The Lithography Expert *(February 2002)*

Using the Normalized Image Log-Slope, part 5: Development

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This recent series of *Lithography Expert* columns has focused on the use of the Normalized Image Log-Slope (NILS) as a metric of image quality and on the propagation of the aerial image into a latent image after exposure and post-exposure bake. Now we will look at how the latent image causes a change in development rate which eventually leads to the formation of a photoresist profile.

In one sense, the goal of selective exposure of resist with an aerial image is to create a solubility differential: exposed and unexposed regions of the photoresist give rise to regions of higher and lower solubility, measured as a development rate (resist removal rate in nanometers per second). The information contained in the aerial image $I(x)$ is used to the expose the photoresist to form a latent image $m(x)$, which is modified by the post-exposure bake to create a new latent image $m^*(x)$, and finally developed based on a development rate "image" $R(x)$ that results in the definition of the feature edge. (A one-dimension example is used here for simplicity.)

The fundamental chemical response of interest is the change in dissolution rate as a function of the exposure dose seen by the resist. A plot of development rate R versus exposure dose E on a log-log scale is called a Hurter-Driffield (H-D) curve (see this column, Autumn 1994) and allows for the definition of the *photoresist contrast, g*. Quite simply, the photoresist contrast is the maximum slope of the development rate H-D curve [1].

$$g \equiv \left.\frac{\partial \ln R}{\partial \ln E}\right|_{\max} \tag{1}$$

To be a bit more general, a photoresist contrast function $g\,(E)$ can be defined as the slope of the H-D curve at any point.

The photoresist contrast is a measure of the discrimination of the resist with respect to exposure. Higher contrast means that a given change in dose will result in a greater change in development rate. This point can be seen clearly using the *lithographic imaging equation*, derived from the definition of photoresist contrast:

$$\frac{\partial \ln R}{\partial x} = g\,(E)\,\frac{\partial \ln I}{\partial x} \tag{2}$$

The quality of the development rate image, described by a gradient in the dissolution rate, is determined by the product of the image log-slope and the photoresist contrast function. To create a large solubility differential, one would like a good aerial image (large image log-slope), a good photoresist (large photoresist contrast), and an optimized process (an exposure dose chosen to use the maximum of the photoresist contrast function).

Braking up the response of development to exposure into separate latent and development rate images allows us to relate the development rate gradient to the latent image gradient as derived in the last two editions of this column:

$$\frac{\partial \ln R}{\partial x} = \frac{\partial \ln R}{\partial m^*}\frac{\partial m^*}{\partial x} \tag{3}$$

where m^* is the concentration of the chemical species (after post-exposure bake) that affects the dissolution rate. For example, for a chemically amplified resist m^* would represent the concentration of blocked polymer. From equations (2) and (3) one can see that the definition of photoresist contrast encompasses the exposure, post-exposure bake and development steps in order to relate the final development rate gradient to the original source of the information being imprinted in the resist, the image log-slope.

The variation of development rate with m^* can take on many forms [2], but a simple one can be used here to illustrate the expected response. The model of development shown here provides for a typical non-linear development rate function:

$$R = R_{\max}\,(1 - m^*)^n + R_{\min} \tag{4}$$

where R_{max} and R_{min} represent the maximum and minimum development rates, respectively ($R_{max} >> R_{min}$ is assumed), and n is called the dissolution selectivity parameter and controls how non-linear the development response will be. Using this model of dissolution rate,

$$\frac{\partial \ln R}{\partial m^*} = -\frac{n}{1 - m^*}\left(1 - \frac{R_{\min}}{R}\right) \tag{5}$$

Figure 1 shows a plot of equation (5) as a function of m^* for n = 5 (a low to medium contrast resist) and n = 10 (a medium to high contrast resist). Adjusting the process to set the peak of this curve at the nominal feature edge is a key part of process optimization.

While equation (3) related the development rate gradient to the after PEB latent image gradient, in fact all of the lithographic process steps can be chained together to relate the final development response to the initial source of the imaging information, the aerial image.

$$g\,(E,a) = \left(\frac{\P \ln R}{\P m^*}\right)\left(\frac{\P m^*}{\P m}\right)\left(\frac{\P m}{\P \ln E}\right) \qquad (6)$$

For a chemically amplified resist, the PEB term $\P m^*/\P m$ is a function of the amplification factor α, as described in the previous *Lithography Expert*. Figure 2 shows a plot of $g\,(E,a)$ for the $n = 5$ case.

We have now arrived at the final “image” gradient, the gradient in development rate. As we shall see in the next edition of this column, the last step will be to relate this gradient to the control of the resist feature edge by knowing the development path.

References

1. C. A. Mack, “Lithographic Optimization Using Photoresist Contrast,” *KTI Microlithography Seminar, Proc.*, (1990) pp. 1-12, and *Microelectronics Manufacturing Technology*, Vol. 14, No. 1 (Jan. 1991) pp. 36-42.

2. C. A. Mack, Inside PROLITH: A Comprehensive Guide to Optical Lithography Simulation, FINLE Technologies (Austin, TX: 1997).

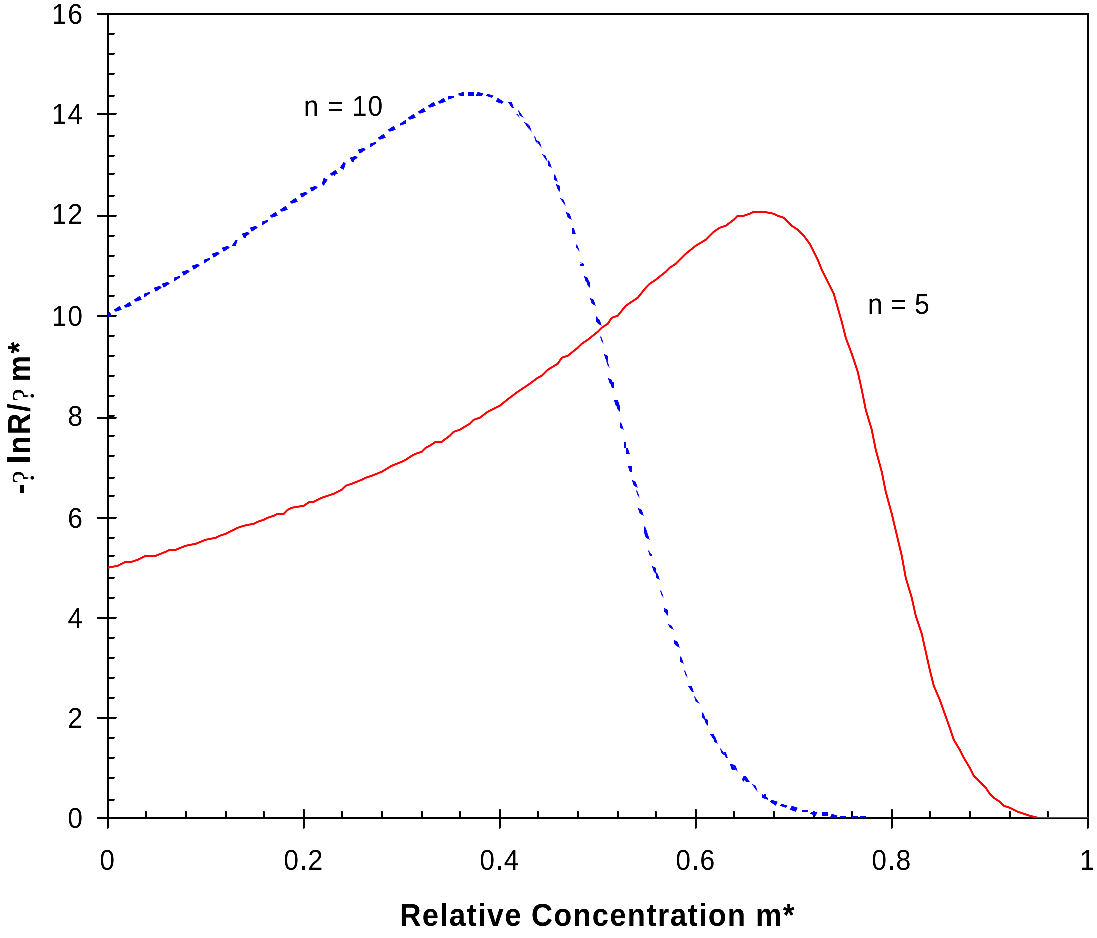

Figure 1. One component of the overall photoresist contrast is the variation in development rate *R* with chemical species *m**.

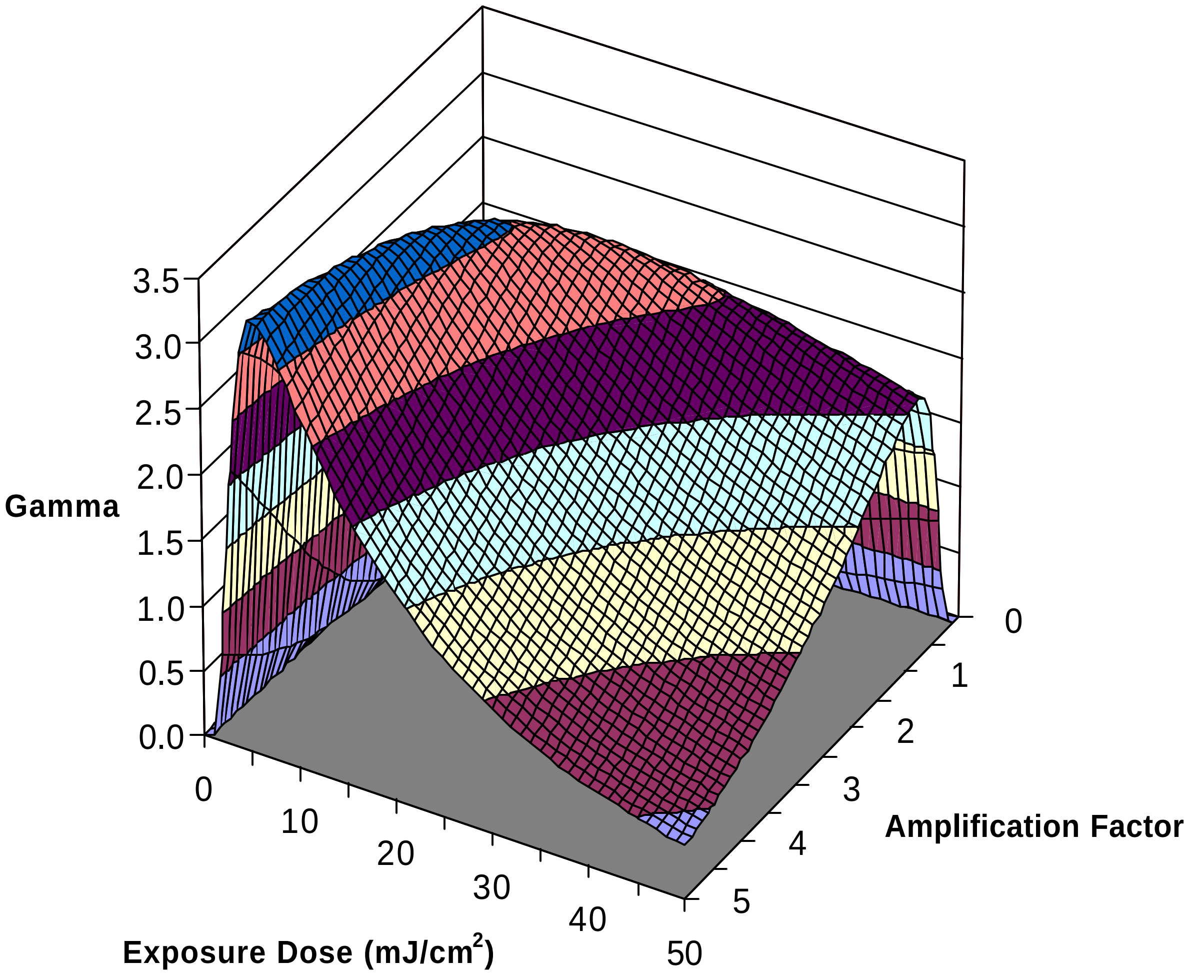

Figure 2. The overall photoresist contrast (gamma) as a function of exposure dose and amplification factor for a chemically amplified resist.