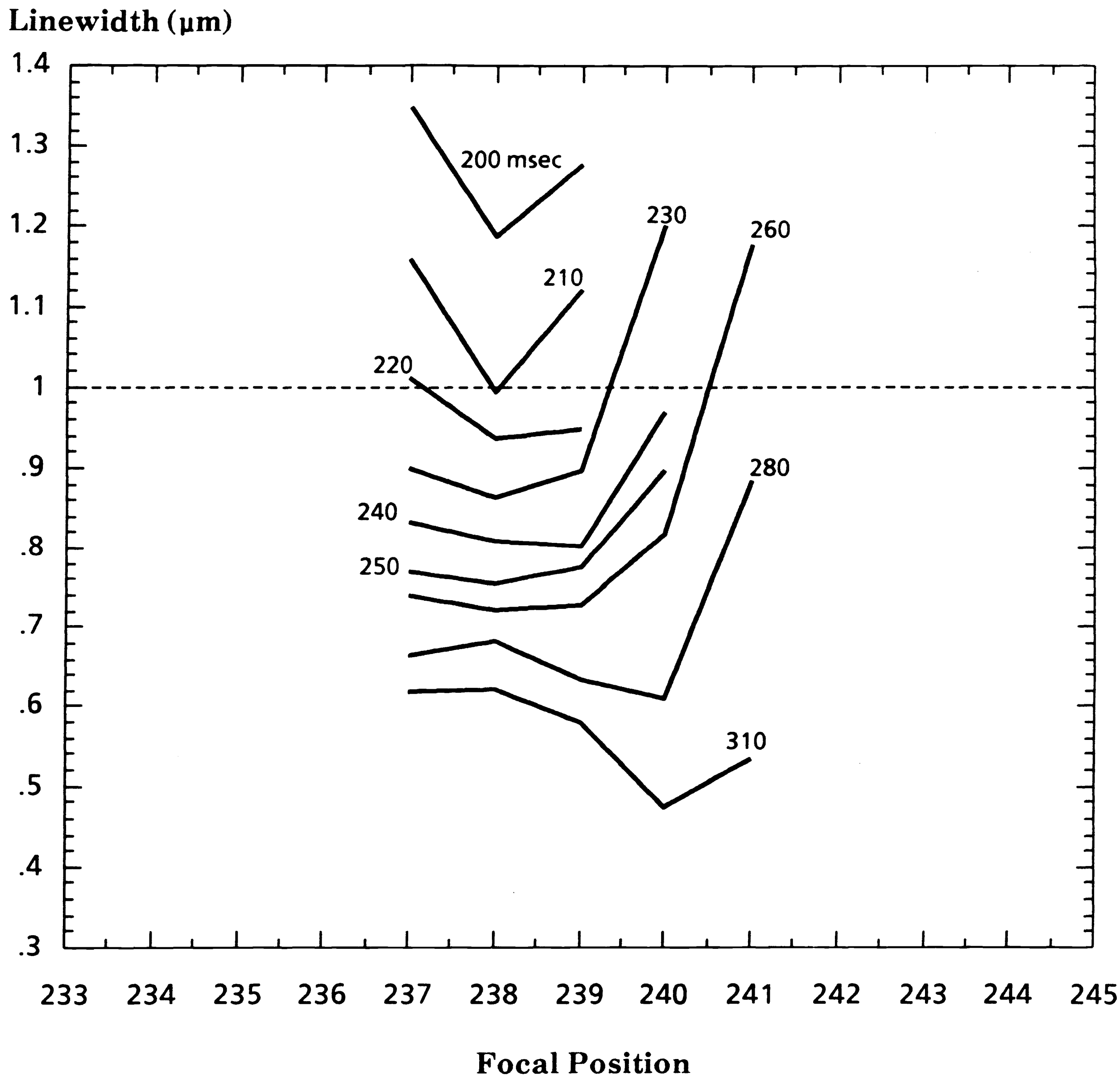

Figure 14 : Experimental focus-exposure matrix for 1.0 µm lines and spaces.

optical projection system. In reality, the performance of a lens is degraded from this ideal by aberrations. To account for this less than ideal performance, a *fixed defocus* can be used in PROLITH, as mentioned above. Some amount of defocus is used to degrade the aerial image of the ideal lens in approximately the same amount as the aberrations of the real lens. Although the lens designer may know the degree of wavefront deviation due to aberrations, this information is not generally available to the user. Thus, it is not at all clear what values of fixed defocus are reasonable for the various lens systems in use today.

As a first approximation, one would expect DOF to decrease linearly with increasing fixed defocus, with a slope of two. That is, a fixed defocus of 0.5 µm would

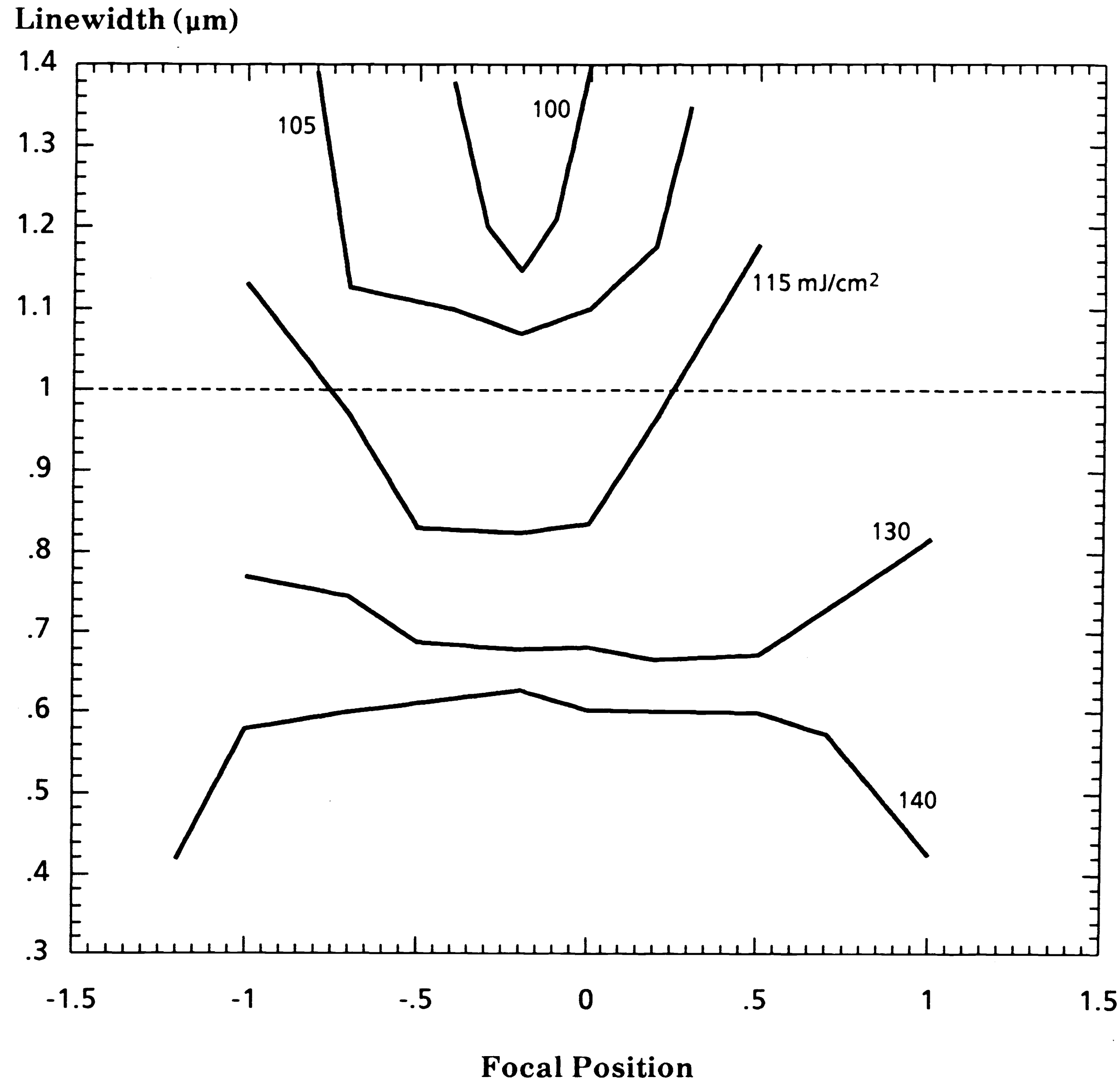

Figure 15 : PROLITH "best fit" to experimental data of Figure 14.

decrease the DOF by 1.0 µm. Figure 16 shows how PROLITH predicts the dependency of DOF on fixed defocus. The effect of defocusing within the resist complicates the situation and results in a curved, rather than straight, variation. Figure 17 shows the process windows with various amounts of fixed defocus.

5. Conclusions

The Rayleigh criteria for resolution and depth-of-focus are not adequate in describing submicrometer optical lithography. In fact, it is quite easy to misinterpret the Rayleigh criteria and draw completely inaccurate conclusions.

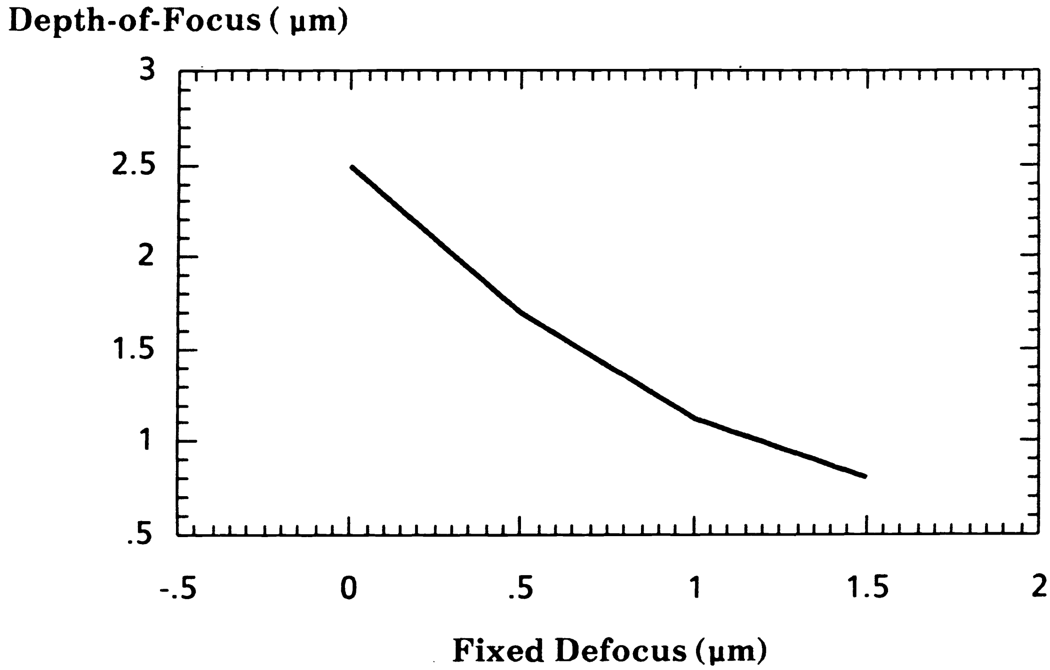

Figure 16 : Fixed defocus versus depth-of-focus at the nominal exposure (as predicted by PROLITH).

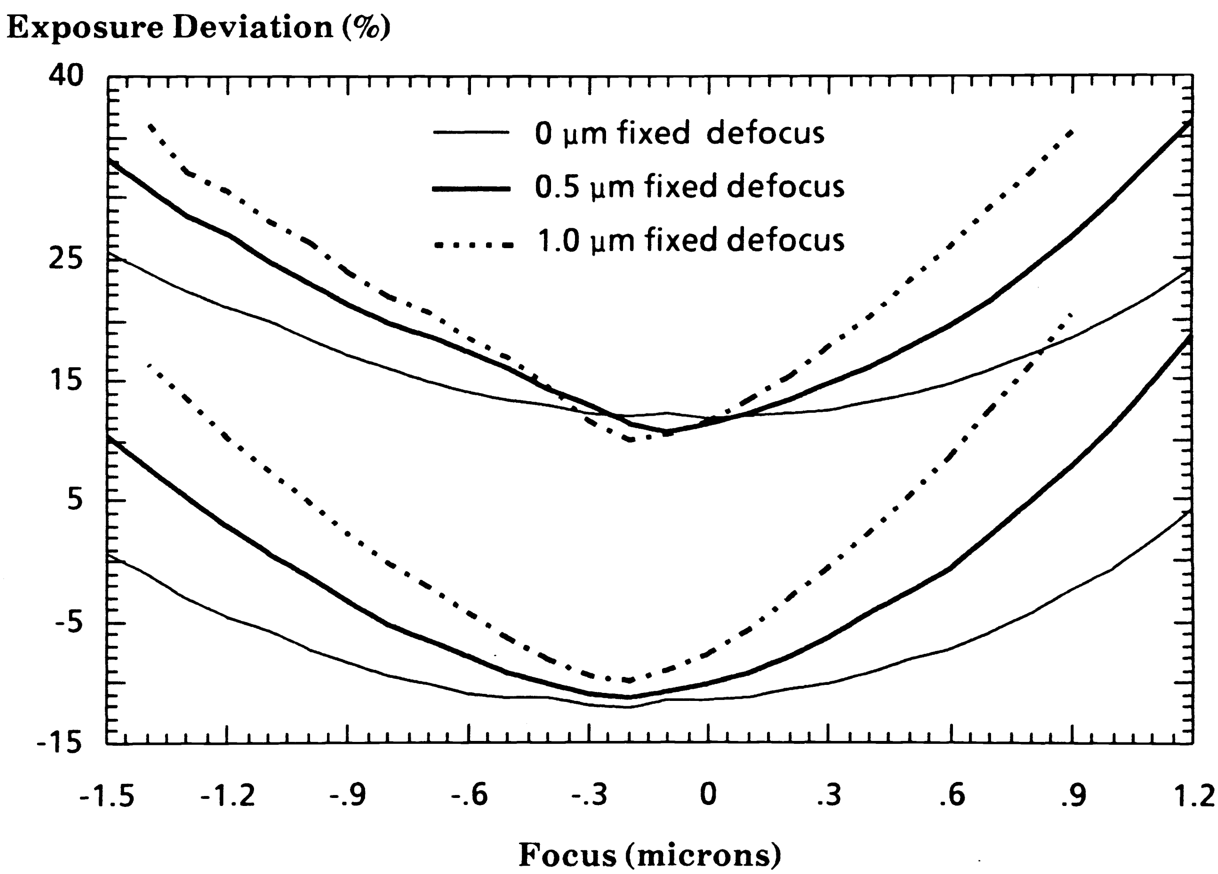

Figure 17 : Focus-Exposure process volume for ± 10% linewidth for 0 µm, 0.5 µm, and 1.0 µm fixed defocus (as predicted by PROLITH).

Thus, a new approach to characterizing resolution and depth-of-focus has been introduced. By examining the interaction of the lithographic tool (via the aerial image) with the photoresist process, a metric for judging aerial image quality has been established. By examining the effects on this metric of feature size and defocus, accurate and meaningful definitions of resolution and depth-of-focus can be made. This technique also leads to an understanding of the influence of various parameters on the depth-of-focus/resolution and the ability to compare the theoretical performance of different lithographic tools.

A variety of parameters were investigated using the lithography simulator PROLITH to determine their effect on depth-of-focus. A fixed defocus was used to account for aberrations in the optical system. The effect of this fixed effective defocus is the expected decrease in DOF, but the behavior is slightly more complicated than a first order analysis suggests. The resist contrast was found to play a large role in determining DOF. Better resists can lead to better focus and exposure latitudes. As expected, thin resist had superior DOF, but the improvement is believed to be due to an effective increase in resist contrast with thinner resists rather than to any optical effects. Finally, standing waves significantly decrease the size of the process window, and thus decrease DOF.

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