Using the Normalized Image Log-Slope, part 6: Development Path

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This is the final column in the series focused on the use of the Normalized Image Log-Slope (NILS) as a metric of image quality. The NILS is a measure of the information content of the aerial image and represents an energy (intensity) gradient at the position of the nominal line edge. Larger NILS means more information as to the proper position of the feature edge. The information from the aerial image then propagates through exposure and post-exposure bake into a gradient of the latent image. Development translates the latent image gradient into a gradient of dissolution rate with the photoresist contrast, γ, converting the NILS into a normalized dissolution rate gradient. But there is one step missing. How does this variation in development rate across the line edge boundary turn into the final resist profile? How does NILS relate to final critical dimension (CD) control (and in particular, exposure latitude)?

To answer these questions, one must know the *path* of development. The development path traces the surface of the resist through the development cycle from the top of the undeveloped resist to a point on the final resist profile. The basic equation which defines the physical process of development is an integral equation of motion:

$$t_{dev} = \oint \frac{ds}{R(x,y,z)} \tag{1}$$

where t_{dev} is the development time, $R(x,y,z)$ is the development rate at every point in the resist, ds is a differential length along the development path, and the path integral is taken along the development path. The endpoint of the development path defines the position of the final resist profile and, consequently, the final critical dimension. But what is the development path? There is only one path possible, determined by the principle of least action: the path will be that which goes from start to end in the least amount of time.

Given a known development rate image $R(x,y,z)$ there are several mathematical techniques for calculating this minimum time path. Unfortunately, for all but the simplest cases these solutions for the development path must be numerical [1]. For our purposes here (to estimate how the NILS affects CD control), we will develop an approximate solution. Since the path of dissolution is always perpendicular to the resist surface, dissolution paths must always start vertically. And since the final resist profile is usually nearly vertical, the final part of the dissolution path must be nearly horizontal (Figure 1). Thus, to a good approximation the development path can be thought of as segmented in a vertical part followed by a horizontal part. This segmented development, when applied to equation (1) and using a suitable function for the development rate *R(x,y,z)*, provides a solution for determining the final end point of the development path, and thus the final CD.

Let's consider one of the simplest possible development rate functions: constant contrast. Recall from the last edition of this column that the definition of development contrast is

$$\gamma \equiv \left.\frac{\partial \ln R}{\partial \ln E}\right|_{\max} \qquad (2)$$

If γ is a constant (i.e., not a function of exposure energy E), the result is a development rate expression where dissolution rate varies as exposure dose to the γ power (positive resist assumed). Applying this development rate expression to equation (1) and using the segmented development assumption leads to a solution of CD as a function of exposure dose for a given aerial image known as the Lumped Parameter Model (LPM) [2,3]. One result of this model is a direct prediction of exposure latitude, the change in CD for a given change in exposure dose. The result is [3]

$$\frac{\partial \ln CD}{\partial \ln E} = \frac{2}{CD} r(x) \gamma\, t_{dev} = \frac{2\gamma D}{CD}\left[\frac{E(x)I(x)}{E(0)I(0)}\right]^{\gamma} \qquad (3)$$

where D is the resist thickness, $I(x)$ is the aerial image, and $E(x)$ is the dose required to produce a CD of $2x$, and $x = 0$ is assumed to be the center of the space feature (the beginning of the development path). Note that this form of the exposure latitude (the slope of the log-CD versus log-dose curve) can be interpreted as the percent change in CD for a 1% change in exposure dose.

Equation (3) can be further simplified for the case of reasonably high γ (which is certainly true for most modern resists today). For that case, the slope of the CD versus exposure curve can be approximated as

$$\frac{\partial \ln CD}{\partial \ln E} \approx \frac{2}{NILS} + \frac{2\gamma D}{CD}\left[\frac{I(CD/2)}{I(0)}\right]^{\gamma} \qquad (4)$$

There are two distinct terms on the right hand side of this expression. The first, 2/NILS, is a pure aerial image term and is the limiting value of the exposure latitude for the case of an infinite contrast resist (Figure 2). The second term is a "development path factor" that includes the aspect ratio of the resist (*D/CD*) and the ratio of the aerial image intensity at the edge of the pattern relative to that in the center of the space (that is, the exposure dose at the end of the path relative to the exposure dose at the beginning of the path). This development path factor is reduced (giving better CD control) by lowering the aspect ratio of the resist, increasing the resist contrast, and reducing the aerial image intensity at the dark line edge (*i.e.* x = CD/2) relative to the bright space center (x = 0).

Equation (4) finally ties all the pieces of the NILS puzzle together, describing the information transfer from the aerial image through development to the final resist image. It relates the fractional change in CD to the fractional change in exposure dose and thus its inverse defines the exposure latitude. The aerial image affects CD control in two ways, through the NILS directly and through the development path factor. The exposure, PEB and development effects can be lumped together into a photoresist contrast term, or can be separated out into individual components as described in the last several editions of this column.

References

1. C. A. Mack, "Photoresist Process Optimization," *KTI Microelectronics Seminar Interface '87, Proc.*, (1987) pp. 153-167.
2. R. Hershel and C. A. Mack, "Lumped Parameter Model for Optical Lithography," Chapter 2, Lithography for VLSI, VLSI Electronics - Microstructure Science Volume 16, R. K. Watts and N. G. Einspruch, eds., Academic Press (New York:1987) pp. 19-55.
3. C. A. Mack, Inside PROLITH: A Comprehensive Guide to Optical Lithography Simulation, FINLE Technologies (Austin, TX: 1997).

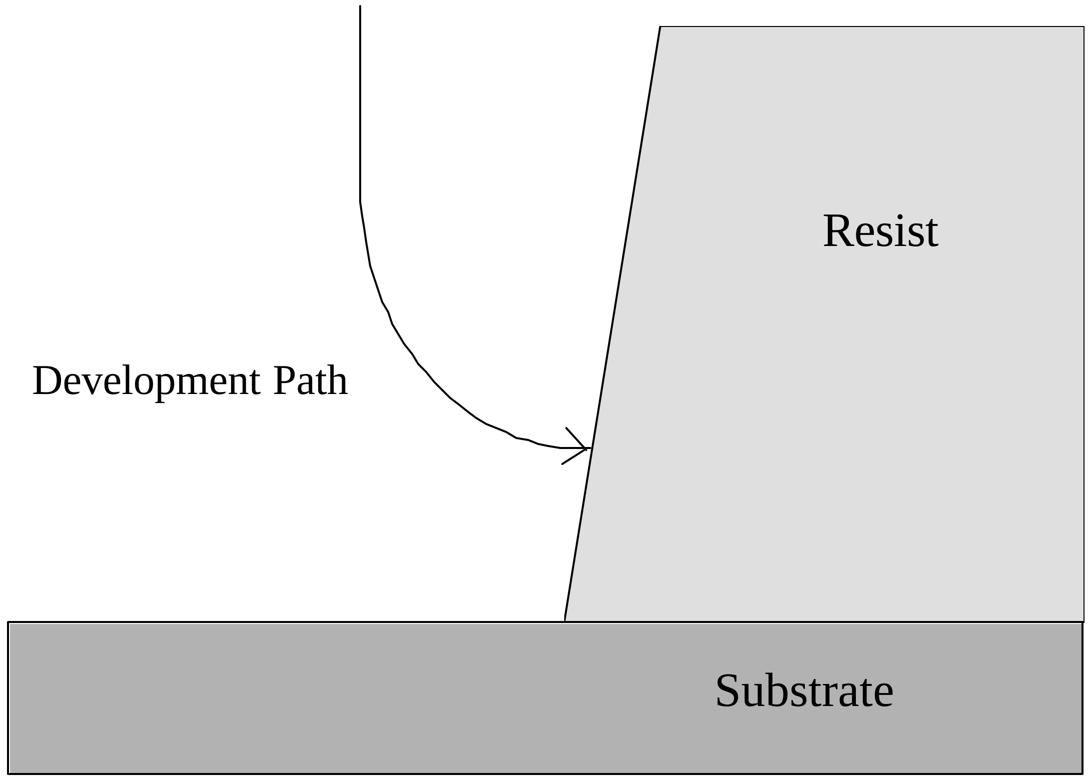

Figure 1. Typical development path starts out vertically, but ends up nearly horizontal by the end of the development cycle.

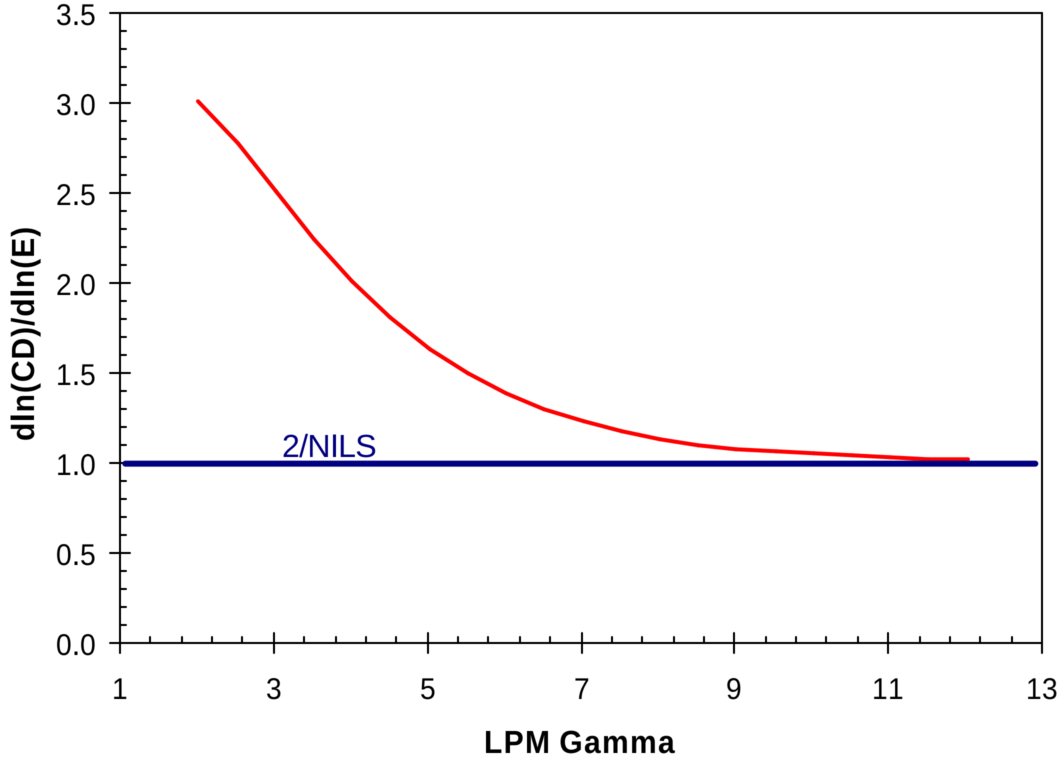

Figure 2. A plot of equation (4) showing how the exposure latitude term approaches its limiting value of 2/NILS as the lumped photoresist contrast increases. In this case, the resist aspect ratio is 2, the ratio I(CD/2)/I(0) is 0.5 and the NILS is 2.