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Determination of proximity effect parameters by means of CD-linearity in sub 100 nm electron beam lithography

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ABSTRACT

Along with the introduction of the 32 nm technology node in the next years, the methods for correcting the proximity effect face certain limitations of measurement performance and the underlying point spread function based models themselves. To extend these methods to future technology nodes, they have to rely on more generalized coherences between nominal and measured feature sizes than just the absolute measurement values. In this work, a method is introduced to determine the forward scattering range and backward scattering ratio by printing isolated lines with various line widths and preassigned variable exposure doses. The line widths are then measured using standard inline scanning electron microscopy and correlated to their nominal values. This is done in terms of linearity to find the best match between the input parameters of the methodology and the intrinsic values of the resist-substrate system. A comparison between simulated and experimental results conclude that significant line width nonlinearities will occur, when relying on conventional methodologies especially for feature sizes below 40 nm.

1. Introduction

In electron beam lithography, feature resolution is mainly determined by the influence of electron scattering and the corresponding proximity effect [1]. Proximity effect correction (***PEC***) methods are inevitable and demand for exact knowledge of the parameters of the underlying electron scattering for feature sizes below 100 nm. Common experimental methods for the determination of those parameters come along with time-consuming experimental effort. Furthermore, the parameter estimates obtained with these methods lack statistical certainty, as they rely on accurate critical dimension (***CD***) values, the stability of the resist process and the reliability of the underlying models [2,3].

A novel method for the determination of the forward scattering range, α, and the backscattering ratio, η, was developed and tested on a standard positive resist by printing isolated lines with line widths smaller than the backscattering range, β.

The obtained results were compared to results derived by conventional methodologies. While the latter rely on absolute CD measures, the present method focuses on generalized coherences between the nominal feature widths and the underlying proximity effect models becoming evident for the 32 nm technology node and beyond.

2. Theoretical background

Scattering of accelerated electrons in the resist-substrate system is the physical reason for the occurrence of the proximity effect in electron beam lithography. It is mathematically described by the point spread function (***PSF***), which represents the exposure dose (***ED***) distribution after point exposure [1]. In its simplest description, the PSF is given by a double Gaussian model with the first term representing forward and the second backward scattering respectively:

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

For an arbitrary incident electron distribution, d_0, the resulting ED profile, d_e, after electron scattering can then be calculated from the convolution of d_0 with Eq. (1) when the normalization condition $\int_0^{2\pi} d\varphi \int_0^{\infty} dr \cdot f(r) = 1$ is considered. Generally, a loss of ED to the environment due to electron backscattering in the substrate may also be accompanied by an unintended contribution to the exposure of neighbored features. Furthermore, small-angle forward scattering and the blur of the incident beam are leading to widening

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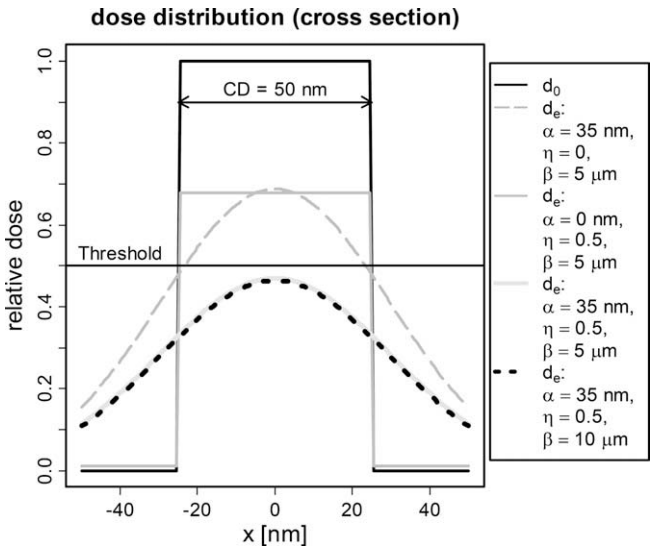

Fig. 1. Cross section of the relative dose distribution of an isolated line for different parameter sets of the PSF. While η and α determine the amplitude ($\alpha = 0$ nm, $\eta = 0.5$) and shape ($\alpha = 35$ nm) of the resulting dose distribution d_e, the latter is showing no dependency on β ($\beta = 5$, 10 µm) as the feature width is significantly smaller. As a relative dose smaller than the resist threshold of 0.5 is not resolved, the feature width decreases significantly with increasing α and η.

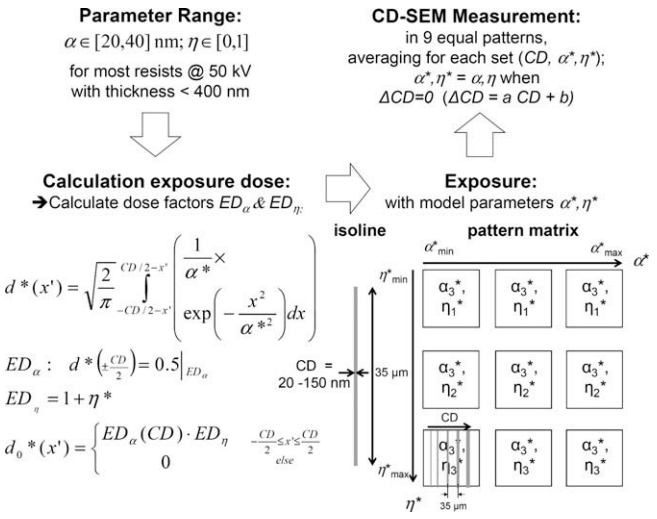

Fig. 2. Proposed workflow for the proximity parameter determination by printing isolated lines. The parameter range is adjusted according to experiences gained with the help of conventional methods. The dose factors are then varied in the pattern matrix according to their model parameters. The exposure and measurement are done repeatedly to achieve better statistical reliability.

and flattening of the electron dose profile in the resist and therefore limit the feature resolution as well. For isolated features, the ED distribution that is resulting from a rectangular incident dose profile (as schematically shown in Fig. 1) is mainly determined by α and η, if the feature width is smaller than β:

$$d_e(\vec{r}) = [f \otimes d_0(\vec{r}')] = \int_{-\frac{CD}{2}}^{\frac{CD}{2}} \int_{-\infty}^{\infty} f(|\vec{r} - \vec{r}'|) dy\, dx \overset{\exp\left(-\frac{x^2}{\beta^2}\right)\to 1;\ \frac{CD}{\beta}=0}{=} \sqrt{\frac{2}{\pi}} \frac{1}{(1+\eta)} \times \int_{-CD/2-x'}^{CD/2-x'} \left(\frac{1}{\alpha} \exp\left(-\frac{x^2}{\alpha^2}\right) dx\right) \quad (2)$$

Assuming the resist to resolve feature edges at a relative ED $\geqslant 0.5$ (marked threshold in Fig. 1), the resulting feature width is then a function of α and η as well. For common variable-shaped beam systems, the shot profile differs from a rectangular shape but might be approximated by an error function. Mathematically spoken, the shaped beam profile results from the integration of a Gaussian beam with specified width α_{BB} within a range determined by the shot width. In that case, Eq. (2) has to be modified by introducing an α which is a function of both α_{BB} resulting from the beam blur and α_{FW} resulting from forward scattering in terms of

$$\alpha = \sqrt{\alpha_{FW}^2 + \alpha_{BB}^2} \cdot [4]$$

3. Parameter determination method

Based on the fundamental principles described above, the printing of isolated lines can be utilized to determine α and η. A possible workflow is shown in Fig. 2. In order to print an isolated line with the correct line width, the exposure dose has to be multiplied by 2 factors ED_α and ED_η:

ED_α accounts for the dose profile flattening due to forward scattering and is CD dependent, while ED_η is chosen in order to compensate the backscattering loss and is therefore CD independent. ED_α is calculated from a single Gaussian model (similar to Eq. (2), see Fig. 2) with the model parameter α^* for each nominal CD individually. ED_η is simply assumed as $1 + \eta^*$ with the model parameter η^*. A matrix of patterns is exposed several times on a single wafer, each matrix element (i,j) consisting of a row of isolated lines[1] with nominal CDs between 20 and 150 nm and corresponding to one parameter set α_i^*, α_j^*. The dose factors $ED_\alpha(CD)$ and ED_η are assigned to each line according to the model parameters α_i^* and α_j^*, which are varied within a reasonable range along the rows and columns of the pattern matrix.

After exposure and development, the resulting line widths are measured via CD-SEM and averaged for each nominal CD and parameter set α_i^*, α_j^*. Thus, the model parameters α_i^* and α_j^* are assumed to match the characteristic intrinsic parameters α and η of the resist-substrate system, in case the obtained overall CD-to-target deviation, ΔCD_{ij}, equals zero.

4. Simulation

As the measurement process might be corrupted by resist shrinkage [5], as well as CD-SEM offset and linearity issues, a parameter determination procedure that is relying on absolute CD values might deliver imprecise and biased results for the Proximity Parameters. While statistical CD errors can be compensated for by averaging multiple measurement results, systematical CD errors are more difficult to overcome. As described above, the model parameters, α_i^* and α_j^*, of the presented method match the characteristic intrinsic parameters, α and η, of the resist-substrate system, when overall (average) $\Delta CD_{ij} = 0$. Since this is representing a special case of linear dependency (with zero slope and offset), a more generalized and robust criterion would then be the linearity of $\Delta CD_{ij}(CD)$ to the nominal target-CD.

To investigate the usability of the linearity criterion for the presented methodology, a simulation has been carried out according to the workflow depicted in Fig. 2. The underlying intrinsic system parameters α and η have been previously derived with the help of conventional methods [2,3] for a standard positive chemically amplified resist on bare silicon as $\alpha = 33$ nm, $\eta = 0.5$ (and $\beta = 9$ µm). The model parameters α^* and η^* were varied in the range

[1] The minimum lateral distance of neighbored lines in the pattern matrix has been chosen as 35 µm, which is approximately 4 times the expected value for β (9µm at 50 kV on bare Si). Therefore these lines can be considered isolated.