Using the Normalized Image Log-Slope, part 2

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As we saw in part 1 of this column, the normalized image log-slope (NILS) is the best single metric to judge the lithographic usefulness of an aerial image. A high NILS describes an aerial image with a steep transition from bright to dark, providing good edge definition. NILS can be used as a numeric quality metric, judging the impact of any lithographic parameter on image quality. A simple and extremely useful example of this is a plot of the impact of defocus on image quality in what is called the log-slope defocus curve.

To see how the log-slope defocus curve can be used to understand imaging, consider the effects of wavelength and numerical aperture on the focus behavior of an aerial image. Figure 1a shows how the NILS of a 0.25μm line/space pattern degrades with defocus for three different wavelengths (365nm, 248nm, and 193nm). It is clear from the plot that the lower wavelength provides better image quality for the useful range of defocus. For a given minimum acceptable value of NILS, the lower wavelength will allow acceptable performance over a wider range of focus. One could conclude that, for a given feature being imaged, the lower wavelength provides better in-focus performance and better depth of focus.

The impact of numerical aperture (NA) is a bit more complicated, as evidenced in Figure 1b. Here, the log-slope defocus curves for three different numerical apertures (again, for a 0.25μm line/space pattern) cross each other. If one picks some minimum acceptable NILS value, there will be an optimum NA which gives the maximum depth of focus (for example, a minimum NILS value of 2.5 has the best depth of focus when NA = 0.6). Using a numerical aperture above or below this optimum reduces the depth of focus.

NILS values are easy and fast to calculate and provide a simple yet valuable metric of image quality. As an example of using this metric, the log-slope defocus curve is one of the easiest ways to quantify the impact of defocus on image quality. By using this tool, we have quickly arrived at two fundamental imaging relationships: when imaging a given mask pattern, 1) lower wavelengths give better depth of focus, and 2) there is an optimum numerical aperture that maximizes the depth of focus. But to make the best use of the NILS as an image metric, one must relate the NILS numerical value to lithographically measurable quantities. How does one determine the minimum acceptable NILS? If the NILS is increased from 2.0 to 2.5, what is the lithographic impact? More fundamentally, why is NILS a good image metric?

The answers to these questions lie with the fact that NILS is directly related to the printed feature's exposure latitude. Exposure latitude describes the change in resulting linewidth for a given change in exposure dose. Mathematically, it can be expressed as the slope of a critical dimension (CD) versus exposure dose (E) curve, ∂CD/∂E. For the simplifying case of a perfect, infinite contrast photoresist the exposure latitude can be related to NILS by

$$w\frac{\partial \ln E}{\partial CD} = \frac{1}{2} NILS \qquad (1)$$

where w is the nominal feature width. To put this in more familiar terms, if we define exposure latitude to be the range of exposure, as a percentage of the nominal exposure dose, that keeps the resulting feature width within ±10% of the nominal size, then exposure latitude can be approximately related to NILS by

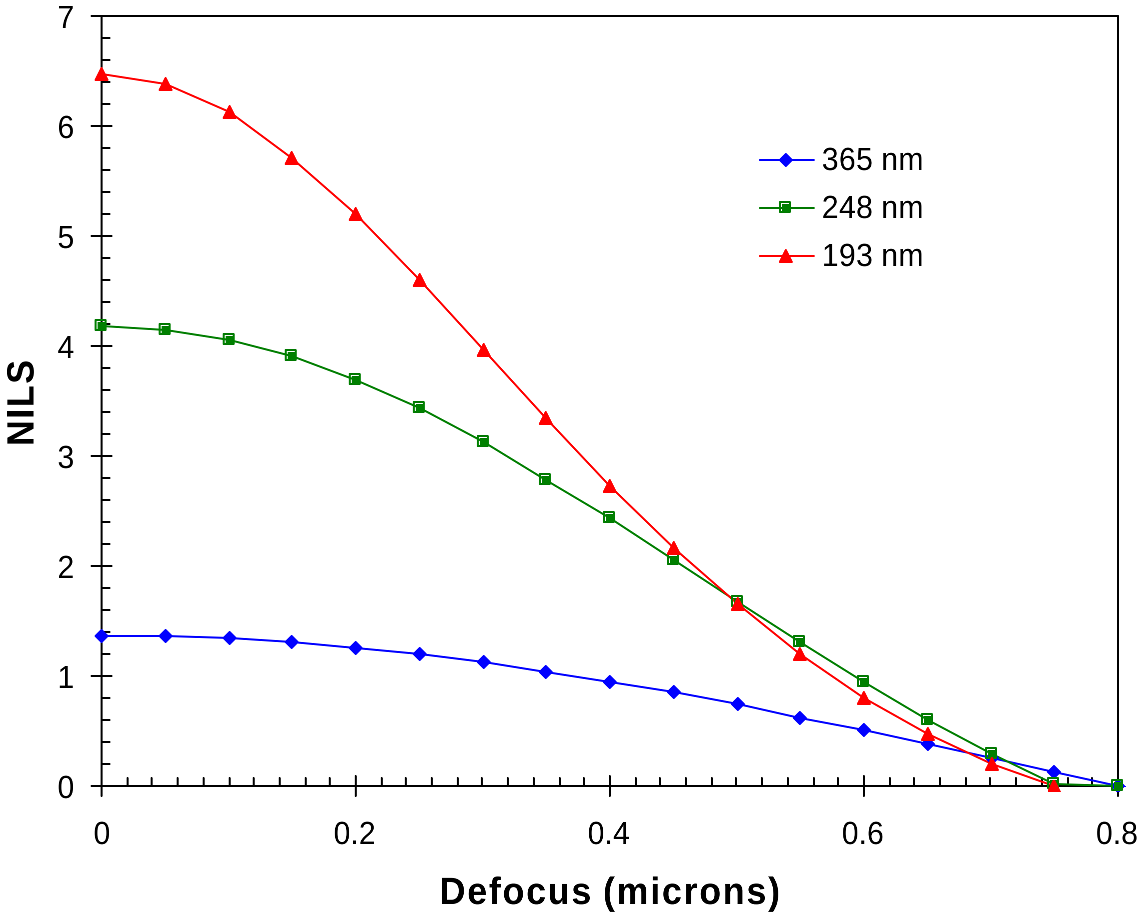
$$\%Exposure\ Latitude \approx 10 * NILS \qquad (2)$$

(the approximation coming from the assumptions that NILS is constant over the ±10% CD range). Thus, in a perfect world (i.e., a perfect photoresist), the impact of NILS can be easily related to a lithographically useful metric: each unit increase in NILS give us 10% more exposure latitude. Unfortunately, the real world is not so perfect and infinite contrast photoresists have yet to enter the commercial market. The real impact of NILS on exposure latitude is somewhat reduced from the above ideal. In general, equation (2) can be modified to account for the non-ideal nature of photoresists as

$$\%Exposure\ Latitude \approx \alpha\,(NILS - \beta\,) \qquad (3)$$

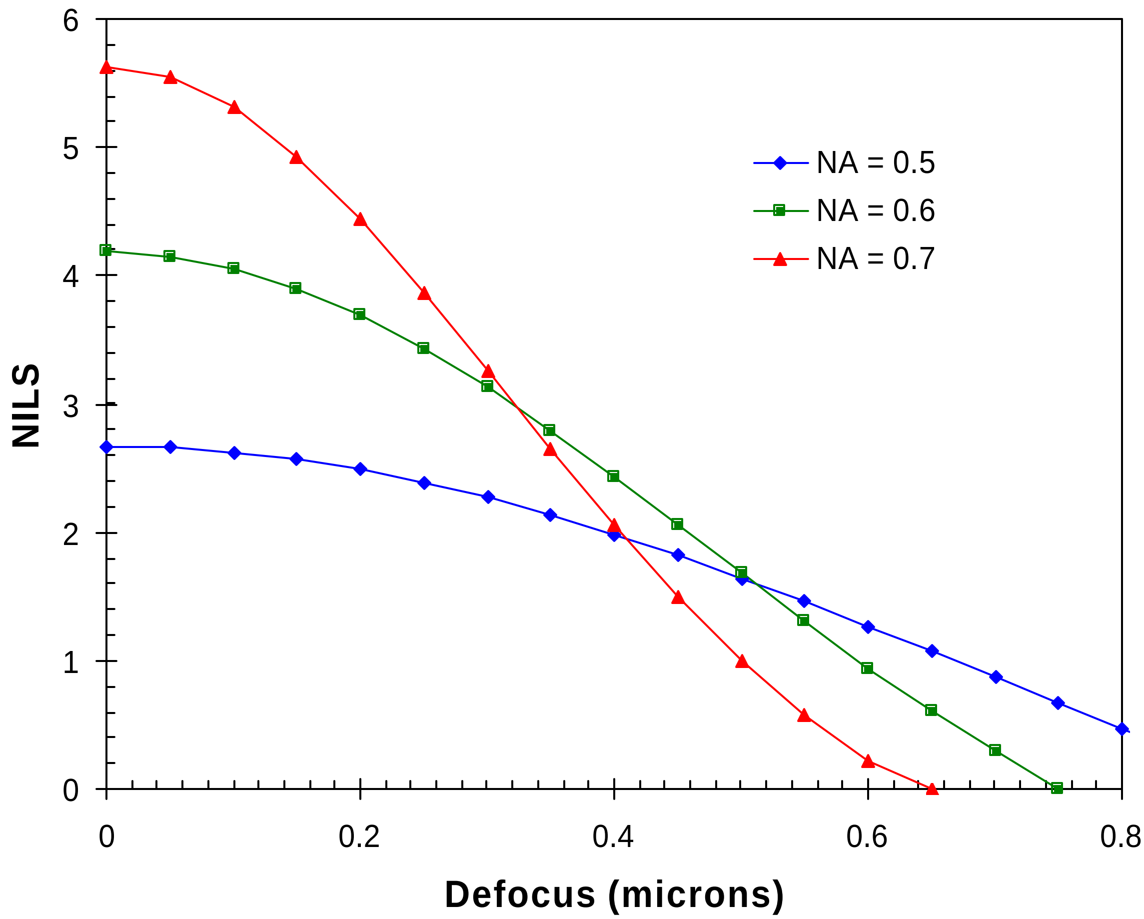
where α and β are empirically determined constants and α has an upper limit of 10 and β has a lower limit of 0. β can be interpreted as the minimum NILS required to get an acceptable image in photoresist to appear. α then is the added exposure latitude for each unit increase in NILS above the lower limit β.

The values of α and β can be determined by comparing a calculated NILS versus defocus curve to experimentally measured exposure latitude versus defocus data. Figure 2 shows a simulation of such an experiment for a very typical case. Once calibrated, a minimum acceptable exposure latitude specification (say, 15%) can be translated directly into a minimum acceptable NILS value (in this case, 2.2). Since α and β are resist and process dependent, the minimum acceptable NILS must be also. And of course, the requirements for the minimum acceptable exposure latitude will impact the required NILS directly. Thus, either using equation (2) for the ideal case, or equation (3) for a calibrated resist case, a quantitative valuation of the importance of NILS can readily be made.



7
6
5
4
3
2
1
0
NILS
0
0.2
0.4
0.6
0.8
Defocus (microns)
365 nm
248 nm
193 nm

(a)



(b)

Figure 1. Using the log-slope defocus curve to study lithography: (a) lower wavelengths give better depth of focus (NA = 0.6, σ = 0.5, 250nm lines and spaces), and (b) there is an optimum NA for maximizing depth of focus (λ = 248nm, σ = 0.5, 250nm lines and spaces).

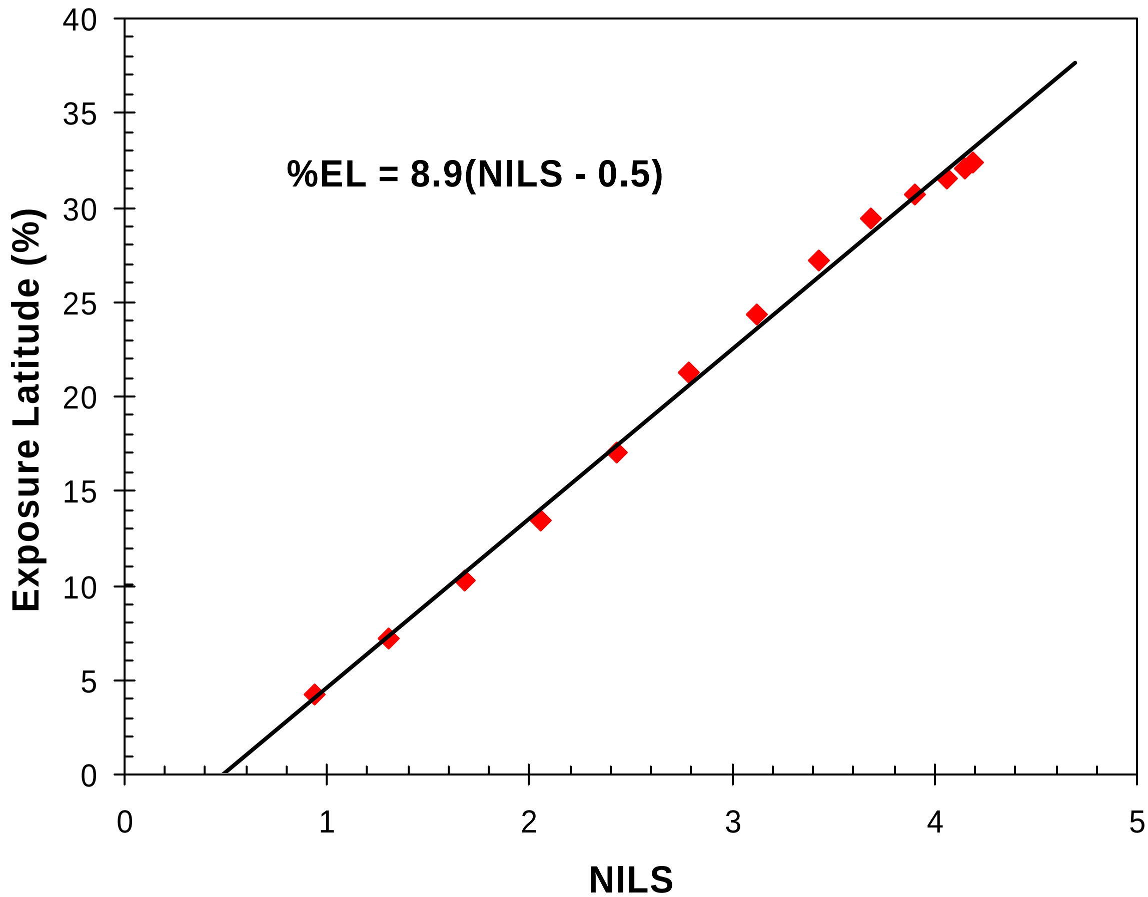


Figure 2. Typical correlation between NILS and simulated exposure latitude data (λ = 248nm, NA = 0.6, σ = 0.5, 500nm of UV6 on ARC on silicon, printing 250nm lines and spaces through focus).