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Sensitivity analysis for accurate determination of PSF parameters

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ABSTRACT

One possible candidate to address future nodes (below 16 nm) is electron beam lithography as sub 10 nm resolution was already demonstrated in PMMA or HSQ resists. If multiple electron beam systems significantly increase the throughput to meet industrial needs, it can be the tool of choice. Nevertheless using a chemically amplified resist (CAR) is mandatory even for systems with a large number of beams. Achieving dense sub 20 nm patterns with CAR is still a challenge as proximity effects degrade the contrast of the aerial image. Bridging, shape rounding or partial development are typical degradation in the desired final pattern shape. Proximity effect correction is needed in order to properly delineate dense features as well as meet the required CD uniformity. Proximity effect correction can only be accurate if a Point Spread Functions (PSF) is precisely determined.

In this paper we demonstrate a strategy that allows accurate determination of Point Spread Function parameters. This strategy consists in using sensitivity analysis in order to define conditions where the calibration features and the measured quantities are sensitive enough to the PSF parameters and this without a correlation between the final results.

1. Introduction

E-beam lithography is the lithography technique that allows yet the best resolution on isolated structure. With non chemically amplified resists, sub 10 nm patterns were reported [1]. Resolution limits with chemically amplified resist is a bit lower and ceils at 20 nm. However whatever the chemistry of the resist, dense structures or structures surrounded by large patterns have lower resolution capability. One of the origins of this resolution degradation is the contrast loss in the absorbed energy in the resist due to proximity effects. Indeed the local deposited energy is dependent on the surrounding. Due to multiple inelastic collisions of electrons with matter, the energy deposited by a point electron beam spreads around and follows a Point Spread Function. Monte Carlo modeling of the electrons trajectories and energy loss when entering normally in a planar stack was modeled and shows that, depending on the initial beam energy, backscattered electrons are responsible of the absorbed energy at long range [2]. Commonly, the distribution of the absorbed energy is approximated by a sum of Gaussian functions [3]. In the case of thin resists films coated on a bare silicon wafer, and for high energies (above 50 keV), the PSF can be approximated by two Gaussian functions (see Eq. (1)).

$$\mathrm{PSF}(r) = \frac{D_0}{\pi(1+n)}\left[\frac{1}{\alpha^2}e^{-r^2/\alpha^2} + \frac{\eta}{\beta^2}e^{-r^2/\beta^2}\right] \quad (1)$$

With α the short range length of scattered incident electrons, β the long range length due to backscattered electrons and η the dimensionless ratio of deposited energy due to the backscattered electrons. D_0 is the relative dose.

However Monte Carlo simulations allow determining theoretical PSF distributions, not experimental ones. Experimental determination of PSF is possible by comparing theoretical pattern contour with experimental contour of the developed patterns. Hence experimental values of PSF parameters are dependent of the substrate and layers stack on top of it but also of the lithography process, for example the PEB and development steps.

Once the values of the PSF parameters are known, one can simulate the absorbed energy in the resist by convoluting the pattern geometry with the PSF. By considering an appropriate resist model, one can predict the final pattern geometry (CD, shape, etc.). Among multiple possibilities, the simplest resist model is a constant threshold model which at first order represents the threshold value of the needed absorbed energy to develop the patterns.

Different strategies for PSF determination exist [4–7]. Some are based on the comparison of measured CDs of patterns with their simulated CDs, the parameters providing the best match being considered as the ones of the PSF to be estimated. Others are based on indirect reconstruction of the PSF by considering the dose to develop circle of increasing radius. Plotting this dose versus the circle radius allows deducing the PSF. Conversely, the accuracy of such

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methodology is linked to the sampling size of the generated array of circle and on the accuracy on the dose in the matrix due to the fact that sometimes it is not clear if the pattern begins to develop or not.

The goal of this work is to use a sensitivity analysis in order to check if the measurements of a given calibration pattern are sensitive to PSF parameters.

2. Sensitivity methodology

In order to check the input parameters impact on the model results, global sensitivity analysis may be used. Such a statistical analysis consists in generating numerous inputs, if possible not correlated, and then to check the impact of variations of these inputs on the model results [8,9]. The first step of the sensitivity analysis study consists in choosing a strategy for the sampling of the inputs. In order to avoid correlation between the values, a random method, such as Monte Carlo, is appropriated. Each parameter of the model varies inside a range, as follows: D_0 is constant ($D_0 = 1$), α (nm) ϵ [5,100], β (nm) ϵ $[1 \times 10^3, 10 \times 10^3]$ and η (dimensionless) ϵ [0.1, 0.9] Since the space to be sample has 3 dimensions, and a high precision is desired, the Latin Hypercube Sampling (LHS) technique was adopted. This technique preserves the randomness that is a part of Monte Carlo sampling while reducing significantly the amount of samples required obtaining a uniform sampling of the search space [10].

3. Modeling step

Inscale software from Aselta Nanographics used in this study is an Electron-Beam Proximity Effect Correction software that uses advanced correction schemes such as a combination of dose and geometry. It also has a built-in simulation module that allows modeling the final pattern shape based on an initial layout. The model needs the geometry of the written patterns (through a gds file), the dose associated to each pattern and the PSF used for the convolution. The energy distribution is then calculated and by fixing a threshold value the energy contour plots of the printed patterns are obtained. Specific CD's of these contours can be measured easily using the metrology module of the software tool. In this study two measurement box are defined, which output is a pair of CD's (CD1, CD2). By recurrently calling the N values of $\{\alpha\beta\eta\}$ in the model, N PSF are generated and N (CD1, CD2) are calculated.

The layout used in this study is inspired by the pattern proposed by Babin [6] defined by the combination of a narrow isolated line (5 nm width, 5 μm long) exposed to a relatively high dose ($D_0 = 10$) with a large plane (2.5 μm wide, 50 μm long) exposed with a linear gradient of dose from 0.1 up to 1. Fig. 1 explains the used layout.

For each modeling, two CD's are measured, the CD of the isolated line 2.25 μm away from the upper limit of the plane and the width of the plane 15 μm away from the centered line. Finally the outputs of the sensitivity analysis are scatter plots of the two CD's as function of the input parameter. All doses are relative but $D_0 = 1$ refers to the base dose of a large pattern in the considered resist for a given lithographic process.

4. Sensitivity analysis results

Figs. 2 and 3 represent scatter plots of the 5000 values of CD1 as a function of α and β, respectively. The scatter plot of CD1 vs. β of Fig. 3 is randomly distributed. No specific trend is visible meaning that CD1 is not sensitive to β. Scatter plots of CD1 with α shows two trends, a fast increase of CD1 for values of α below 25 nm and a decrease of CD1 when α exceeds 25 nm. For α values above 50 nm, the line is not developed any more (CD1 is null), meaning that the absorbed energy is below the threshold value used in the simulation. So CD1 is sensitive to α if the absorbed energy is high enough to develop the isolated line. In order to be sensitive to a wider range of α, the dose of the simulation must be increased.

Figs. 4 and 5 are scatter plots of CD2 vs. α and β. CD2 represents the width of the 50 μm long plane for the 5000 values of $\{\alpha\beta\eta\}$. Fig. 4 shows that CD2 is not sensitive to α. Fig. 5 shows that CD2 is function of β but the dispersion of the points is quite large. Finally it can be concluded that CD1 is sensitive to α but not to β, and CD2 is sensitive to β, not to α. Therefore by measuring CD1 and CD2 it is possible to determine both α and β without a correlation between these two parameters. However both CD measurements are sensitive to η as it impacts on the absorbed energy.

Sensitivity scatter plots of CD1 and CD2 with η are plotted on Figs. 6 and 7. Both measurements are sensitive to η. This sensitivity to η was expected as the maximum dose in Eq. (1) is a function of $1/(1+\eta)$, but only a slight impact on CD1 is measured whereas the effect on CD2 is stronger.

The same scatter plots are calculated at various relative doses in order to estimate the variation of the sensitivity with the relative dose exposing the patterns. Seven values of D_0 are used: 1, 2, 3, 4, 5, 7 and 10. For α, β and η, average sensitivity values are evaluated using a linear fit of the scatter plots, removing points of null value. Absolute values of the slope of the line are mean sensitivity values and this in the whole range of variation for each parameter. Fig. 8 shows bar plots of the variation of the normalized mean sensitivity with the relative dose used in the simulation.

The first observation is that whatever the relative dose, CD1 is mainly sensitive to α. For the highest doses the mean sensitivity of α on CD1 increases (20 times highest at $D_0 = 10$ than at $D_0 = 2$). Thus if narrow lines are exposed at high doses, the experimental determination of α will be more accurate. Sensitivity of CD2 on η diminishes when the dose increases while the sensitivity on β diminishes but remains sufficiently high. Therefore it is possible to avoid a correlation between β and η by choosing the appropriate exposure dose of large patterns. Nevertheless sensitivity

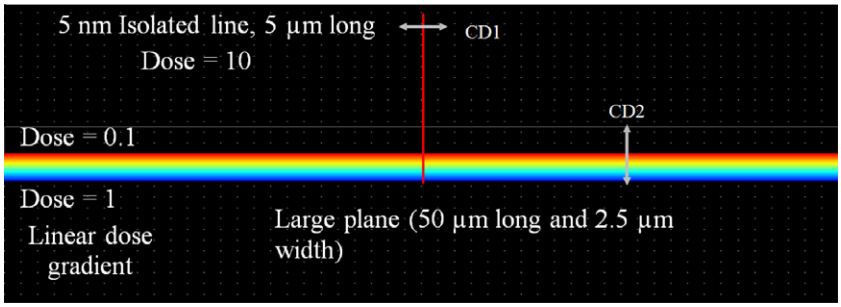

Fig. 1. Layout used in the study.