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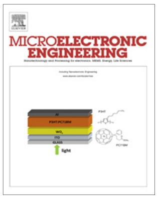

Dependency analysis of line edge roughness in electron-beam lithography

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ABSTRACT

The line edge roughness (LER) has become one of the critical issues which affect the minimum feature size and the maximum circuit density realizable in most lithographic processes. Since the LER does not scale with the feature size, it needs to be minimized as the feature size is reduced well below 100 nm. One of the main factors contributing to the LER is the stochastic fluctuation of exposure. In the past, most of the LER researches were based on a 2-D model without considering the resist depth dimension. In this study, the dependency of the LER, caused by the stochastic fluctuation of exposure due to electron scattering in the resist and the shot noise due to variation of electron influx, on lithographic parameters such as shot noise, beam energy, exposing interval, dose, etc., has been investigated with a 3-D model, as the first step toward developing an effective method for minimizing the LER. In the case of CAR, the effect of developing process on LER is also considered. In this paper, the results from an extensive simulation are reported with a detailed discussion.

1. Introduction

Electron-beam (e-beam) lithography is one of the widely-used methods for transferring patterns onto the resist layer [1–4]. Despite the low throughput due to pixel-by-pixel or feature-by-feature writing and the proximity effect caused by electron scattering, its capability of being able to write ultra-fine features has a variety of applications such as fabrication of photo-masks, low-volume production of semiconductor components, experimental circuit patterns, etc. The well-known proximity effect, which causes deviation from the target dimensions of a feature in the written pattern, has been studied over three decades. Many proximity correction schemes have been devised to minimize the critical dimension (CD) error and eventually increase the circuit density, i.e., dose modulation, pattern biasing, GHOST, etc. [5–8]. Another related issue is the variation of CD within a feature due to the stochastic nature of lithographic and developing processes. A quantitative measure of such variation which is being extensively studied these days is the line edge roughness (LER) [9]. 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 [10,11]. 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 e-beam lithography. One of the major factors is the stochastic fluctuation of *exposure* (energy deposited in the unit volume of resist), which is caused by shot noise (variation of electron flux) and random scattering of electrons. In order to develop an effective method to reduce the LER, it is essential to analyze the characteristics of LER. 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. However, different layers of resist may exhibit different behaviors of LER. In this study, a 3-D model of substrate system is employed to thoroughly analyze the dependency of LER, caused by the stochastic fluctuation of exposure, on factors such as edge location, resist layer, resist thickness, etc. Also, the e-beam lithographic parameters which affect the stochastic fluctuation of exposure and therefore the LER are identified, e.g., shot noise, *dose* (the amount of charge given to each unit area of resist surface), beam energy, beam diameter, and exposing interval, and their effects on the LER are analyzed with the 3-D model. The type of resist may also have a substantial effect on the LER. Two different types of resists, PMMA (poly(methyl methacrylate)) and chemically amplified resist (CAR) PHS (poly(4-hydroxystyrene)), are considered. In the case of CAR, the effect of the randomness involved in

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the resist developing process is also analyzed. It needs to be pointed out that the main focus of this study is on understanding the behavioral trend (not the absolute level) of LER as those factors and parameters vary.

The rest of the paper is organized as follows. The model of the LER simulation is introduced in Section 2. The detail of simulation procedures is described in Section 3. Simulation results are discussed in Section 4, followed by a summary in Section 5.

2. Modeling of LER

Modeling the LER may be done analytically or via simulation. In this study, a simulation approach is taken mainly for its flexibility at the expense of high computational requirement. The stochastic exposure distribution in the resist is computed, and the exposure is converted into the developing rate (a quantitative measure of how fast resist is developed) point-by-point. Then, the 3-D remaining resist profile is obtained through simulation of resist development. From the resist profile, the boundaries of a feature are determined on each layer of resist and the LER is quantified by a certain measure, e.g., the standard deviation of edge location.

2.1. Exposure distribution

A *point spread function* (PSF), $psf(x,y,z)$, describes the spatial distribution of exposure throughout the resist when a single point is exposed. Due to the random nature of electron scattering and shot noise, the PSF is stochastic, i.e., $psf(x,y,z)$ is random at each point (x,y,z). An instance of stochastic PSF is shown in Fig. 1. Since the PSF is stochastic, the exposure distribution is accordingly stochastic.

The stochastic exposure distribution may be obtained by employing the Monte Carlo simulation at each point exposed by the e-beam, which is equivalent to generating an instance of stochastic PSF for each point exposed. This approach may lead to a more realistic exposure distribution. However, its computational complexity of generating the PSF's is too high to be practical for most patterns of realistic size. Hence, a new method to greatly reduce the number of stochastic PSF's (instances) to be generated, referred to as the simplified Monte Carlo simulation (SMC) method, was recently developed [12]. It generates only a small number of stochastic PSF's and selects a PSF randomly for each point exposed for calculation of the exposure distribution. Note that we are mainly interested in certain measures of the exposure fluctuation, not the exact distribution of exposure itself. Through simulation, it was shown that the SMC method is able to generate exposure distributions statistically equivalent to those by the direct Monte Carlo method. Therefore, in this study, the SMC method is employed without compromising the accuracy of estimating the LER.

A typical substrate system is shown in Fig. 2 where the X–Y plane corresponds to the surface of resist and the Z-axis is along the resist depth dimension. The exposure distribution $e(x,y,z)$ in the resist for a feature is computed by the convolution between the stochastic PSF $psf(x,y,z)$ and dose distribution function $d(x,y,0)$ defined on the surface of resist,

$$e(x,y,z) = \iint d(x-x',y-y',0)\cdot psf(x',y',z)dx'dy' \tag{1}$$

In the case of a uniform dose distribution, $d(x,y,0)$ can be expressed as,

$$d(x,y,0) = \begin{cases} D & \text{for exposed points} \\ 0 & \text{otherwise} \end{cases} \tag{2}$$

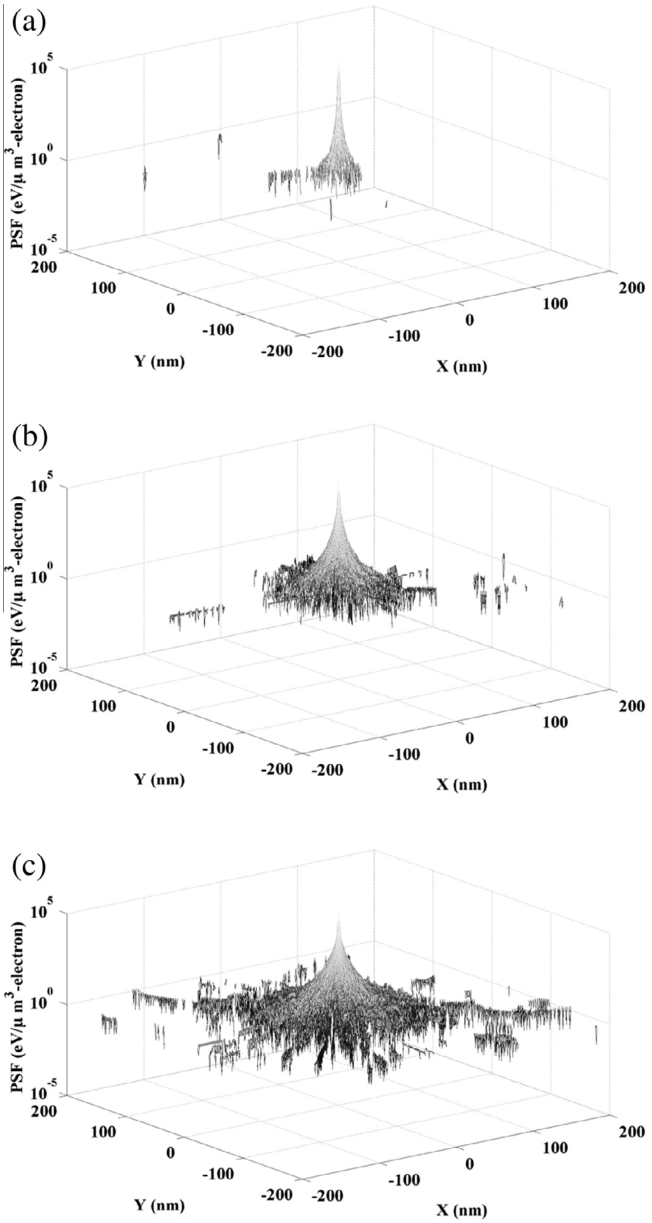

Fig. 1. An instance of the stochastic PSF at (a) top, (b) middle, and (c) bottom layers: 40 electrons per shot with exposing interval of 1 nm (640 μC/cm^2), 300 nm PMMA on Si, 50 keV and beam diameter of 3 nm.

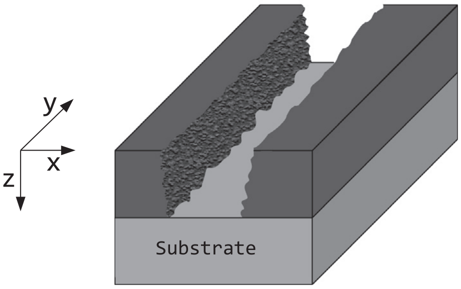

Fig. 2. A 3-D model of substrate system.