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Chris A. Mack

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Fractilia, LLC, 1605 Watchhill Rd, Austin, TX 78703

Abstract

Background: The stochastic nature of extreme ultraviolet (EUV) lithography produces many undesirable effects such as line-edge roughness and local critical dimension variations. These stochastic problems are worse when trying to manufacture at high throughput and high resolution.
Aim: There is a need for greater understanding of the sources of stochastic variability in EUV lithography, and whether photon shot noise or photoresist variabilities dominate.
Approach: From first-principle arguments, the basic scaling relationships of roughness versus dose, image quality, and resist properties can be derived that account for most of the important affects that control stochastic outcomes.
Results: From these derivations, it is shown that acid yield controls the relative importance of resist versus photon shot noise, with acid yield equal to 1 producing equal contributions of acid shot noise and photon shot noise. Quencher adds uncertainty to the amount of acid generated, but the increase in final latent image gradient can make up for this increase in noise with less loss in signal.
Conclusions: Although a full model of line-edge roughness is not complete (with much more work yet to be done), the results to date provide a roadmap for resist design, though without a silver bullet for roughness improvement.

Keywords: Stochastic modeling, EUV photoresist, exposure kinetics, line-edge roughness, linewidth roughness, LER, LWR, quencher

I. INTRODUCTION

Stochastic effects in lithography, such as line-edge roughness (LER), linewidth roughness (LWR), local critical dimension uniformity (LCDU), local edge placement error (LEPE), and stochastic defects, have been a serious concern in extreme ultraviolet (EUV) lithography for many years. There is worry that attempts to scale feature sizes smaller while implementing EUV in manufacturing will lead to unacceptable yield loss due to stochastic effects. Thus, there is considerable interest in understanding how these stochastic effects scale with lithographic parameters such as feature size, exposure dose, image-log slope (ILS), and various resist parameters. One question of particular interest, and generating considerable debate, is the relative role of photon shot noise (exposure dose) versus resist contributions to stochastic variability.

The scaling of LWR or LCDU due to photon shot noise is well known: stochastic effects (as described by a standard deviation) should be proportional to one over the square root of exposure dose. Generally, any experimental measurement of LWR or LCDU that varies in this way with dose is thought of as evidence that EUV lithography is shot-noise limited. (As will be shown below, this is not necessarily the case.) Early seminal work on the impact of photoresist by Gallatin showed an additional scaling relationship: LWR should be proportional to one over the feature size to the 3/2 power.[1] The reason for this scaling will be described below.

This paper aims to build on previous stochastic modeling work to develop a limited, but still useful, model for LWR and/or LCDU in lithography.[2] One important goal is to provide a reasonable

answer to the question of what limits stochastics in EUV lithography: photon shot noise, or the resist? The answer, as we shall see, is most likely both.

II. A BASIC MODEL FOR LWR OR LCDU

One way to think of LER is to consider how that roughness comes about in the final photoresist processing step of development. This basic model for roughness has been proposed many times before: an error in the final resist edge position (x) is the result of an error in the development rate R, and is equal to that error at the edge of the resist divided by the gradient in development rate.[1,3]

$$\Delta x = \frac{\Delta R}{dR/dx} \tag{1}$$

For a random variation in development rate characterized by a mean and standard deviation, the resulting edge position will have a variation described by the 1-sigma LER (σ_{LER}):

$$\sigma_{LER} = \frac{\sigma_R}{dR/dx} \tag{2}$$

In this simple model, variation in the development path is ignored, which might be reasonable for small variations in development rate.[4-7]

Following a previous exposition,[8] development rate is determined by the relative level of remaining protecting groups (m) for a chemically amplified resist. This, in turn, is determined by the relative acid concentration (h) during a process of reaction-diffusion (which may also include the impact of quencher). Acid concentration is determined by the intensity of absorbed light (I_{abs}). In other words, an aerial image leads to an absorbed light image that leads to an acid latent image that leads to a protecting group latent image that leads to a development rate latent image. In a standard top-down lithography process the only source of information about the desired position of the resist feature edge comes from the aerial image. Thus, at each step in this sequence, errors can increase the uncertainty (noise) and decrease the gradient (signal), making their ratio higher.[9,10] This can be expressed as a propagation of noise/signal ratios:

$$\sigma_{LER} = \frac{\sigma_R}{dR/dx} \geq \frac{\sigma_m}{dm/dx} \geq \frac{\sigma_h}{dh/dx} \geq \frac{\sigma_{I_{abs}}}{dI_{abs}/dx} \tag{3}$$

Ideally, our models would be able to predict σ_R, the variation in development rate, and dR/dx, the gradient in development rate at the line edge, from fundamental parameters. Unfortunately, our stochastic models are not yet that good. Another approach is to start at the far right of equation (3) and try to move to the left with models of absorption, then acid generation, then reaction-diffusion, etc., as far as our understanding will allow. That will be the approach taken here.

The uncertainty σ_h in acid generated (or, in fact, the product of any first-order exposure reaction) has been previously derived for EUV photoresists.[2] The assumed mechanism is that an absorbed photon generates, with yield Y_e, a photoelectron which then cascades to form some number of secondary electrons. These secondaries travel some mean distance d_e, releasing energy with the potential to excite a photoacid generator (PAG) to generate an acid. Let $\langle h \rangle$ be the mean acid concentration relative to the initial mean PAG concentration. Thus $\langle h \rangle = 1$ means that every PAG has been converted into an acid. If $\langle n_{0-PAG} \rangle$ is the mean number of PAGs found in the unexposed resist film within a small volume V, then[2]

$$(\sigma_h)^2 = \frac{[(1 - \langle h \rangle)\, ln(1 - \langle h \rangle)]^2}{\langle n_{photoelectrons} \rangle} + \frac{\langle h \rangle}{\langle n_{0-PAG} \rangle}$$

$$\langle n_{photoelectrons} \rangle = Y_e \langle n_{photons} \rangle (1 - e^{-\alpha D})$$

$$\langle h \rangle = 1 - e^{-C \langle E \rangle} \tag{4}$$

where $\langle n_{photoelectrons} \rangle$ is the mean number of photoelectrons generated in the volume, $\langle n_{photons} \rangle$ is the mean number of photons incident on a surface of area A during an exposure of dose $\langle E \rangle$, and D is the vertical depth of the volume such that $V = AD$. The exposure rate constant C is given by

$$\frac{C}{\alpha} = Y_e \varphi_{PAG} d_e \sigma_{e-PAG} = \varphi_{e-PAG} V_{e-PAG} \tag{5}$$

where α is the resist absorption coefficient. The product of the photoelectron generation efficiency (Y_e) and the PAG quantum efficiency (ϕ_{PAG}) will be called the electron-PAG quantum efficiency (ϕ_{e-PAG}), and the product of the secondary electron mean-free path (d_e) and the electron-PAG reaction cross-section (σ_{e-PAG}) will be called the electron-PAG interaction volume (V_{e-PAG}). Thus, C/α can be thought of as the effective interaction volume of the secondary electrons with the PAGs (thus describing the secondary electron blur).

The gradient of exposure-generated acid, dh/dx, has also been previously derived as a function of the image log-slope (ILS).[3]

$$\frac{d\langle h \rangle}{dx} = (1 - \langle h \rangle) ln(1 - \langle h \rangle) \frac{dlnI}{dx} = (1 - \langle h \rangle) ln(1 - \langle h \rangle) ILS \tag{6}$$

Combining equations (4) and (6) gives

$$\left(\frac{\sigma_h}{d\langle h \rangle/dx} \right)^2 = \left(\frac{1}{ILS^2} \right) \left(\frac{1}{\langle n_{photoelectrons} \rangle} + \frac{\langle h \rangle}{\langle n_{0-PAG} \rangle [(1 - \langle h \rangle)\, ln(1 - \langle h \rangle)]^2} \right) \tag{7}$$

For $\alpha D \ll 1$ (a very likely scenario), the mean number of photons can be related to the mean incident dose $\langle E \rangle$ over a given area A,

$$\langle n_{photoelectrons} \rangle \approx Y_e \langle n_{photons} \rangle \alpha D = Y_e \alpha \langle E \rangle V \tag{8}$$

Here, the mean exposure dose $\langle E \rangle$ has units of photon flux, #photons/nm^2. It is reasonable to assume the photoelectron generation efficiency is very close to 1, but will be kept in the equations that follow for completeness. Using this same ambit volume, the mean initial number of PAGs $\langle n_{0-PAG} \rangle$ can be related to the initial PAG density ρ_{PAG} as

$$\langle n_{0-PAG} \rangle = \rho_{PAG} V \tag{9}$$

The acid yield (Y_{acid}) can be defined as the mean number of acids generated per mean number of absorbed photons.

$$Y_{acid} = \frac{\langle h \rangle \langle n_{0-PAG} \rangle}{\langle n_{photons} \rangle \alpha D} = \frac{\langle h \rangle \rho_{PAG} V}{\alpha \langle E \rangle V} = \frac{(1 - e^{-C \langle E \rangle}) \rho_{PAG}}{\alpha \langle E \rangle} \tag{10}$$

Obviously, acid yield changes with dose. In the limit of low dose, acid yield approaches a constant, the initial acid yield:

$$Y_{0-acid} = \frac{\rho_{PAG} C}{\alpha} \tag{11}$$

Thus, the acid yield, which decreases with dose due to the depletion of PAG, can be expressed as

$$Y_{acid} = Y_{0-acid} \frac{\langle h \rangle}{C \langle E \rangle} = Y_{0-acid} \frac{\langle h \rangle}{-ln(1 - \langle h \rangle)} \tag{12}$$

Now equation (7) can be expressed in terms of yields.

$$\left(\frac{\sigma_h}{d\langle h \rangle / dx}\right)^2 = \left(\frac{1}{ILS^2}\right) \left(\frac{1}{\alpha \langle E \rangle V}\right) \left(\frac{1}{Y_e} + \frac{1}{Y_{acid}} \left[\frac{\langle h \rangle}{(1 - \langle h \rangle) \, ln(1 - \langle h \rangle)}\right]^2\right) \tag{13}$$

This expression can be simplified by noting that

$$Y_{acid} \left[\frac{(1 - \langle h \rangle) \, ln(1 - \langle h \rangle)}{\langle h \rangle}\right]^2 \approx Y_{acid}(1 - \langle h \rangle) \approx Y_{0-acid}(1 - \langle h \rangle)^{3/2} \tag{14}$$

giving

$$\left(\frac{\sigma_h}{d\langle h \rangle / dx}\right)^2 \approx \left(\frac{1}{ILS^2}\right) \left(\frac{1}{\alpha \langle E \rangle V}\right) \left(\frac{1}{Y_e} + \frac{1}{Y_{0-acid}(1 - \langle h \rangle)^{3/2}}\right) \tag{15}$$

The addition of acid generation uncertainty to absorbed photon uncertainty is made clearer by noting that

$$\left(\frac{\sigma_{I_{abs}}}{dI_{abs}/dx}\right)^2 = \left(\frac{1}{ILS^2}\right) \left(\frac{1}{\alpha \langle E \rangle V}\right) \tag{16}$$

so that

$$\frac{\sigma_h}{d\langle h \rangle / dx} \approx \frac{\sigma_{I_{abs}}}{dI_{abs}/dx} \sqrt{\frac{1}{Y_e} + \frac{1}{Y_{0-acid}(1 - \langle h \rangle)^{3/2}}} \tag{17}$$

For the wide range of EUV resists in use today, typical values of C/α are between 5 and 30 nm^3 (the absorption coefficient is typically between 0.006 and 0.015 nm^{-1}). Typical values of ρ_{PAG} are between 0.05 and 0.1 nm^{-3}. Thus, the initial acid yield is typically in the range of 0.3 to 3. Thanks to the cascade of secondary electrons, acid yields greater than 1 are possible and have been the focus of much resist research and development.[11,12] It is likely that all commercially viable EUV resists in use today have an initial acid yield greater than 1. Note that $\langle E \rangle$ and $\langle h \rangle$ are the dose and relative acid concentration at the line edge, and typical lithography processes have $\langle h \rangle$ between 0.1 and 0.3. Thus, the photoresist contribution term $Y_{acid}(1 - \langle h \rangle)$ would typically be between 0.2 and 2. A value of this term of about 1 means that the acid shot noise would add equally to photon shot noise, doubling the LER variance compared to the case of only photon shot noise. A value of 2 (probably the best that current resists are capable of) means that photon shot noise contributes twice as much to roughness as acid shot noise.

Equation (15) describes the scaling of LER (and also LCDU) with dose, at least at this simple level of explanation. At low dose (such that $(1 - \langle h \rangle)^{3/2}$ is near 1), LER will vary as $1/\sqrt{dose}$ regardless of whether the stochastics are dominated by photon shot noise or by resist acid shot noise. At higher dose, the resist term $(1/Y_{0-acid}(1 - \langle h \rangle)^{3/2})$ in equation (15) will grow larger (when $\langle h \rangle = 0.4$ the resist term about doubles in size as compared to $\langle h \rangle \sim 0$), so that the dose dependence changes. At a high enough dose, increasing dose may even make the LWR worse rather than better (Figure 1), though changes in ILS with dose (through changing linewidth) would have to be considered as well.
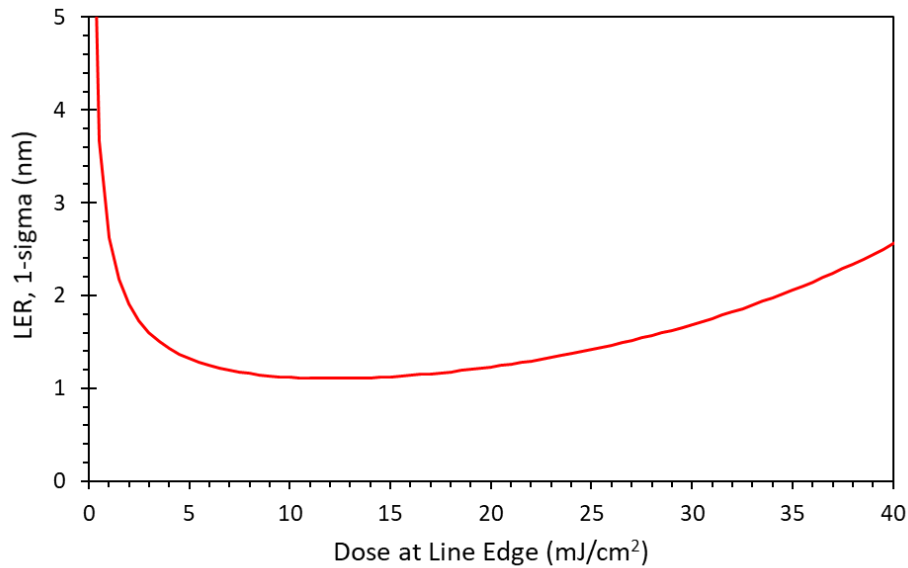

Fig. 1. A plot of the square root of equation (13) for $ILS = 0.15$ nm^{-1}, $\alpha = 0.01$ nm^{-1}, $C/\alpha = 10$ nm^3, $\rho_{PAG} = 0.1$ nm^{-3}, $Y_{0-acid} = 1$, $Y_e = 1$, and $V = 2000$ nm^3. Since ILS is constant in these calculations, the line edge position (that is, the linewidth) is assumed to be constant.

To make equation (15) quantitatively predictive of LER, a value for the ambit volume V must be assigned. However, there is no rigorous way to determine V *a priori*. One suggestion has been to use the correlation length (essentially the resist blur) cubed as the volume,[8] but this is at best correct to within an unknown constant. Another approach would be to calibrate the model of equation (15) using experimental data, a topic that will be discussed later in this paper. The term V also relates to Gallatin's scaling relationship with feature size. Shrinking feature size over time must be accompanied by a proportional shrink in resist blur, which means V will shrink in proportion to feature size cubed.

An assumption of the above derivations is that the secondary electron blur is sufficiently small compared to the feature size so that the acid gradient as given by equation (6) is not affected by this blur. One way to grow the initial acid yield is to increase C by increasing the range of secondary electrons (d_e in equation (5)). But the improvement in LER that results will have diminishing returns when the secondary electron blur begins to have an appreciable impact on the resulting acid latent image gradient. This would occur if the range of secondary electrons reaches an appreciable fraction of the feature size.

It is important to note that the above discussion applies to any EUV resist with first order exposure kinetics based on indirect photolysis, and thus the model in equations (15) or (17) can apply to both non-chemically amplified and chemically amplified resists.

III. THE IMPACT OF QUENCHER

Quencher, a base added to the resist formulation, is a key component of modern chemically amplified resists, controlling the diffusion of acid and increasing the latent image gradient after PEB compared to the case of no quencher. The use of quencher also increases the required dose, since a certain amount of dose is needed to overcome the quencher before any acid is available for polymer deprotection. The impact of quencher on LER, however, is not well understood. Is it possible, for example, to optimize the quencher concentration for minimum LER at a specified dose? And does that optimum depend strongly on the dose chosen? (Photodecomposable bases will not be considered in this paper.)

A stochastic description of acid-base quenching (known in the literature as $A + B \rightarrow 0$) is well known to be a very difficult problem.[13] Here, some simplifying assumptions will make the problem tractable, but at the cost of an accurate description of the phenomena. Consider the region near the line edge such that the amount of acid generated by exposure equals or exceeds the initial amount of quencher in the film, on average. If q_0 is the initial quencher concentration relative to the initial PAG concentration, then after acid-base neutralization the remaining acid, h^*, can be easily determined if diffusion of acid and base is ignored or assumed to be contained within the ambit volume V:

$$h^* = h - q_0 \tag{18}$$

Neglecting diffusion is a risky assumption, but possibly acceptable if only the first-order impact of quencher on roughness is desired.

The variance in the after-quench acid concentration will be

$$\sigma_{h^*}^2 = \sigma_h^2 + \sigma_q^2 \tag{19}$$

Since q_0 is a concentration relative to the initial PAG concentration, we have

$$\sigma_q^2 = \frac{\langle q_0 \rangle}{\langle n_{0-PAG} \rangle} \tag{20}$$

and this term can be simply added to the top equation (4). This will modify our result from equation (17) to be

$$\left(\frac{\sigma_{h^*}}{d\langle h^* \rangle/dx}\right)^2 \approx \left(\frac{1}{ILS^2}\right)\left(\frac{1}{\alpha \langle E \rangle V}\right)\left(\frac{1}{Y_e} + \frac{1 + \langle q_0 \rangle/\langle h \rangle}{Y_{0-acid}(1 - \langle h \rangle)^{3/2}}\right) \tag{21}$$

or

$$\frac{\sigma_{h^*}}{d\langle h^* \rangle/dx} \approx \frac{\sigma_{I_{abs}}}{dI_{abs}/dx}\sqrt{\frac{1}{Y_e} + \frac{1 + \langle q_0 \rangle/\langle h \rangle}{Y_{0-acid}(1 - \langle h \rangle)^{3/2}}} \tag{22}$$

Further, it is common to design a resist with quencher so that final after-quench acid concentration near the line edge is close to zero (or in any case, small). It is clear that $\langle q_0 \rangle$ can never be greater than $\langle h \rangle$ (otherwise developer could never reach the line edge), so that a worst-case impact of quencher is a doubling of the resist's contribution to the LER based only on the acid noise-to-signal ratio.

At this point, it is clear that quencher will increase the noise (uncertainty) in the acid concentration near the line edge, presumably making the LER worse. However, we have not yet taken into account the way in which quencher controls the latent image degradation due to acid diffusion during PEB. Without quencher, acid diffusion during the reaction-diffusion processes of PEB reduces the latent image gradient of the effective (PEB time averaged) acid concentration h_{eff} according to[3]

$$\frac{\partial \langle h_{eff} \rangle}{\partial x} \approx \frac{\partial \langle h \rangle}{\partial x} \left(\frac{1 - e^{-2(\pi \sigma_D/CD)^2}}{2(\pi \sigma_D/CD)^2} \right) \approx \frac{\partial \langle h \rangle}{\partial x} \left(1 - \left(\frac{\pi \sigma_D}{CD} \right)^2 \right) \tag{23}$$

where σ_D is the acid diffusion length and CD is the feature size, assumed to be near the resolution limit. The assumption that the diffusion length is small compared to the CD produces the final approximation on the right side of equation (23).

Diffusion reduces the gradient of the effective acid concentration and thus degrades the LER that will result. Quencher, on the other hand, diminishes this effect. In a well optimized resist system,[3]

$$\frac{\partial \langle h_{eff} \rangle}{\partial x} \approx \frac{\partial \langle h \rangle}{\partial x} \frac{1}{\eta} \tag{24}$$

where η is the ratio of the rate of diffusion to the rate of reaction during PEB.

$$\frac{1}{\eta} = 2K_{amp}t_{PEB} \left(\frac{CD}{\pi \sigma_D} \right)^2 \tag{25}$$

where K_{amp} is the amplification rate constant and t_{PEB} is the PEB time. If the reaction rate during PEB exceeds the rate of diffusion, quencher will control the diffusion and prevent degradation of the resulting latent image gradient (Figure 2). If the increase in the latent image gradient exceeds the impact of the greater acid uncertainty due to quencher, the net result will be an improvement in LER.
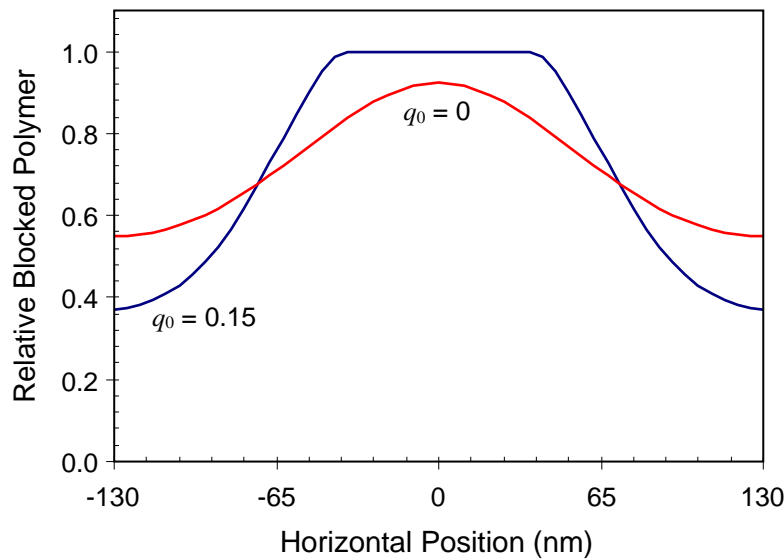

Fig. 2. The effect of quencher on the shape of the latent image after PEB. Both resists have identical processing, except that the dose for each is adjusted to be the dose to size (130 nm lines and spaces). Figure from Ref. 3.

The impact of quencher on roughness is difficult to tease out since higher quencher concentrations inevitably lead to higher dose-to-size. Thus, if a resist with higher quencher concentration exhibits lower LER (or LWR or LCDU), it is unclear how much of that improvement comes from the reduced impact of photon shot noise or the improved latent image gradient. To see the impact on dose, assume that everything about the resist is kept constant except the addition of quencher. Further, assume that the dose required to achieve a certain mean acid concentration $\langle h^* \rangle$ at the line edge without quencher is $\langle E \rangle$. If quencher of concentration $\langle q_0 \rangle$ is added to the resist, the dose required to achieve the same after-quenching acid concentration will be $\langle E_q \rangle$. Then

$$\frac{\langle E \rangle}{\langle E_q \rangle} = \frac{ln(1 - \langle h^* \rangle)}{ln(1 - \langle h^* \rangle - \langle q_0 \rangle)} = \frac{ln(1 - \langle h \rangle + \langle q_0 \rangle)}{ln(1 - \langle h \rangle)} \approx (1 - \langle q_0 \rangle / \langle h \rangle)(1 - \langle q_0 \rangle / 2) \qquad (26)$$

where the approximation on the right-hand side comes from taking the Taylor series approximation to the expression out to second order (that is, for small $\langle h \rangle = \langle h^* \rangle + \langle q_0 \rangle$). Interestingly, to first order the dose increases by a factor $(1 + \langle q_0 \rangle / \langle h \rangle)$, which compensates for the impact of quencher on the acid uncertainty term in equation (21). As a consequence, the overall impact of quencher on the resist term is to reduce it by a factor of $(1 - \langle q_0 \rangle / 2)$ (to first order), with an even greater improvement in the photon shot noise term. Thus, adding quencher improves roughness by slowing down the resist (requiring a higher dose) even before the impact of quencher on the latent image gradient is considered. Of course, slowing down the resist has the obvious negative impact on the manufacturing throughput of EUV lithography.

Further work on adding the impact of quencher to a model of post-PEB latent image gradient would make these trade-offs clearer.

IV. DESIGNING A LOW-ROUGHNESS CHEMICALLY AMPLIFIED RESIST

Absent quencher, the best approach to designing a low roughness resist was previously described.[2]

1. Keep Y_e close to 1 (probably true by default for most materials).
2. Increase the initial acid yield as high as possible (see equation (11)) by increasing PAG density and increasing C/α (see equation (5)). Understand, however, that pushing the secondary electron range too far will blur the acid latent image and eventually degrade roughness performance.
3. Increase resist absorption.

One factor that remains unclear is the ambit volume V. Is it possible to increase V? If, for example, V can be increased by an increase in acid diffusion length, is there an optimum acid diffusion length?[8] Are the factors that control V also affecting the correlation length, and thus affecting the mix of low-frequency versus high-frequency roughness? Does the lowest three-sigma LER necessarily correspond to the lowest PSD(0), the low-frequency value of the roughness power spectral density? These questions deserve further investigation.

The addition of quencher to our description of stochastic effects adds a new variable to optimize: quencher concentration. Since the design goal is generally to reduce roughness without increasing dose (or reduce the dose required without increasing roughness), simply adding quencher is not an obvious solution. Instead, quencher can be used to balance out other design choices that speed up the resist, keeping shot noise and the latent image gradient at acceptable (or possibly improved) levels.

It is important to keep in mind what is missing from these models so far. Development has not been included, but it is very likely that high development contrast will be critical to a low-roughness resist. Thus, all of the standard resist design criteria that emphasize high development contrast will continue to be important.

Conspicuously absent from the discussion so far has been any mention of polymer size. A naïve approach assumes smaller polymer size will lead to lower roughness, but experience with molecular glass and nanoparticle resists has not borne this out. In fact, if the volume of the polymer is smaller than the ambit volume over which averaging takes place, then polymer size will cease to influence roughness. And if the ambit volume were to be reduced to the size of the polymer, then smaller polymers would in fact make the roughness worse. However, the real influence of polymer size is likely through its impact on development contrast. High development contrast results from requiring a large number of deprotection events to make one polymer molecule soluble in developer. This is hard to accomplish without also making the polymer large enough to accommodate many protected sites.

V. CONCLUSIONS

First-order models that take into account the most important physical stochastic effects in lithography can be usefully employed to understand scaling and limits when working to reduce roughness or local CDU. Here, prior work that derived the stochastic uncertainty in the acid concentration after exposure for both chemically amplified and non-chemically amplified resists for EUV lithography has been extended to predict LER in the limit of high-contrast resist (so that development's influence on LER can be ignored). The result showed that the resist's contribution to roughness is controlled by the acid yield, so that higher acid yield reduced the relative contribution of resist compared to photon shot noise. An acid yield near 1 means that the resist contributes about equally to roughness as photon shot noise.

Quencher affects stochastic roughness in three ways. The added uncertainty of quencher concentration increases the resist's relative contribution to acid uncertainty. However, the impact of quencher on the latent image gradient can more than compensate for the increased acid uncertainty to produce lower roughness. Additionally, the increase in required dose with higher levels of quencher can often mask other effects by reducing roughness simply through the higher dose.

The models derived in this paper suggest an approach to validating and calibrating the scaling of LER with dose, ILS, and resist parameters. An experiment of LWR or LCDU versus quencher concentration (at the dose to size, all other things being equal) could be used to estimate the ambit volume after predicting (using simulation, for example) the impact of quencher on the latent image gradient.[14] It is clear, however, that more work is required to finish out these models and to make them more predictive.

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