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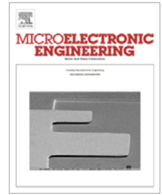

Fast backscattering parameter determination in e-beam lithography with a modified doughnut test

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ABSTRACT

For feature sizes smaller than 100 nm, proximity effect correction gains more importance in electron beam lithography. Several methods have been proposed for the determination of the proximity parameters, most of them being extensive and time-consuming. This paper investigates the reliability of the doughnut test and specifies the electron backscattering portion with a given resist-process. The functionality of the method for negative resist systems exposed by a variable shaped e-beam writer is shown for the first time. Compared with conventional methods, the modified doughnut test was proven to be a fast, straightforward and reliable method for determining the backscattering proximity parameters when utilized together with sensitive scanning electron microscopy.

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1. Introduction

The proximity effect in electron beam lithography is understood as the contribution of electrons, which have been scattered in the resist or in the substrate, to the exposure of nearby pattern features [1]. An accurate proximity effect correction gains more and more importance for the production of feature sizes smaller than 100 nm. Different methods are used to compensate for the proximity effect including background exposure [2], shape bias [3] and dose modulation [4]. Since the layout geometry corresponds to the exposure geometry, the density of the pattern shapes is not influenced and the process windows do not deteriorate. Hence, dose modulation is mainly applied in high-resolution electron-beam lithography. In this method, the point spread function (PSF), which describes the scattering of the electrons, is approximated as a multiple Gaussian distribution. A precise determination of the PSF parameters is necessary, but these parameters cannot be directly experimentally determined. Indirect methods like printing line structures with different duty ratios [5] need several iteration loops and are therefore time-consuming. It must be pointed out that, in addition to pure scattering, experimentally derived data also contain process influences as well as tool influences like beam blur, etc.

In this work, we employ the doughnut test to improve the parameter determination of the long-range part of the PSF. The test was first mentioned by Stevens [6] who investigated PMMA resist on different substrates. The test patterns account for the radial symmetry of the PSF. In particular, we specify the backscattering portion of the electron scattering with a given resist process and sensitive scanning electron microscopy unlike Stevens [6], who used optical microscopes, which are insufficient in detecting resist thicknesses of about 10–20 nm. Furthermore, we enhance the method and apply it to a negative resist system and exposure by a variable shaped e-beam writer for the first time. The results from the doughnut test are compared with the data from the conventional used “PROX-In” method [5] and interpreted.

2. Mathematical approach and principle of the method

In a system of resist and substrate the energy-deposition distribution of the electrons, starting from the primary impinging point, can be modeled by the PSF or proximity function. The proximity function $f(r)$ is often approximated by a sum of three Gaussian terms:

$$f(r) = \frac{1}{\pi(1+\eta+\nu)}\left[\frac{1}{\alpha^2}\exp\left(-\frac{r^2}{\alpha^2}\right)+\frac{\eta}{\beta^2}\exp\left(-\frac{r^2}{\beta^2}\right)+\frac{\nu}{\gamma^2}\exp\left(-\frac{r^2}{\gamma^2}\right)\right] \quad (1)$$

where α is the forward scattering range, β and η characterize the intermediate backscattering range and ratio, γ and ν refer to the corresponding long-range backscattering parameters. In the doughnut test, the constant outer radius of the doughnut pattern (Fig. 1a) has to be as large as necessary to take full advantage of the

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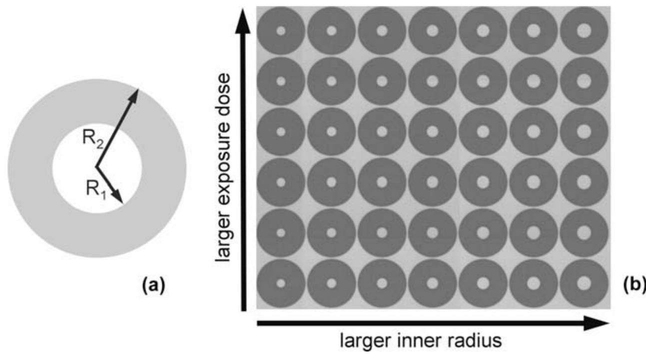


Fig. 1. Scheme of a doughnut matrix with increasing exposure dose and increasing inner radius.

backscattering ($R_2 \gg \beta, \gamma$). Thus, due to backscattering, the resulting dose D_{Center} in the center of the doughnut can be derived from:

$$D_r(\vec{r} = \vec{0}) \equiv D_{Center} = D_{Ring} \cdot \int_0^{2\pi} d\varphi \int_{R_1}^{R_2} dr' \cdot r' \cdot f(r')$$
$$D_{Ring} = D_{Center}\left[2\pi \cdot \int_{R_1}^{R_2} dr' \cdot r' \cdot f(r')\right]^{-1} \quad (2)$$

Here $D_r(\vec{r})$ is the resulting areal dose distribution dependent on the position vector $\vec{r}$ and $d\varphi$ corresponds to the differential argument in polar coordinates. D_{Ring} is the dose applied during exposure which is constant inside of the doughnut ring. Together with Eq. (1) the following expression is obtained:

$$D_{Ring}(R_i) = D_{Center}(1 + \eta + \nu)\left[\eta \exp\left(-\frac{R_i^2}{\beta^2}\right) + \nu \exp\left(-\frac{R_i^2}{\gamma^2}\right)\right]^{-1} \quad (3)$$

α is too small to be observed with the considered test pattern size ($R_1 \gg \alpha$) and its Gaussian term is therefore canceled with no consequences for the normalization. A matrix of doughnut cells (Fig. 1b) with varying inner radius R_i and different exposure doses $D_j(R_i)$ can be compiled and exposed by electron-beam lithography. After development, each combination (R_i, D_j) has to be identified where the inner circle is just starting to be covered with exposed resist due to backscattering. Optical microscopy observes this as a contrast inversion, but only in a broadened range around the clearing dose D_{cl} (where the resist is fully crosslinked). Scanning electron microscopy (SEM) is more sensitive to a critical remaining resist thickness t_{crit} which is given by the secondary electron (SE) emission depth of the used resist. For most non-conductive materials, the values for t_{crit} are between 10 and 20 nm in low-voltage SEM [7]. Below t_{crit} the corresponding SE yield contains both SE contributions from the resist and the substrate. A contrast inversion occurs when the signal is completely delivered by SE emitted from the resist. Thus, the interesting dose is the threshold dose D_0 where the resist starts to crosslink and has a low thickness. Although negative resists have the characteristic to swell at low exposure doses, the determination of the resist contrast $\gamma_r = [\log(D_{cl}/D_0)]^{-1}$ with D_0 and D_{cl} is not affected since only the linear portion of the contrast curve and its extrapolation is used [8]. Even dark erosion does not play an important role.

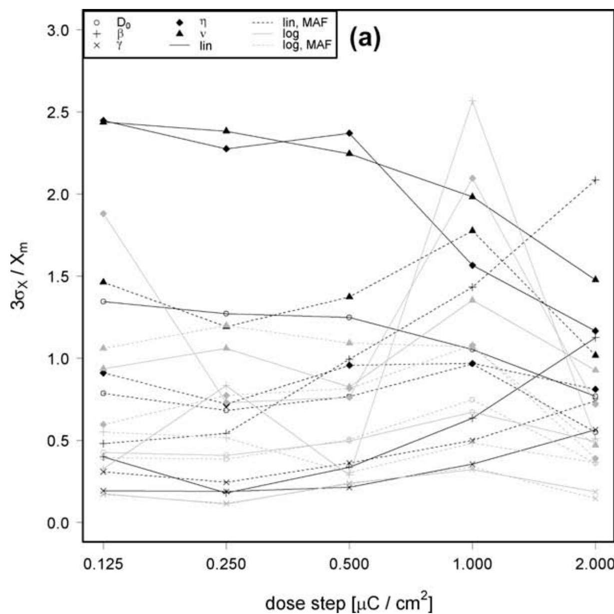
3. Accuracy and statistical analysis

The accuracy of the proximity effect correction is mainly determined by the reliability of the utilized PSF. This depends on the numerical error provided by the finite sized radius and the dose step of the doughnut grid as well as the SE signal range in which the contrast inversion is observed. By defining the resist contrast γ_r and applying a linear approximation to the dependency of t_{crit} on $\log(D_0 + \Delta D_0)$, an uncertainty range ΔD_0 can be calculated as follows:

$$\Delta D_0 = \left[10 \wedge \left(\frac{t_{crit}}{\gamma_r \cdot d}\right) - 1\right] \cdot D_0 \quad (4)$$

which yields relative values $\Delta D_0/D_0$ in the range of 2% (for t_{crit} = 15 nm, γ_r = 14 and a resist thickness d = 134 nm).

Based on the assumptions mentioned above, we estimated the reliability of the PSF delivered by the doughnut test with a simplified, random walk-based calculation. In a first approach, linear steps for both R_i and D_j may be considered. In Eq. (3), $D_{Ring}(R_i)$ is linearly dependent on D_{Center} and the dependency on R_i is Gaussian. Hence,



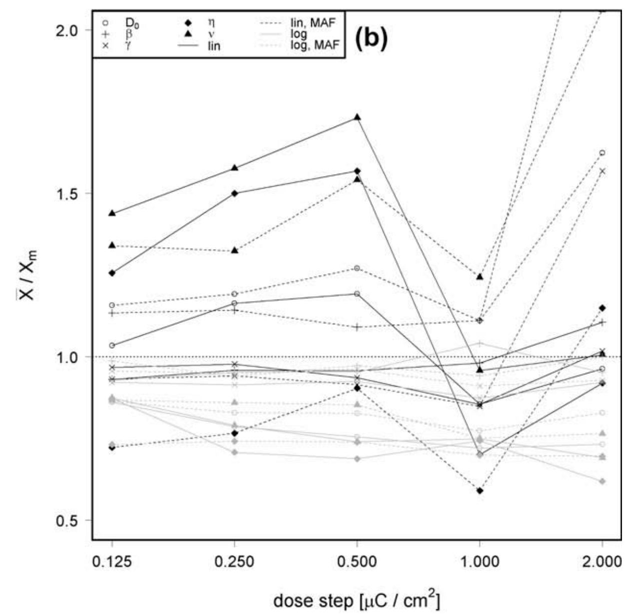


Fig. 2. Relative statistical error $3\sigma_X/X_m$ (a) and systematical error $\overline{X}/X_m$ (b) of the dependent random variable $X = D_0, \eta, \beta, \nu, \gamma$ derived by random walk as functions of the dose step in the range between 0.125 and 2 μC/cm^2.

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