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# LUMPED PARAMETER MODEL OF THE PHOTOLITHOGRAPHIC PROCESS

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## ABSTRACT

The lumped parameter model for optical lithography is introduced. This model allows for quick calculation of exposure and focus latitude for a given lithography system based on test wafer results. Once the model has been fit to a particular process, it can be used to predict the effects of focus and exposure errors for any exposure tool of the same wavelength (i.e., for any numerical aperture, partial coherence, etc.) on the dimension of any feature. This allows for quick comparison of process latitude between lithography tools, determination of optimum reticle sizing, and estimation of the performance of next-generation lithography tools.

## INTRODUCTION

In this paper a new concept in lithography modeling will be introduced. Previous lithography modeling efforts, such as PROLITH (the Positive Resist Optical Lithography model) [1–4] and SAMPLE [5], can be classed as primary parameter models in which each parameter affecting the process is defined and characterized. Determining the values of these parameters for each process to be modeled can be a significant task. This difficulty has impeded the use of primary parameter lithography models, especially in production environments. Here, production engineers tend to use a very few lumped parameters to describe their lithography process. Thus, there is a need for a lithography model which uses a few parameters to produce accurately effects which are important to the process engineer, such as exposure and focus latitude.

In this paper, a lumped parameter model for optical lithography is presented [6], resulting in a direct relationship between the image intensity distribution and the critical dimension of the resulting pattern. This extremely simple model allows one to predict the effect on llinewidth of the two most important variables in photolithography: focus and exposure. Further, the "lumped parameters" are determined from experimental linewidth versus exposure data, which are routinely available for most processes. The lumped parameter model predicts the exposure and focus latitude of any feature quickly and accurately and requires no unusual or lengthy data collection.

The mathematical description of the resist process incorporated in the lumped parameter model uses a simple photographic model relating development time to exposure, while the image simulation is derived from the standard optical parameters of the lithographic tool. The result is a fast and simple process simulator, based on test wafer results, which can accurately predict the behavior of resist critical dimensions over a sizable range of imaging parameters (numerical aperture, focus, etc.). With this model as a process controller, the photoengineer, can quickly determine process latitude, i.e., the range of exposure and focus which maintains feature sizes to within specified limits. The process latitude information can be used in selecting design rules and for reticle specification, for realistic comparisons of present and future lithography systems, as well as for process control. This model also provides the framework for real-time optimization of the next generation of optical projection tools, which will offer variable numerical aperture and field size.

## BACKGROUND

### A. Image Intensity

The "image intensity," also called the aerial image, is the image of the mask which is projected onto the wafer. Mathematically, the image intensity can be expressed as $I(x,y)$ where the wafer is in the x–y plane. Typically, this function is normalized to the intensity in a large clear area so that $I(x,y)$ is the relative image intensity and is dimensionless. The simplest type of mask feature to study is an infinitely long line or space so that the image is one-dimensional (e.g., $I(x)$). Methods for calculating the image intensity for typical projection printers have been reported [7,8], and an example of the resulting image is shown in Figure 1. The variables which determine the shape of the image intensity are the numerical aperture of the objective lens, the partial coherence and wavelength of the illumination, the size and shape of the mask feature, and the distance the wafer is removed from the plane of perfect focus (called the defocus distance).

There are three regions of interest in the image profile, as indicated in Figure 1. The tail region is made up of the tail of the image plus any background intensity (caused, for example, by scattering and reflections from the lens surfaces). A typical background intensity may range from 1 – 4%. The tail controls photoresist erosion in the nominally unexposed regions (this is often called resist thinning). This may or may not be of importance, depending on the process. The second and most important part of the image profile is the toe. This is the region of the image near the mask edge. It is this region which controls the slope of the resist sidewall and, as we shall see, the exposure latitude. The center of the image, and in particular the value of the peak intensity, is important in determining the exposure energy needed to clear the feature in question relative to the energy needed for a large feature (which will have a speak intensity of 1, by definition).

There is another way to view the image intensity which yields useful information and insight. Figure 2 shows a plot of $-\ln\{I(x)\}$. This type of plot indicates an interesting feature of the image intensity: the toe region is nearly linear in log-space. This can be found to be true not only for small features, but for larger features as well. This fact will become very important when determining the effect of the image on exposure latitude.

### B. Exposure and Focus Latitude

A photolithographic process can be defined by the functional relationship between the dimension of a critical feature (CD) and two process variables, focus and exposure. Thus, one of the most important curves in photolithography is the CD versus exposure energy curve (also called the exposure latitude curve). Typical examples of such a curve are shown in Figure 3. The ability to control the size of a critical feature is related to the slope of this curve. In the vicinity of the nominal feature size, one can see that the slope changes very rapidly. This, it is difficult to characterize dimensional control using a single value of the slope. (One should note that these curves are useless for comparison purposes unless plotted relative to the nominal exposure energy.)

Again, we will find it useful to plot these curves on a log-exposure scale, as in Figure 4. One can see that there are regions of the CD curve which are nearly linear. Thus, the linewidth of a feature responds to the logarithm of the exposure energy over some range. The slope of this log curve will provide a more meaningful measure of the exposure latitude. The observed log-linear relationship is extremely important in understanding the behavior of photoresists and will form the basis of the lumped parameter model given in the following section.

From curves such as Figures 3 or 4, process latitude can be determined as a function of exposure variations. These exposure variations include dose errors, illumination nonuniformity, changes in resist sensitivity and thickness, wafer reflectivity variations, etc. It is important to note that exposure errors generally vary as a percentage of the nominal exposure energy. For example, a 10% illumination nonuniformity will result in a 10% exposure error regardless of the exposure time. Thus, the most useful way of expressing exposure is relative to the nominal exposure energy.

The second important variable is focus. Focus errors result from autofocusing errors, wafer flatness, and topography and lens aberrations. As can be easily seen in Figure 4, the exposure latitude decreases greatly with defocus. Thus, the two important process variables, focus and exposure, are not independent. As an example, consider a linewidth variation specification of $\pm$ 10%. For the perfect focus case, one could determine from the exposure latitude curve the allowable exposure variation which would keep the linewidth "in spec." Following this same procedure for the defocused case, one would see a marked decrease in the allowable exposure error. In fact, by plotting the maximum exposure error as a function of defocus distance for a given linewidth specification, one will define a focus-exposure window called the "process volume." (A typical example of such a plot will be shown in Figure 1.)

A simple model will now be defined which predicts the effects of these focus and exposure errors on critical dimensions.

## LUMPED PARAMETER MODEL

### A. Derivation

A complete derivation of the lumped parameter model is given elsewhere [6]. Here, an outline of that derivation will be given pointing out the important assumptions made.

The lumped parameter model will be based on a model for the development process, which in turn will be based on the characteristic curve (also called the contrast curve) of a photoresist. Following the discussion above, logarithmic definitions of the image intensity and exposure energy will be made in hopes of deriving a formalism for the observed log-linear relationship of the CD curve. Let E be the nominal exposure energy (i.e., the intensity in a large clear area times the exposure time) and I(x) the normalized image intensity. It is clear that the exposure energy as a function of the lateral mask dimension x is

$$E(x) = EI(x) \qquad (1)$$

where x - 0 is the center of the mask feature. Defining logarithmic versions of these quantities,

$$\epsilon(x) = \ln\left[ E(x) \right]$$

$$\epsilon = \ln[E]$$

$$i(x) = \ln[I(x)]. \qquad (2)$$

Thus, equation (1) becomes

$$\epsilon(x) = \epsilon + i(x). \qquad (3)$$

These logarithmic definitions will also be useful when dealing with the characteristic curve of a photoresist, which uses $\epsilon$ as the abscissa.

The photoresist contrast curve relates resist thickness remaining after development to the logarithm of exposure energy. By examining a typical contrast curve, one might expect that a reasonable fit to this curve can be obtained using an exponential function. In particular, the relative thickness remaining, $T_r$, can be modeled as

$$T_r = 1 - e^{\gamma(\epsilon-\epsilon_0)} \tag{4}$$

where $\epsilon_0$ is the energy required to just clear the photoresist in the allotted development time. The use of the letter $\gamma$ for the constant in the exponential is not arbitrary. It is easy to show that the slope of the curve given by equation (4) at $\epsilon-\epsilon_0$ is just $-\gamma$. Thus, $\gamma$ is related to the conventional base 10 contrast of the resist process, which we shall call $\gamma_{10}$, by

$$\gamma_{10} = 2.303\ \gamma. \tag{5}$$

If the development rate is assumed constant through the resist, then the relative thickness remaining can be related to the development rate and

$$r(x) = r_0\, e^{\gamma(\epsilon(x) - \epsilon_0)} \tag{6}$$

where $r_0$ is the development rate needed just to clear the resist in the allotted development time.

Equation (6) is an extremely simple-minded model relating development rate to exposure energy based on the characteristic curve of a photoresist. In order to use this expression, we will develop a phenomenological explanation for the development process. This explanation will be based on the assumption that development occurs in two steps: a vertical development to a depth z, followed by a lateral development to position x (measured from the center of the mask feature) as shown in Figure 5. A development ray, which traces out the path of development, starts at the point $(x_0,0)$ and proceeds vertically until a depth z is reached such that the resist to the side of the ray has been exposed more than the resist below the ray. At this point the development will begin horizontally. The time needed to develop in both vertical and horizontal directions, $t_z$ and $t_x$, respectively, can be computed from equation (6). The sum of these two times must equal the total development time. Differentiating this expression with respect to exposure energy, the following equation can be derived [6]:

$$i(x) = \frac{1}{\gamma} \ln\left(\frac{dx}{d\epsilon}\right) - (\epsilon(x) - \epsilon_0) + \frac{1}{\gamma} \ln\left(\frac{1}{\gamma D}\right) \tag{7}$$

where $\epsilon(x)$ is the (log) energy needed to expose a feature of width 2x and D is the resist thickness. Equation (7) is the differential form of the lumped parameter model and relates the CD versus log-exposure curve and its slope to the image intensity. A more useful form of this equation is given below, however, some valuable insight can be gained by examining equation (7). In the limit of very large $\gamma$, one can see that the CD versus exposure curve becomes equal to the aerial image. Thus, exposure latitude becomes image limited. For small $\gamma$, the other terms become significant and the exposure latitude is process limited. Obviously, an image limited exposure latitude represents the best possible case.

A second form of the lumped parameter model can also be obtained giving [6]

$$\epsilon(x) = \epsilon_0 + \frac{1}{\gamma} \ln\left[1 + \frac{1}{D}\int_0^x \left(\frac{I(x)}{I(0)}\right)^{-\gamma} dx\right]. \tag{8}$$

Equation (8) is the integral form of the lumped parameter model. Using this equation, one can generate a normalized CD vs. exposure curve by knowing the image intensity, $I(x)$, the resist thickness, D, and the (base e) contrast, $\gamma$. Note that $\epsilon(0)$ represents the exposure energy needed to give a CD of 0, i.e., just to clear the resist and thus is equivalent to $\epsilon_0$.

**B. Contrast**

It is obvious from equation (8) that the contrast, $\gamma$, is a very important parameter in determining the exposure latitude. Therefore, some comments on the definition and derivation of the contrast used in the lumped parameter model are in order. The simple development model given by equation (6) is derived by assuming a non-absorbing resist and fitting the contrast curve of this resist to a simple equation. Although later the effects of absorption are added to our development model [6], the parameter $\gamma$ still applies to this idealized non-absorbing resist. It is known that the effect of resist absorption is to decrease the contrast (heavily dyed resists have very low contrast values). However, the value of $\gamma$ used in the lumped parameter model still applies to a non-absorbing resist.

It has been proposed [3] that the contrast of a resist system can be broken up into two components, development contrast, $\gamma D$, and exposure contrast, $\gamma E$, due to absorption. The development contrast is the contrast of the resist system with no absorption (i.e., infinite exposure contrast). The exposure contrast is the contrast of the system assuming perfect development (i.e., an infinite development contrast). The overall contrast, $\gamma T$, is then given by [3]

$$\gamma_T = \left( \frac{1}{\gamma_D} + \frac{1}{\gamma_E} \right)^{-1} . \qquad (9)$$

Thus, the gamma used in equations (7) and (8) is not the conventional photoresist contrast $\gamma T$, but the development contrast. Throughout the rest of this paper, use of the term contrast will refer to the development contrast. One should note, however, that it is the nature of lumped parameter models to include (or lump) several effects into a single variable, thus allowing a simple model to accurately describe a complicated process. One should be somewhat cautious when applying theoretical significance to the lumped parameters of this model.

### C. Using the Model

Equation (8) can now be used to generate exposure latitude curves (critical dimension versus exposure energy). Figure 6 shows one such curve for a 1.0 $\mu$m line with a pitch of 2 $\mu$m simulated using typical g-line projection printer parameters (NA = 0.28, $\sigma$ = 0.7) and using 0.9 $\mu$m of resist. The image intensity distribution was simulated using PROLITH v1.2 and the resulting data numerically integrated in equation (8). As can be seen, the process contrast (gamma) plays a critical role in determining the process latitude. Increasing resist thickness results in a loss of process latitude, as shown in Figure 7. This effect is quite noticeable in a low gamma process, but for higher contrast resist systems, thickness has less of an effect on exposure latitude. Figure 8 illustrates the well known fact that features near the resolution limit of the printer have less exposure latitude than larger features. Finally, Figure 9 shows how defocus degrades exposure latitude.

All data in FIgures 6-9 were generated using the lumped parameter model. Some of the trends shown in these figures may be obvious to an experienced lithography engineer; some may not. In any case, these trends will be verified by comparing the lumped parameter model to experimental data. As was previously mentioned, it is useful to represent exposure and focus latitude data in terms of the process volume. The effects of $\gamma$ and D on the process volume are shown in Figures 10 and 11.

## COMPARISON WITH EXPERIMENTAL DATA

The true test of any model is its ability to describe adequately experimental data. In this case, the data is SEM automatic linewidth measurements made for a variety of exposure energies repeatable to $\pm$ 0.02 $\mu$m and accurate to $\pm$ 2.5%. An Ultratech 1000 stepper with a 1 $\mu$m production lens (NA = 0.315, $\sigma$ = 0.45) was used to expose 1.1 $\mu$m of AZ1470 resist on silicon wafers. The wafers were developed for 90 seconds in 5:1 AZ developer. Although the Ultratech uses broadband exposure in the range of 390 - 450 nm, for the purposes of calculating the image intensity of a wavelength of 420 nm was used. Equal lines and spaces of 1.0 $\mu$m were imaged for five different focus distances, 0 (in perfect focus), $\pm$ 2 $\mu$m, and $\pm$ 3 $\mu$m, all accurate to $\pm$ 0.25 $\mu$m. The resulting data are shown in Figure 12.

### A. Lumped Parameter Estimation

According to equation (8), there is only one parameter which can be varied in order to fit the lumped parameter model to experimental data, $\gamma$. However, modeling studies using PROLITH to generate exposure latitude data for different substrates indicate that changes in substrate reflectivity modify the shape of the CD curves in the same way as changes in resist thickness [9]. Thus, there is physical significance in allowing the resist thickness, D, to be replaced by an effective resist thickness, $D_{eff}$, in order to account for substrate differences, i.e., standing waves. The effective thickness can be thought of in terms of the time required to develop through the photoresist. When standing waves are present it takes longer to develop through the resist, which is the same effect as having a thicker resist. Thus, $D_{eff}$ will be larger when the standing waves are more pronounced (for example, a broadband exposure should have a lower $D_{eff}$ than a monochromatic exposure, all other factors being equal). Note that the wavelength of exposure will also effect $D_{eff}$, since wavelength will change the standing wave effect.

The lumped parameters can now be easily determined for the given experimental data. An excellent fit was obtained over the full range of CDs and for all five focus settings using $\gamma = 1.6$ and $D_{eff} = 1.5$ (Figure 13).

### B. Process Interpolation and Extrapolation

Given the excellent fit of the model to the wide range of exposure and focus data, one would expect that the model could then accurately predict the behavior of the process at other focus settings and reticle sizings. Thus, one could predict, for example, the maximum defocus which would keep the linewidth within $\pm 10\%$ for a given exposure variation. Using the lumped parameters given above, the focus-exposure process volume was generated for a $1.0 \pm 0.1$ µm linewidth (Figure 14). Focus and exposure errors within this volume will keep the linewidth within specifications.

The lumped parameter model can also be used to explore the effects of mask biasing on process latitude. For example, a series of 1.0 µm lines and spaces can be modeled and the process volume determined. Similarly, a 1.1 µm line, 0.9 µm space combination (i.e., a 0.1 µm mask bias) can be modeled and the process volume determined for a desired linewidth of 1.0 µm. One can then see the advantage (or disadvantage) of mask biasing with respect to increased process latitude.

The performance of the resist process can also be estimated for other printers (e.g., different numerical apertures). Thus, the trade-off between resolution and depth of focus can be determined for a specific resist process and for a particular linewidth specification. This type of analysis can be very useful when evaluating the purchase of a new lithographic tool. Also, the ability to predict the effects of a numerical aperture change on a particular resist process will be an essential part of the operation of variable numerical aperture tools, which are currently under development. As an example, the process volume for a 1 µm line is shown in Figure 15 for 0.28 and 0.40 numerical aperture printers. Although not shown in this paper, it is also very useful to compare the effects of numerical aperture on the process volume, as in Figure 15, for different feature sizes. Thus, one can determine for a process with known focus and exposure errors a realistic resolution versus numerical aperture relationship.

As a final note, CD versus exposure data can also be used to calculate the image profile, i(x), using equation (7). Thus, the lumped parameter model represents one of the few methods of determining the image profile experimentally. Using the in-focus data of Figure 12, equation (7) was applied and a predicted image profile was determined. Further, two more sets of CD versus exposure data were taken using 30 second and 180 second development times and values for i(x) were calculated. These values are shown in Figure 16. The solid line represents the theoretical image profile as predicted by partial coherence theory. One can see that the fit is remarkable, with only slight deviation near the center of the image.

## SUMMARY

A simple model has been presented which predicts the exposure latitude of a resist process for a given image profile. The resist process is governed by two lumped parameters, the development contrast and the effective resist thickness. Once these two parameters have been determined (using measured CD versus exposure data), the exposure latitude for any image profile can be predicted. Thus, the effect of defocus on exposure latitude can be quickly determined allowing for the calculation of the process volume of the resist process. A knowledge of the process volume is absolutely essential in order to provide adequate process control for a high resolution lithographic process. The ability to describe the process volume mathematically is the first step in the development of an automated photolithographic process control system.

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7. R. Hershel, "Effects of Partially Coherent Illumination on Resist Profiles in Projection Printing," *Kodak Microelectronics Interface '78* (1978) pp. 62-67.

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9. Modeling studies comparing primary and lumped parameter models will be published elsewhere.

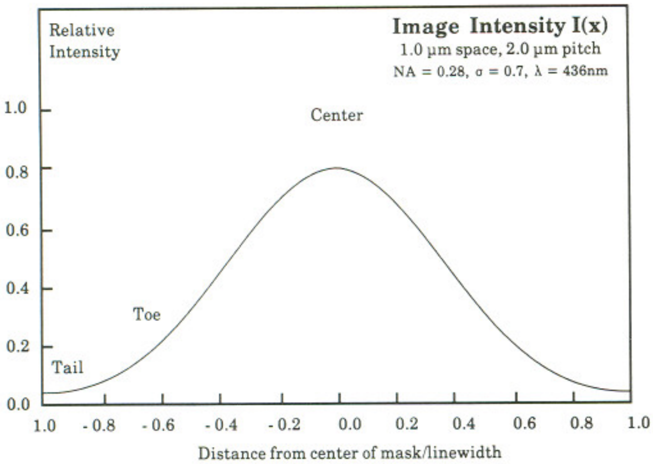


Figure 1: Image intensity distribution for a typical step-and-repeat type projection printer.

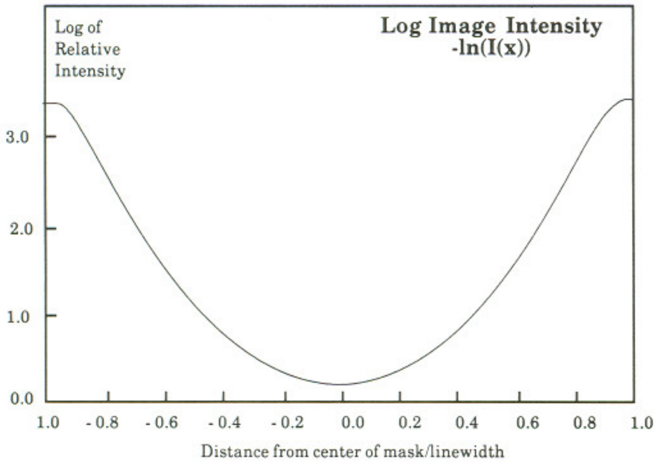


Figure 2: Log-image plot of a typical image intensity distribution.

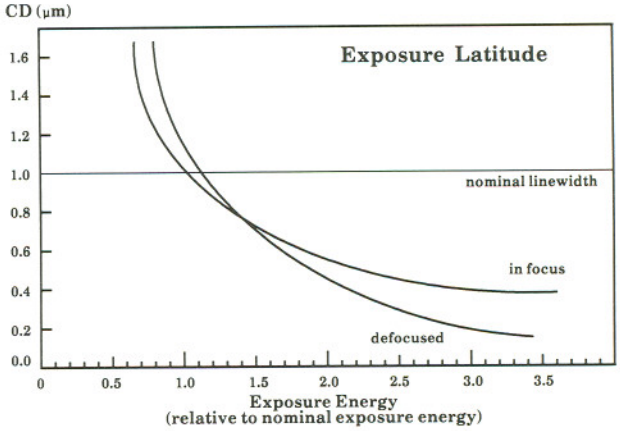


Figure 3: Typical critical dimension (CD) versus exposure curve for a 1.0 µm line.

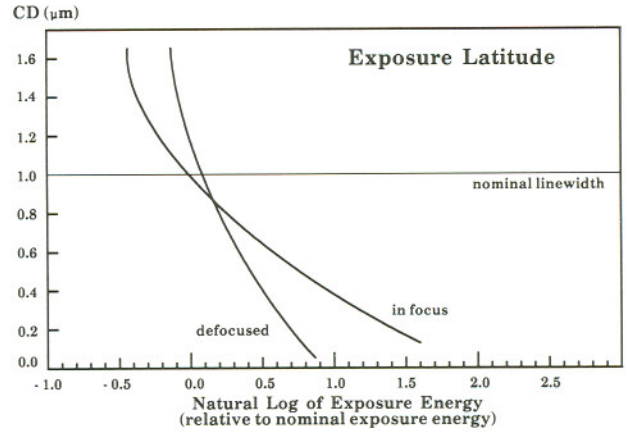


Figure 4: Log-exposure plot of a typical CD curve.

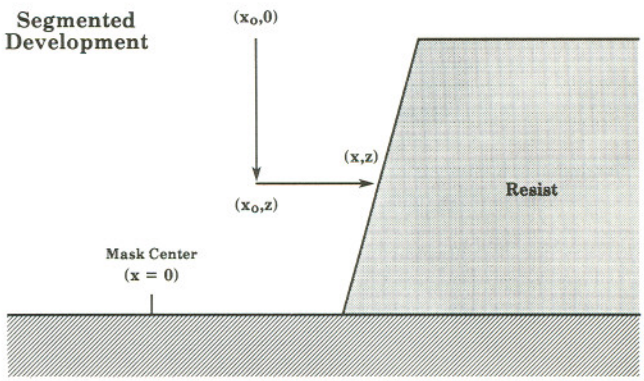


Figure 5: Segmented development concept.

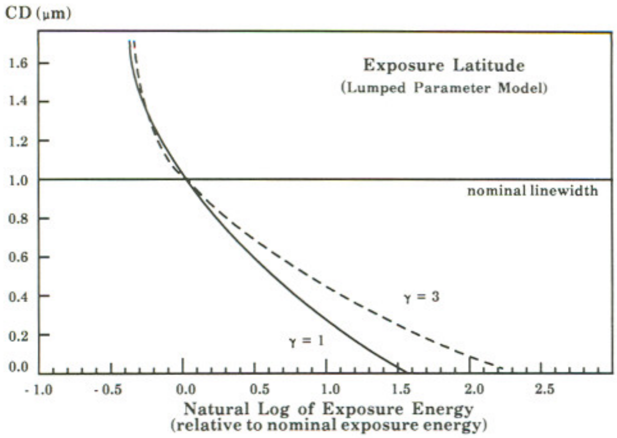


Figure 6: CD variation of a line with exposure energy for different gammas as predicted by the lumped parameter model (0.9 μm resist, 1.0 μm lines and spaces).

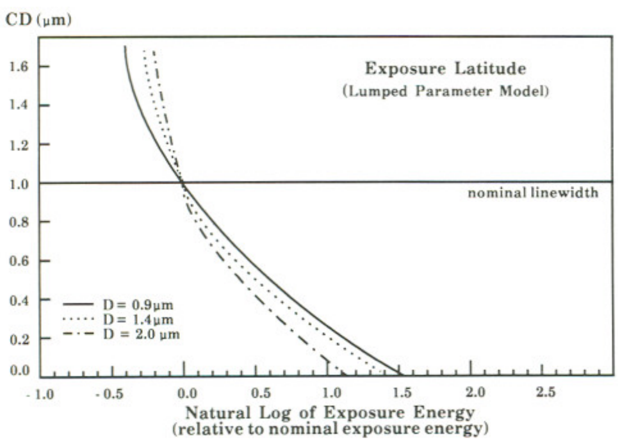


Figure 7: CD variation with exposure energy for different resist thicknesses as predicted by the lumped parameter model ($\gamma$ = 1, 1.0 μm lines and spaces).

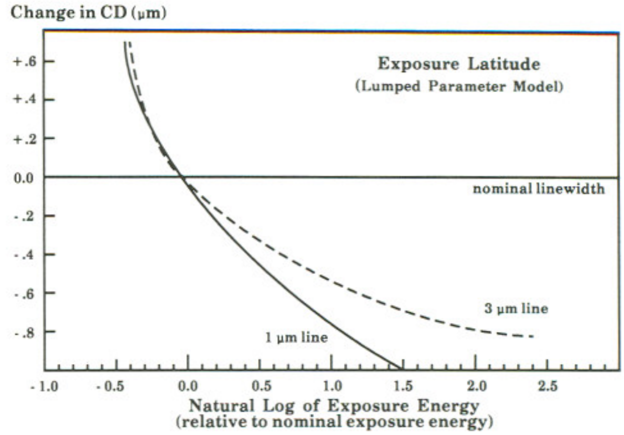


Figure 8: CD variation with exposure energy for different feature sizes as predicted by the lumped parameter model ($\gamma$ = 1, 0.9 μm resist).

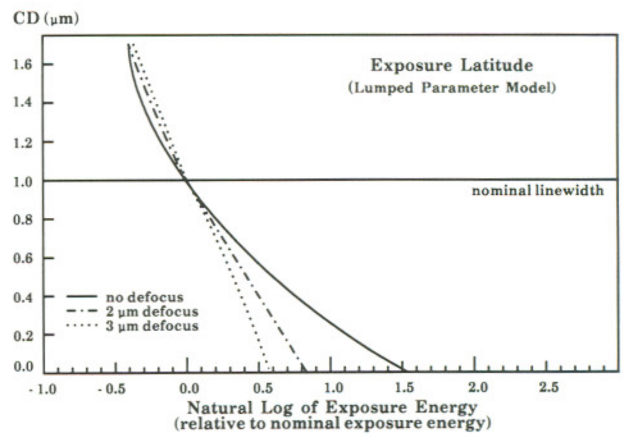


Figure 9: Relative CD variation with exposure energy for different amounts of defocus as predicted by the lumped parameter model ($\gamma$ = 1, 0.9 μm resist, 1.0 μm lines and spaces).

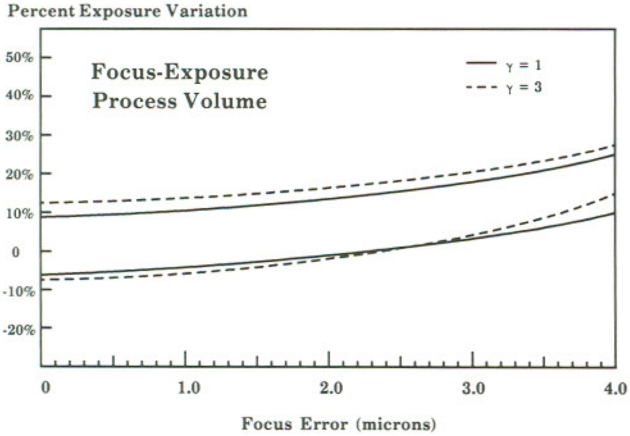


Figure 10: The effect of $\gamma$ on the process volume as predicted by the lumped parameter model ($D_{eff}$ = 1 $\mu$m).

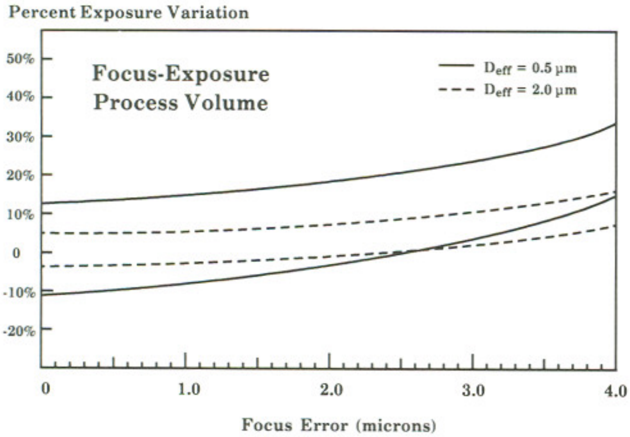


Figure 11: The effect of $D_{eff}$ on the process volume as predicted by the lumped parameter model ($\gamma$ = 1).

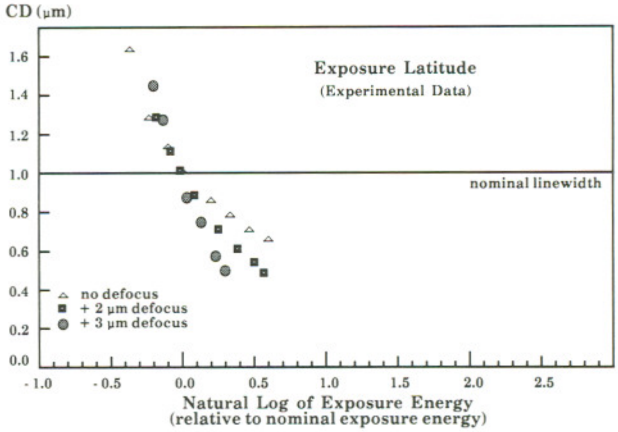


Figure 12: CD variation with exposure energy – data taken for Ultratech 1000 with a 1 $\mu$m lens (1.1 $\mu$m AZ1470 resist on silicon, 90 second development, 1.0 $\mu$m lines and spaces).

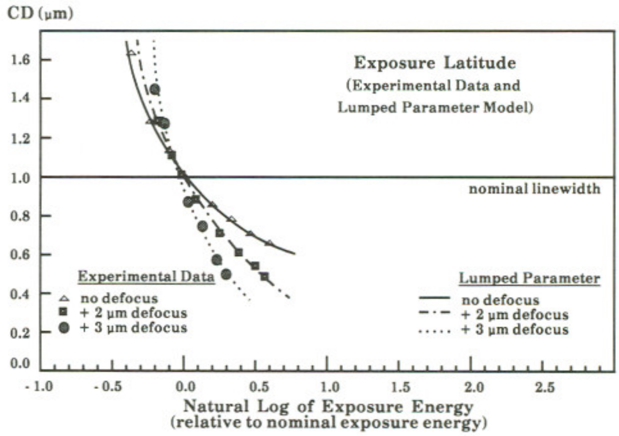


Figure 13: Fit of Ultratech experimental data with the lumped parameter model. All lumped parameter curves use $\gamma$ = 1.6 and $D_{eff}$ = 1.5 $\mu$m.

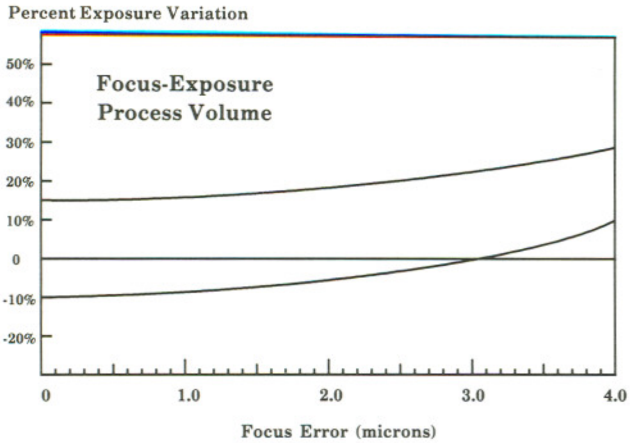


Figure 14: Process volume – maximum exposure/focus variations which keep linewidth variations within specified limits (calculated using the data in Figure 13).

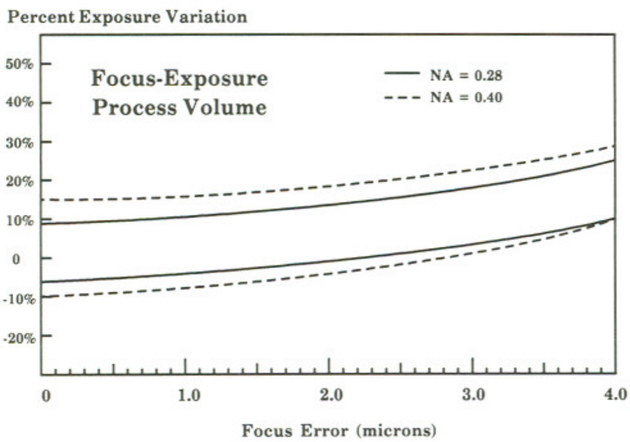


Figure 15: Comparison of predicted process volumes for 0.28 and 0.40 numerical aperture printers ($\gamma$ = 1, $D_{eff}$ = 1 $\mu$m, $\lambda$ = 436 nm, $\sigma$ = 0.7).

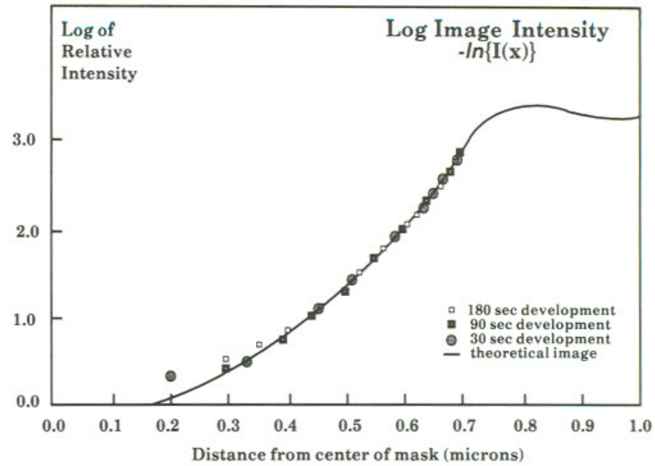


Figure 16: Determination of the image profile base on three sets of measured CD versus exposure data. Solid line represents the theoretical image profile.