Process Settings and Process Latitude

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Over the last six editions of this column we have explored the use of the normalized image log slope (NILS) and related metrics to describe the major impacts of image quality and process settings on critical dimension (CD) control. In the end, exposure latitude (the change in CD for a given change in exposure dose) was related to the NILS and a comprehensive parameter of resist response to dose, the photoresist contrast [1]. Along the way we defined metrics of image quality at each step in the process (the latent image gradient before and after post-exposure bake, the development rate gradient) and explored how process settings (exposure dose, amount of diffusion) influence these metrics. Although it may not have been obvious from these discussions, different process variables fall into two distinct categories based on how they influence the final CD control. I call these two categories set points and slopes.

Perhaps the easiest way to explain the meaning of these two categories is by way of example. And the most obvious and clear example of the difference between set points and slopes is exposure dose (a set point parameter) and focus (a slope parameter). An imaging tool projects an image of a photomask onto a resist coated wafer. The information on the mask is encoded in its transmission function where the desired position of an edge is determined by the transition from high transmittance (bright) to low transmission (dark). The projected image of this transmission function is the aerial image where again the position of the photoresist edge is determined by a transition of energy from bright to dark. For a given aerial image $I(x)$ (simplifying to one dimension for this example) and exposure dose E, the projected energy distribution at the wafer is $EI(x)$. This energy distribution contains all of the information about the mask that actually reaches the wafer. One way to describe the information content of this energy distribution is to describe the properties of the energy distribution function at the nominal line edge. In particular, the energy at the nominal line edge, equal to $EI(x=CD/2)$, and the slope, described by the NILS, are the main properties of the energy distribution function that will influence CD control.

How do focus and exposure affect this information? How do they influence final CD control? As we saw last time [1], exposure latitude is given approximately by

$$\frac{\partial \ln CD}{\partial \ln E} \approx \frac{2}{NILS} + \frac{2\gamma D}{CD}\left[\frac{I(CD/2)}{I(0)}\right]^{\gamma} \qquad (1)$$

where $I(0)$ is the intensity at the peak of the aerial image (in the bright region), D is the resist thickness, and γ is the resist contrast. The effect of focus is to both reduce the NILS and the ratio of the image intensity in the space to the intensity at the line edge (Figure 1). In other words, focus affects the slope of the energy distribution at the edge of the line. Does exposure dose have a role in determining exposure latitude? From equation (1), the only influence of exposure dose is through the resist term γ. As shown in Figure 2, contrast is a function of exposure dose. At the extremes of exposure dose (zero and infinite), the contrast of the resist goes to zero and the change in CD with dose by equation (1) will be infinite. When the dose at the line edge is properly set, the resist contrast will be at its maximum and the resulting exposure latitude will also be maximized.

Although equation (1) describes the exposure latitude specifically, similar equations would relate CD change to many other process variables. In general, the concepts described above will be the same. Variables like focus affect the slope of the energy gradients or other information metrics at the line edge. Variables like exposure dose affect the absolute value of the energy at the line edge and represents a set point for the process. Parameters like photoresist contrast, which describe how the resist responds to the energy information supplied by the imaging tool, are affected by this set point. The influence of almost any process parameters can be described by its effect on slope or set point or both.

Take, for example, a small error in the feature size on the mask. To first order, the NILS is only slightly affected by this error. But the energy at the nominal line edge will have a definite change (if the chrome on the mask was increased in size, for example, the energy at the nominal line edge will be reduced). Thus, mask errors are most like set point errors. In fact, by relating the mask error to an effective dose error at the nominal line edge, equation (1) can be used to predict the affect of this error on resist CD (thus predicting the mask error enhancement factor). An example of a variable that affects both set point and slope is the post-exposure bake time for a chemically amplified resist. Increased diffusion causes a reduction in the slope at the line edge [2]. Increased chemical amplification is the same as an increase in dose, changing the set point of the process.

Although focus was used as the prototype for a slope change variable, in fact focus can cause a set point change as well. In general, defocus will cause both a decrease in NILS and a change in the intensity at the nominal line edge. Interestingly, it is the combination of these factors that gives rise to a phenomenon called isofocal bias. But that is the topic of some future edition of the *Lithography Expert*.

References

1. C.A. Mack, "Using the Normalized Image Log-Slope, part 6: Development Path", *Microlithography World* (May, 2002).

2. C.A. Mack, "Using the Normalized Image Log-Slope, part 4", *Microlithography World* (November, 2001).

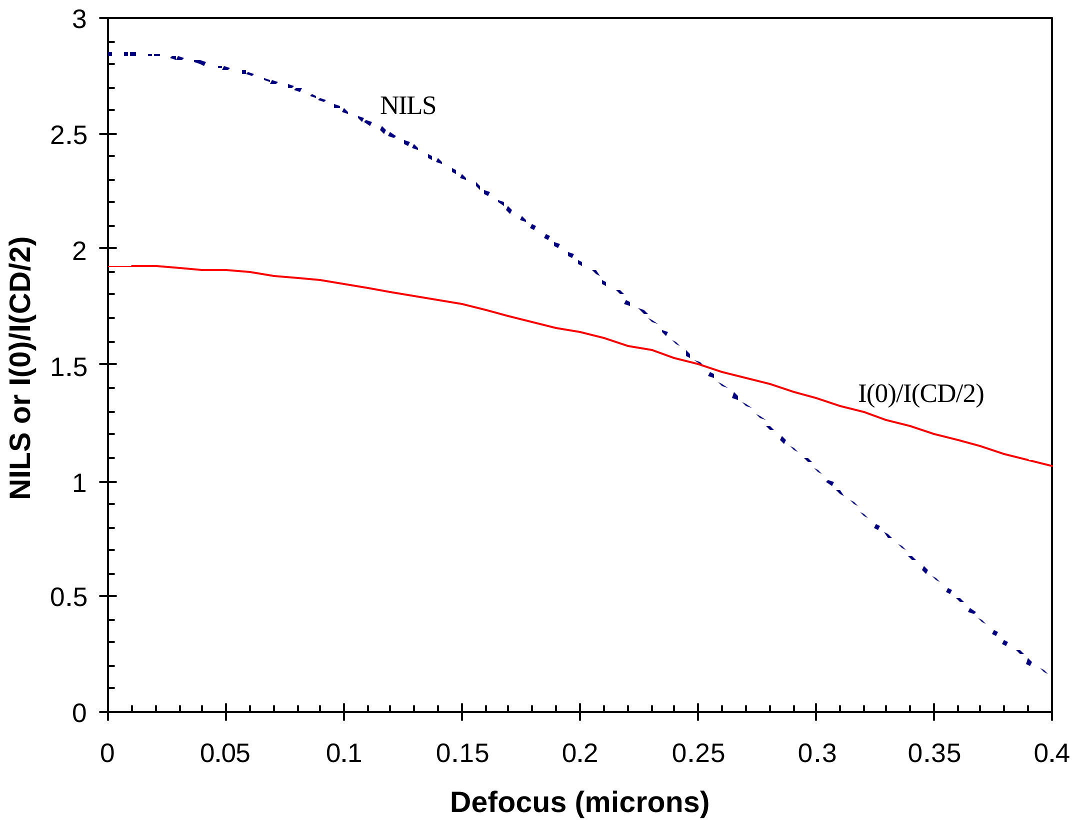

Figure 1. Defocus affects the slope of the aerial image, shown here by the NILS and the ratio of the center to edge intensities (λ = 248nm, NA = 0.7, σ = 0.5, binary mask of 180nm lines and spaces).

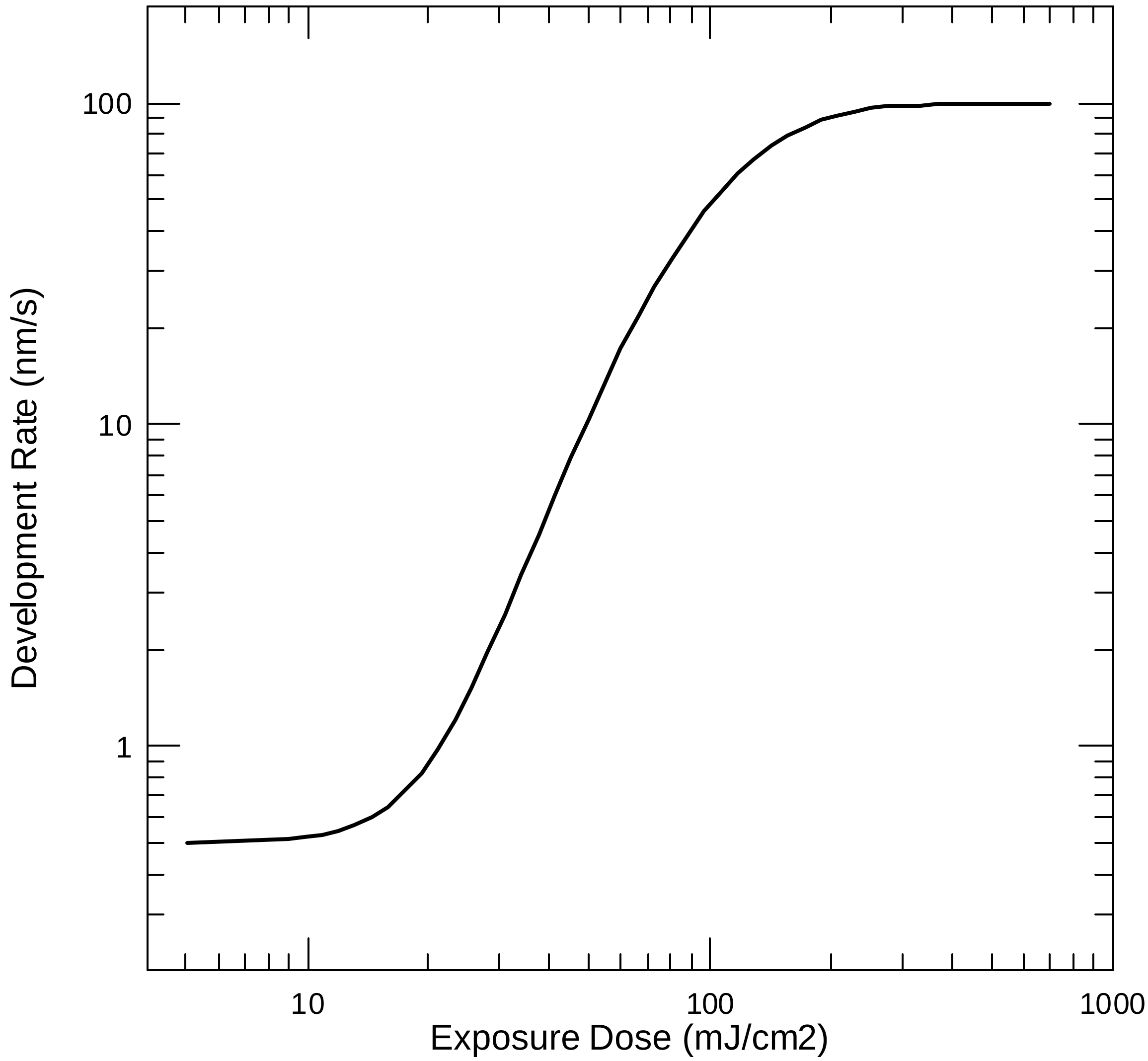

Figure 2. Typical development rate function of a positive photoresist. Photoresist contrast $\gamma(E)$ is defined as the slope of this curve.