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The Lithography Expert *(August 2007)*

Line Edge Roughness, part 3

In the last two editions of this column [1,2], a *stochastic modeling* approach to the fundamental mechanisms behind the formation of line edge roughness (LER) was given. The model begins with photon shot noise, which follows Poisson statistics, then looks at the initial distribution of photoacid generator (PAG) in the resist, which also follows Poisson statistics. The exposure reaction itself is probabilistic, with the probability that any particular PAG will be exposed given by the solution to the continuum kinetic equation of exposure. Reaction-diffusion of chemically amplified resists is reasonably complicated, but still amenable to this type of treatment. The time-averaged concentration of acid controls the amount of deprotection (deblocking) at any location, and it is the ratio of the diffusion length of the acid to the capture range of the deprotection reaction that determines how much statistical smoothing this time-averaging will cause.

As a review, for a given volume of resist under consideration, the statistical variance in the final blocked polymer concentration is given by

$$\sigma_m^2 = \frac{\langle m \rangle}{\langle n_{0-blocked} \rangle} + \left(\langle m \rangle \ln \langle m \rangle\right)^2 \left(\frac{a}{\sigma_D}\right)^p \left(\frac{1}{\langle n_{0-PAG} \rangle \langle h \rangle} + \frac{\left[\left(1-\langle h \rangle\right)\ln\left(1-\langle h \rangle\right)\right]^2}{\langle h \rangle^2 \langle n \rangle}\right) \qquad (1)$$

where $\langle h \rangle$ is the mean value of the acid concentration, $\langle m \rangle$ is the mean value of the blocked polymer concentration after PEB, σ_D/a is the ratio of acid diffusion length to the capture range of the deblocking reaction, p is the dimensionality of the problem, $\langle n \rangle$ is the mean number of photons (to account for photon shot noise), $\langle n_{0-PAG} \rangle$ is the mean initial number of PAGs in the control volume at the start of exposure, and $\langle n_{0-blocked} \rangle$ is the mean initial number of blocked polymer groups in the volume before PEB. For 193 nm lithography, photon shot noise tends to be a small component of the total uncertainty and can usually be ignored. For EUV, this may not always be the case.

While development can also be included, for the sake of simplicity we will assume an infinite contrast development process so that the line edge will be determined by the blocked polymer latent image. Thus, a simple threshold model for the latent image will determine the resist critical dimension. A Taylor series expansion of the blocked polymer concentration, cut off after the linear term, allows us to predict how a small change in blocked polymer concentration (Δm) will result in a change in edge position (Δx):

$$\Delta x = \frac{\Delta m}{dm/dx} \qquad (2)$$

From this, we can devise a simple qualitative model for line edge roughness. The standard measure of line edge roughness, from a top-down SEM, will be proportional to the standard deviation of blocked polymer concentration divided by its gradient perpendicular to the line edge:

$$LER \propto \frac{\sigma_m}{dm/dx} \tag{3}$$

To achieve a low LER it will necessary to make the standard deviation of the deprotection small and make the gradient of deprotection large. There is one interesting variable in common to both: acid diffusion. Increasing acid diffusion will reduce σ_m, but will reduce the latent image gradient as well. One would expect, then, an optimum level of diffusion to minimize the LER. In a previous edition of this column [3], the impact of acid diffusion on the deprotection gradient for chemically amplified resists was given:

$$\frac{dm}{dx} \propto \frac{1}{\sigma_D{}^2}\left(1 - e^{-\pi^2 \sigma_D{}^2 / 2L^2}\right) \tag{4}$$

where L is the width of the line-edge region (equal to half the pitch for a small pitch pattern, or about equal to the feature size for a small isolated pattern).

To investigate the impact of diffusion on LER, we can combine equations (1) and (4) into (3). Thus, ignoring photon shot noise,

$$LER \propto \frac{\sigma_D{}^2}{1 - e^{-\pi^2 \sigma_D{}^2 / 2L^2}} \sqrt{\frac{\langle m \rangle}{\langle n_{0-blocked} \rangle} + \left(\langle m \rangle \ln\langle m \rangle\right)^2 \left(\frac{a}{\sigma_D}\right)^p \left(\frac{1}{\langle n_{0-PAG} \rangle \langle h \rangle}\right)} \tag{5}$$

To evaluate this expression, consider some typical values. Let $\langle n_{0-blocked} \rangle / \langle n_{0-PAG} \rangle$ = 28.7, $\langle h \rangle$ = 0.3, $\langle m \rangle$ = 0.6. For these conditions, the LER becomes proportional to

$$LER \propto \frac{\sigma_D{}^2}{1 - e^{-\pi^2 \sigma_D{}^2 / 2L^2}} \sqrt{1 + 15\left(\frac{a}{\sigma_D}\right)^p} \tag{6}$$

Figure 1 shows the trend of LER versus acid diffusion for a 45 nm feature for three different values of the deprotection capture range a: 1, 2 and 3 nm. In each case, there is a diffusion length that minimizes the LER. Below the optimum diffusion length, LER is limited by σ_m so that increasing the diffusion will improve LER. Above the optimum diffusion length the LER is gradient limited, so that increases in diffusion further degrade the gradient and worsen the LER. The optimum diffusion length is constrained by the feature size at one end and the deblocking reaction capture range at the other:

$$a << \sigma_D << L \tag{7}$$

As *L* decreases, there becomes less room for the diffusion length to fit within these constraints.

Unless, of course, *a* is allowed to decrease as well. This capture range for the deblocking reaction is not an easy parameter for the resist chemist to manipulate, but it can be adjusted. There is a consequence, however. The rate of the deblocking reaction is a strong function of this capture range. In fact, assuming that the amplification reaction is in the diffusion-limited regime, the amount of amplification will be controlled by the amplification factor α_f:

$$\alpha_f = K_{amp} t_{PEB} = 2\pi\sigma_D^2 a G_0 N_A \tag{8}$$

where K_{amp} is the amplification rate constant, t_{PEB} is the PEB time, G_0 is the initial concentration of photoacid generator, and N_A is Avogadro's number. To keep line edge roughness small for smaller features, both the diffusion length and the reaction capture range should be lowered in proportion to *L*. But this means that the amplification factor will decrease as L^3. Lower amplification factor will require increased exposure dose to cause the same amount of amplification, meaning that dose would have to rise dramatically to keep LER low in the presence of shrinking feature sizes. There is one other term, however, that can slow this unfortunate scaling relationship. By increasing the PAG loading G_0, the amplification factor can be kept higher while diffusion and capture range are decreased. There are very real, practical limits to PAG loading, however, and it is doubtful that this lever will provide much long-term relief. It seems that the fundamental stochastic nature of resist chemistry creates a need for much higher exposure dose to keep small features from being dominated by LER.

References

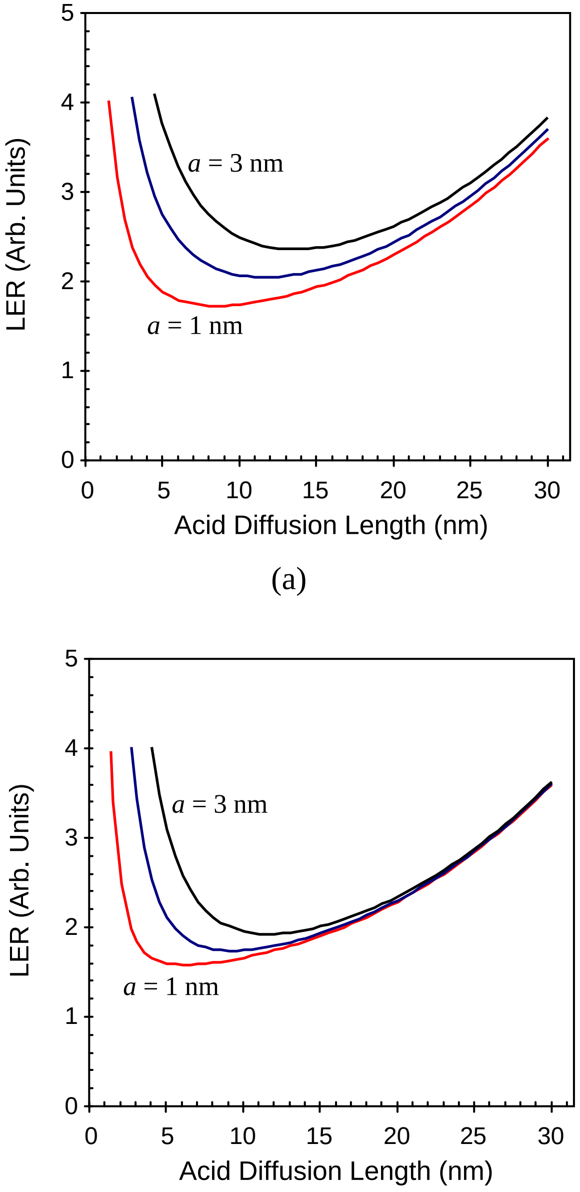
1. C. A. Mack, The Lithography Expert: Line Edge Roughness, Part 1, Microlithography World 16.1, p. 13 (Feb. 2007) or http://sst.pennnet.com/display_article/284620/28/ARTCL/none/none/The-Lithography-Expert:-Line-edge-roughness,-Part-1/

2. C. A. Mack, The Lithography Expert: Line Edge Roughness, Part 2, Microlithography World 16.2, p. ?? (May 2007) or http://sst.pennnet.com/?????

3. C. A. Mack, The Lithography Expert: Diffusion and Resolution for Chemically Amplified Resists, Microlithography World 15.3, p. ?? (August 2006).

Figure Captions

Figure 1 Prediction of LER trends for a 45 nm feature using the generic conditions found in equation (6) and using three values of the deblocking reaction capture range *a* (1, 2, and 3 nm): a) assuming a 2-dimensional problem, and b) for a 3-dimensional problem.



(a)

(b)

Figure 1 Prediction of LER trends for a 45 nm feature using the generic conditions found in equation (6) and using three values of the deblocking reaction capture range a (1, 2, and 3 nm): a) assuming a 2-dimensional problem, and b) for a 3-dimensional problem.