Dependency Analysis of Line Edge Roughness in Electron-beam Lithography

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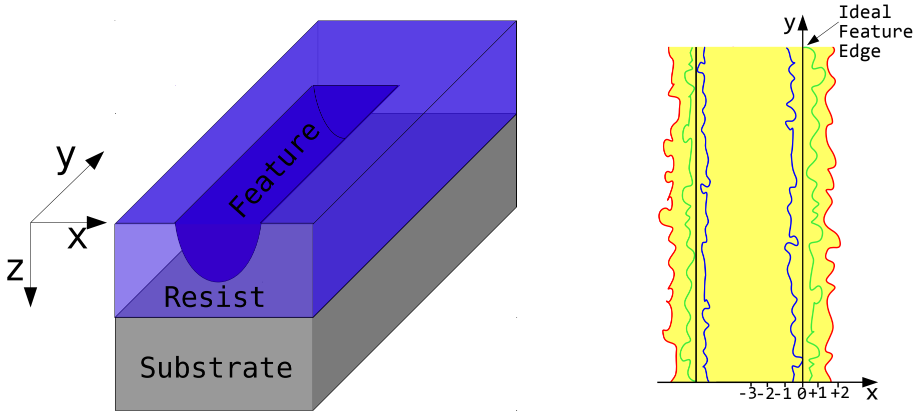
One of the issues which cause a serious problem in a nano-lithographic process is line edge roughness (LER) in the written patterns. Since the LER does not scale with the feature size, it can significantly limit the minimum feature size and maximum pattern density that can be achieved as the feature size is reduced well below 100 *nm*. Therefore, it is unavoidable to address the issue of LER in order to be able to continue to shrink the feature size and minimize the malfunctioning of a device due to the LER. There are several factors which contribute to the LER in electron-beam (e-beam) lithography. One major factor is the stochastic fluctuation of exposure (energy deposited in the resist), which is caused by shot noise (variation of electron flux) and random scattering of electrons. In order to develop a method to reduce the LER, it is important to analyze the characteristics of LER due to the exposure fluctuation. In the past, the LER was studied using a two-dimensional (2-D) model in most cases, i.e., the resist depth dimension was ignored. In this study, a 3-D model of substrate system (refer to Fig. 1(a)) is employed to thoroughly analyze the dependency of LER on edge location, resist layer, resist thickness, etc. Also, the e-beam lithographic parameters which affect the LER are identified, e.g., shot noise, dose, beam energy, beam diameter, and pixel (exposing) interval, and their effects on the LER are analyzed with the 3-D model.

Based on the 3-D model, the exposure distribution $e(x, y, z)$ in the resist for a long line feature is computed using a set of stochastic point spread functions (PSF) generated through Monte Carlo simulation. The shot noise is simulated by varying the number of electrons traced to generate each PSF according to the Poisson distribution. The exposure is converted into the developing rate by the conversion formula determined through experiment. Then, the resist development process is simulated to obtain the 3-D profile of remaining resist given a developing time. In each layer of resist, the feature edges are detected and the LER is quantified as the standard deviation of edge location along the length dimension of feature.

The line feature considered in the simulation study is 25 $nm \times 500$ nm in size and is exposed with a uniform dose. The LER is examined in three layers of resist, i.e., top, middle and bottom layers, and at different edge locations controlled by the developing time (refer to Fig. 1). For the convenience, the (ideal) right edge of the feature is assumed to be along the Y-axis (refer to Fig. 1(b)). Then, the X coordinate represents the edge location and also edge location error. Also, the effects that the e-beam lithographic parameters have on the LER are analyzed. The three beam energies are considered, 20, 50 and 100 keV. In order to maintain the same exposure level, the dose level (the number of electrons) is accordingly adjusted for different beam energies. The resist thickness is varied from 100 to 500 *nm*, the beam diameter from 3 to 20 *nm*, and the exposing interval from 2.5 to 10 *nm*.

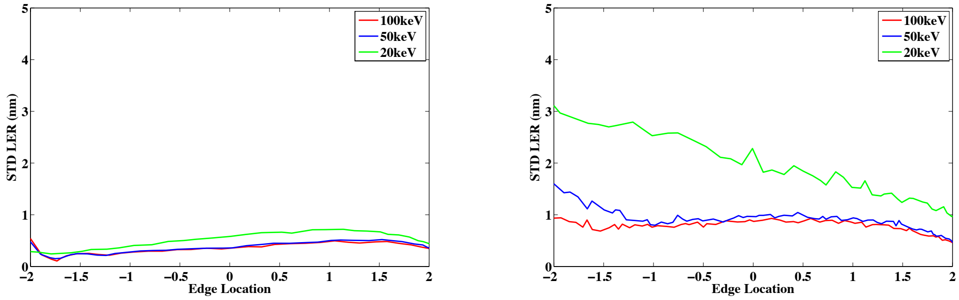
In Fig. 2, some of the simulation results are provided where, in each graph, the LER is plotted as a function of edge location (refer to Fig. 1(b)). The following observations can be made from the results. (*i*) The LER is substantially larger at a lower layer of resist. (*ii*) The LER decreases as the beam energy increases. Note that the dose (number of electrons) is increased for a higher beam energy so that the exposure level remains unchanged. (*iii*) The LER exhibits different behaviors at different layers as the edge location is varied. As the edge location is moved from the inside of feature to the outside, the LER decreases at the bottom layer while it slightly increases at the top layer. (*iv*) The LER becomes smaller for a thinner resist. (*v*) The LER is larger for a larger exposing interval. (*vi*) The LER tends to be larger for a larger beam diameter when the edge location is outside the feature. In this paper, a comprehensive set of simulation results will be presented with detailed discussion, in order to suggest a possible approach to reducing the LER.



(a) 3-D model of substrate system

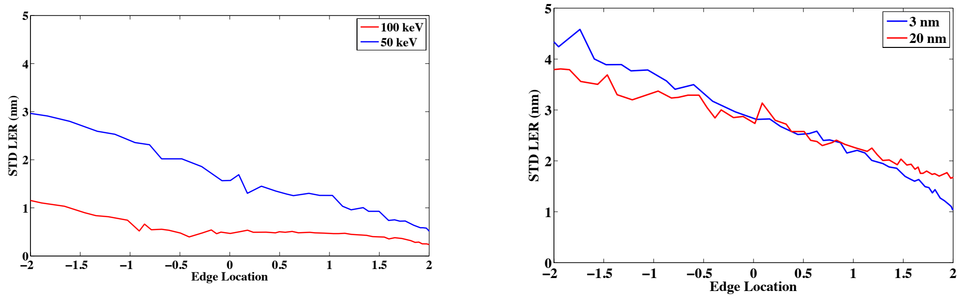
(b) LER at different edge locations (red, green: over-developed, blue: under-developed)

Figure 1: Simulation model



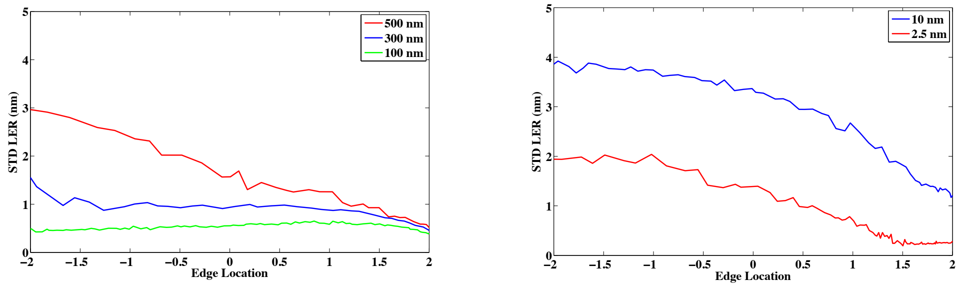
(a) Beam energy (top layer)

(b) Beam energy (bottom layer)



(c) Beam energy (bottom layer; 500nm PMMA)

(d) Beam diameter (bottom layer)



(e) Resist thickness (bottom layer)

(f) Exposing interval (bottom layer)

Figure 2: Dependency of LER as a function of edge location which also represents the edge location error (the X coordiate in Fig. 1(b)). Unless specified otherwise, beam energy: 50 keV, resist thickness: 300 nm, beam diameter: 3 nm, and exposing interval: 5 nm.