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Using the Normalized Image Log-Slope

Chris A. Mack, *FINLE Technologies, A Division of KLA-Tencor, Austin, Texas*

Projection imaging tools, such as scanners, steppers, or step-and-scan tools, project an image of a mask pattern into air, and then ultimately into the photoresist. The projected image in air is called the *aerial image*, a distribution of light intensity as a function of spatial position in the image plane. The aerial image is the source of the information that is exposed into the resist, forming a gradient in dissolution rates that enables the three-dimensional resist image to appear during development. The quality of the aerial image dictates the amount of information provided to the resist, and subsequently the quality and controllability of the final resist profile.

How do we judge the quality of an aerial image? If, for example, aerial images are known for two different values of the partial coherence, how do we objectively judge which is better? Historically, the problem of image evaluation has long been addressed for applications such as photography. The classical metric of image quality is the *image contrast* (Figure 1). Given a mask pattern of equal lines and spaces, the image contrast is defined by first determining the maximum light intensity (in the center of the image of the space) and the minimum light intensity (in the center of the line) and calculating the contrast as

$$Image\ Contrast\ = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}} \tag{1}$$

Since the goal is to create a clearly discernible bright/dark pattern, ideally I_{min} should be much smaller than I_{max}, giving a contrast approaching 1.0 for a high-quality (“high contrast”) image.

Although this metric of image quality is clear and intuitive, it suffers from some problems when applied to lithographic images. First of all, the metric is only defined for equal lines and spaces. Although it is possible to modify the definition of image contrast to apply, for example, to an isolated line or to a contact hole, it is not clear that these modified definitions are useful or comparable to each other. Secondly, the image contrast is only useful for patterns near the resolution limit. For large features the image contrast is essentially 1.0, regardless of the image quality. Finally, and most importantly, the image contrast is not directly related to metrics of lithographic quality, such as resist linewidth control.

Fundamentally, the image contrast metric samples the aerial image at the wrong place. The center of the space and the center of the line are not the important regions of the image to worry about. What is important is the shape of the image near the nominal line edge. The edge between bright and dark determines the position of the resulting photoresist edge. This transition from bright to dark within the image is the source of the information as to where the photoresist edge should be. The steeper the intensity transition, the better the edge definition of the image, and as a result the better the edge definition of the resist pattern. If the lithographic property of concern is the control of the photoresist linewidth (i.e., the position of the resist edges), then the image metric that affects this lithographic result is the slope of the aerial image intensity near the desired photoresist edge.

The slope of the image intensity as of function of position (dI/dx) measures the steepness of the image in the transition from bright to dark. However, to be useful it must be properly normalized. For example, if one simply doubles the intensity of the light, the slope will also double, but the image quality will not be improved. Dividing the slope by the intensity will normalize out this effect. The resulting metric is called the image log-slope:

$$Image\ Log-Slope \ = \ \frac{1}{I}\frac{dI}{dx} \ = \ \frac{d\ln(I)}{dx} \tag{2}$$

where this log-slope is measured at the nominal (desired) line edge (Figure 2). Since variations in the photoresist edge positions (linewidths) are typically expressed as a percentage of the nominal linewidth, the position coordinate x can also be normalized by multiplying the log-slope by the nominal linewidth w, to give the normalized image log-slope (NILS).

$$NILS \ = \ w\frac{d\ln(I)}{dx} \tag{3}$$

The NILS is the best single metric to judge the lithographic usefulness of an aerial image [1-3].

How can the NILS be used? Since the NILS is a measure of image quality, it can be used to investigate how optical parameters affect image quality. One of the most obvious examples is defocus. The effects of focus on an image are quite familiar to most of us from everyday examples such as on overhead projector: as an image goes out of focus, it gets blurry! Specifically, the edges become blurred so that it is harder to distinguish the exact point where the image transitions from bright to dark. In other words, the slope of the aerial image at the edge between bright and dark features is reduced as we go out of focus. Using our metric of image quality, the NILS decreases as the image goes out of focus.

Figure 3a shows the aerial image of a space at best focus, and at two levels of defocus. The "blurred" images obviously have a lower image log-slope at the nominal line edge compared to the in-focus image. By plotting the log-slope or the NILS as a function of defocus, one can quantify the degradation in aerial image quality as a function of defocus (Figure 3b). This log-slope defocus curve provides a very important tool for understanding how focus affects a lithographic process. For example, suppose one assumes that there is a minimum acceptable NILS value, below which the aerial image is not good enough to provide adequate resist images or linewidth control. In Figure 3b, for example, a minimum acceptable NILS value of 2.5 would mean that this imaging process can tolerate about ±1µm of defocus and still get aerial images of acceptable quality. Thus, an estimate of the minimum acceptable NILS can lead to an estimate of the depth of focus.

In the next issue of this column, we'll discuss the interpretation of the NILS and how to relate its numerical value to actual lithographic metrics.

References

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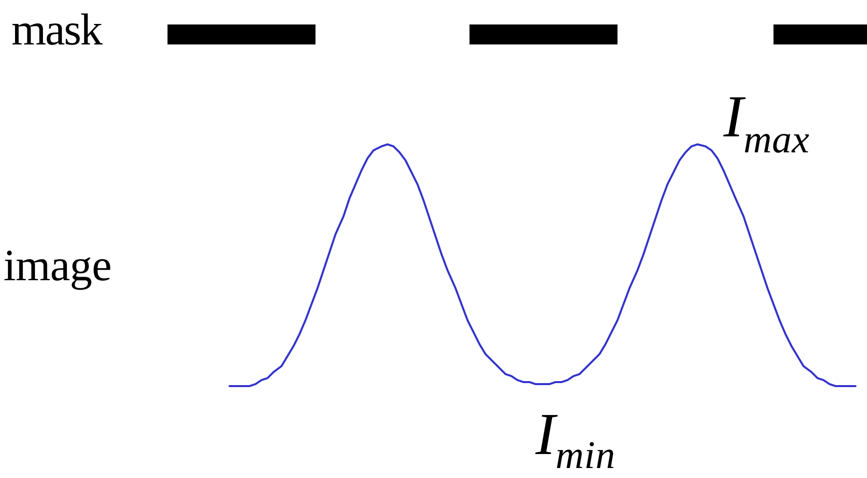
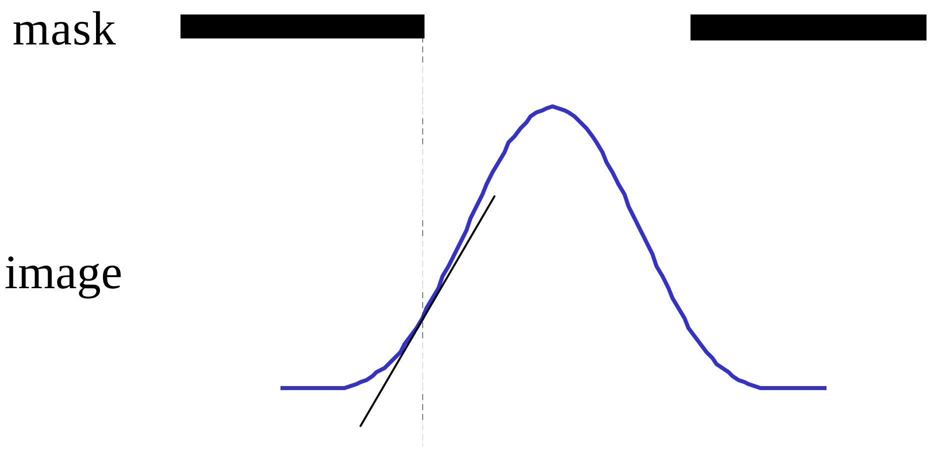
2. H. J. Levinson and W. H. Arnold, "Focus: the critical parameter for submicron lithography," *Jour. Vac. Sci. Tech.*, Vol. B5, No. 1, pp. 293-298 (1987).

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



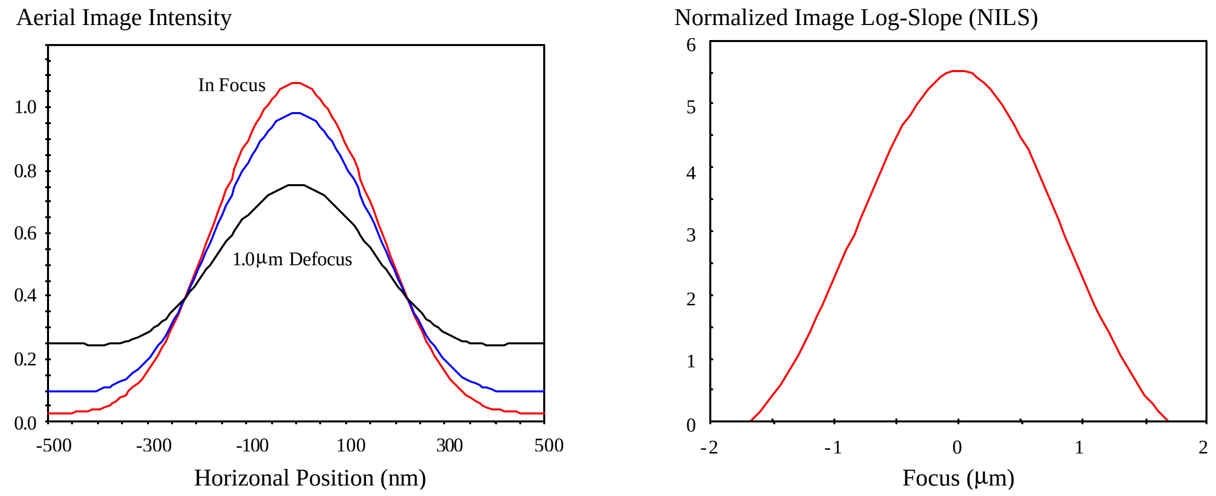
$$Image\ Contrast = \frac{I_{\mathrm{max}} - I_{\mathrm{min}}}{I_{\mathrm{max}} + I_{\mathrm{min}}}$$

Figure 1. Image Contrast is the conventional metric of image quality used in photography and other imaging applications, but is not directly related to lithographic quality.



$$Image\ \ Log - Slope = \frac{\partial \ln I}{\partial x} = \frac{1}{I}\frac{\partial I}{\partial x}$$

Figure 2. Image Log-Slope (or the Normalized Image Log-Slope, NILS) is the best single metric of image quality for lithographic applications.



(a) (b)

Figure 3. The effect of defocus is to (a) “blur” an aerial image, resulting in (b) reduced log-slope as the image goes out of focus.