A Practical Approach to Modeling Scanning Electron Microscope Images for Minimization of Line Edge Roughness and Critical Dimension Error

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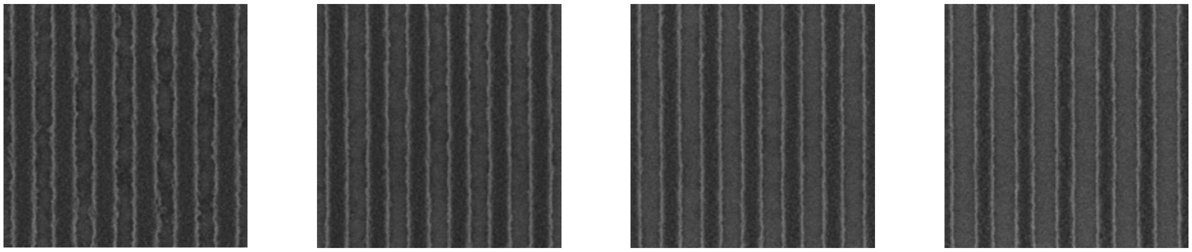
Electron-beam (e-beam) lithography is often employed in transferring patterns onto the resist layer of a substrate system, especially when a pattern includes fine features. However, the proximity effect due to electron scattering in the resist causes the blurring in the written pattern (features) and has been one of the major drawbacks in addition to the low throughput in e-beam lithography. Also, the stochastic nature of the exposure and development processes leads to the roughness in the feature boundaries. These two problems, i.e., critical dimension (CD) error and line edge roughness (LER), become more conspicuous as the feature size continues to get smaller. Various schemes for correcting the proximity effect have been developed over a few decades and methods for reducing the LER are actively investigated more recently. In most of these efforts, a point spread function (PSF) is involved in computing the exposure (energy deposited) distribution in the resist layer for a given pattern. The PSF is usually modeled with specific functions such as Gaussian functions or numerically obtained through a Monte Carlo simulation, given a substrate system. The stochastic processes in the e-beam exposure and resist development are modeled based on the chemical processes involved. In this study, a practical approach to modeling the e-beam lithographic process directly from SEM images for minimization of the CD error and LER has been developed for line/space (L/S) patterns.

A L/S pattern is exposed with a few different dose levels (Fig. 1) and a top-down SEM image of the remaining resist after development is taken for each dose level. The line width and LER are measured from the SEM images using an image processing technique involving edge detection. The exposure distribution is directly estimated from the relationship between the dose level and line width through an iterative optimization. Through iterations, the difference between the measured and estimated line widths is minimized for each dose level and the relationship between the exposure and the developing rate is also established. In this step, the non-stochastic exposure (to be referred to as "deterministic exposure") is used in estimating line widths. Then, certain stochastic distributions such as a Poisson distribution are employed to model the stochastic fluctuation of exposure due to shot noise and electron scattering. The parameters of the stochastic distribution are determined through another iterative optimization by minimizing the difference between the measured and estimated LER's. A stochastic exposure distribution is obtained by including the stochastic fluctuation of exposure in the deterministic exposure distribution.

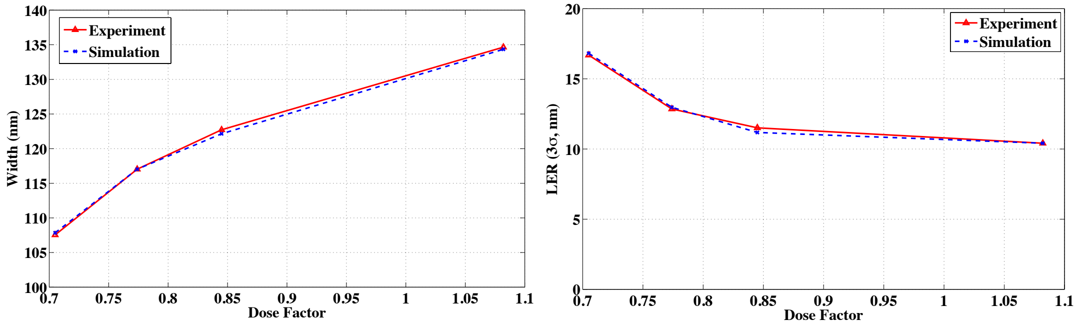
In our method for minimizing the CD error and LER, the width of line to be exposed is reduced (by ΔW) with the dose level adjusted. This method has been shown to be effective in our and others' previous studies. The optimal amount of ΔW and dose level are determined through an iterative optimization procedure, based on the above-described model for the stochastic exposure distribution. In this optimization, the exposure distribution needs to be computed for each reduced width of line. The line spread function derived from the exposure distribution estimated in the above modeling step is employed, which enables the exposure computation for different line widths.

In Fig. 2a, the line widths measured from the SEM images are compared with those estimated through simulation using the stochastic model of exposure distribution model. It can be seen that they are closely matched indicating high accuracy of our modeling approach. In Fig. 2b, a similar comparison result is provided for the LER. In Fig. 3, the contours of the remaining resist at the top and bottom layers of resist are shown without ($\Delta W = 0$) and with the optimization of ΔW. With ΔW optimized (and the dose level accordingly adjusted), the line width is closer to the target width (120 nm) and the LER is smaller, especially at the bottom layer. In this paper, the modeling and optimization procedures will be described in detail with more comprehensive results.



(a) (b) (c) (d)

Figure 1: The top-down SEM images of the resist remaining profile for a L/S pattern with various normalized dose level (dose factor): (a) 0.705, (b) 0.774, (c) 0.845, and (d) 1.082 where L = S = 120 nm.



(a) (b)

Figure 2: Line-width and LER measured from the SEM images ("experiment") are compared with the line-width and LER estimated through the modeling ("simulation"): (a) line width and (b) LER.

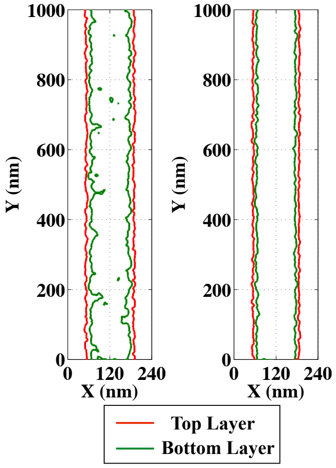


Figure 3: Contours of the remaining resist profiles without optimization (left) and with optimization (right) of ΔW, line-width reduction.