Analytic Model of Line Edge Roughness from Stochastic Exposure Distribution in Electron-beam Lithography

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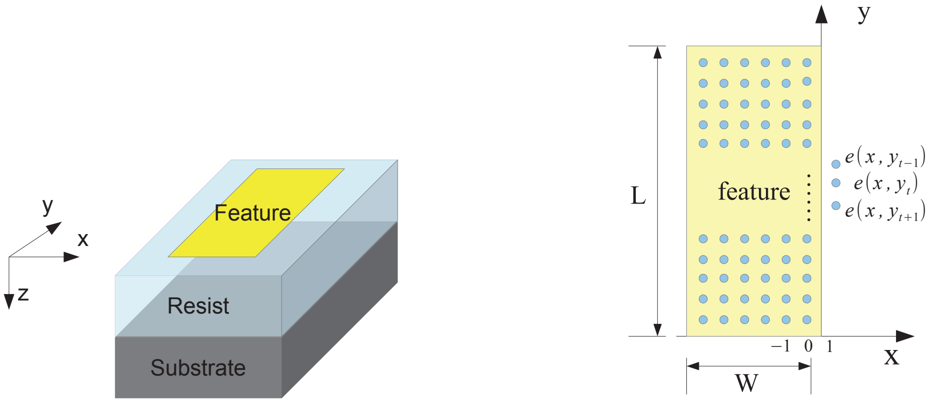
Line edge roughness (LER) in a pattern transferred onto the resist by electron-beam (e-beam) lithographic process is independent of the feature size. As the feature size continues to decrease, the relative effect of LER becomes larger. Therefore, it is unavoidable to minimize the LER in order to maximize the feature density in a pattern of nanoscale features. One important step required in developing an effective method to minimize the LER is to analyze and estimate the LER. A possible approach to such analysis is to rely on simulation. While the simulation approach is flexible, the main drawback is that it is computationally intensive, in particular the step of simulating resist development. In this study, an analytic approach is taken in estimating the LER in order to avoid the repetitive time-consuming simulation. One of the major factors affecting the LER is the stochastic fluctuation of *exposure* (energy deposited) in the resist. The objective of this study is to develop an analytic method for estimating the LER caused by the stochastic exposure distribution. It should be pointed out that the method is still applicable even when other factors are to be also considered.

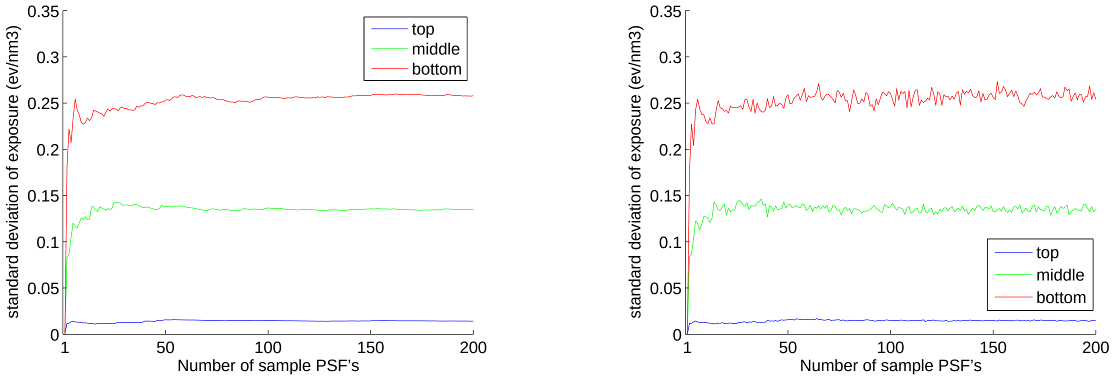
The coordinate system of the analytic three-dimensional model employed in the study is shown in Fig. 1-(a). A rectangular feature of which LER is to be modeled is long in the Y-dimension and its right edge is on the Y-axis as shown in Fig. 1-(b). The exposure distribution is stochastic since the point spread function (PSF) is stochastic, which in turn is due to the random scattering of electrons. It is assumed that the PSF at each point, i.e., $psf(x,y,z)$, has a Gaussian distribution with a certain mean ($m(x,y,z)$) and standard deviation ($\sigma(x,y,z)$). Let $e(x,y,z)$ denote the exposure at a point in the resist, which is stochastic. The estimation of LER is done through two steps: (1) the mean and standard deviation of $e(x,y,z)$ are derived from $psf(x,y,z)$, and (2) the LER, defined as the standard deviation of the edge location, is derived using the mean and standard deviation of $e(x,y,z)$. In the first step, the mean and standard deviation of $e(x,y,z)$ can be computed through the convolution of the mean and standard deviation of $psf(x,y,z)$ and the feature (dose distribution), respectively, e.g., standard deviation $\approx \sqrt{\sum_w \sum_l \sigma^2(x-x_w, y-y_l, z)}$ assuming that the feature is exposed with a uniform dose. In the second step, the exposure $e(x,y,z)$ is converted into the resist developing rate $r(x,y,z)$ using a conversion formula obtained experimentally and the edge location is estimated based on $r(x,y,z)$ which is also stochastic. The resist development process may be modeled by many developing paths starting from the resist surface. Then, the edge (boundary) of a feature is determined by the developing path reaching the farthest point given a developing time T. For the convenience of notation, let x denote the location of edge (refer to Fig. 1-(b)). In order to compute the LER (i.e., standard deviation of x), the probability density function (PDF) of x given T, $f(x|T)$, is derived by $f(x|T) = \frac{f(T|x)f(x)}{f(T)}$. The PDF of developing time given an edge location, $f(T|x)$, can be computed from $r(x,y,z)$, and the PDF of edge location (for any T) can be obtained from the relationship, $f(T) = \int f(T|x)f(x)dx$. For each possible path, the mean and standard deviation of x given T are computed. The LER is estimated to be the standard deviation of x for the developing path giving the largest mean.

The results, standard deviation of exposure and LER, obtained using the analytic model are compared with those by simulation in Fig. 2 and Fig. 3. The substrate system consists of 300 nm PMMA on Si. The e-beam energy is 50 keV and the dose is 640 $\mu C/cm^2$ where the pixel interval is 5 nm. The size of line feature is 0.08×1.5 μm^2. It can be seen in the figures that the analytic results, both standard deviation of exposure and LER, are well matched with the simulation results. In this paper, the complete analytic model and detailed steps to derive the LER will be presented with more comprehensive comparison results.



(a) (b)

Figure 1: Simulation Model: (a) substrate system and (b) a long line feature.



(a) (b)

Figure 2: Exposure variation along Y-axis at the top, middle and bottom layers: (a) analytic model and (b) simulation. The number of sample PSF's used in computing exposure is varied to observe the convergence property.

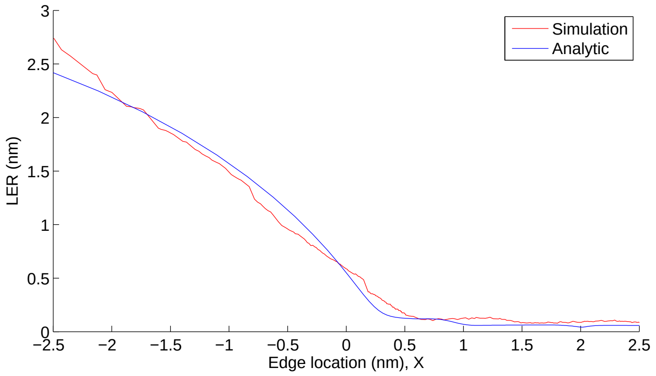


Figure 3: LER estimated by the analytic model and simulation on the bottom layer of resist for varying edge location where X=0 corresponds to the target location of edge (refer to Fig. 1-(b)).