Microelectronic Engineering 112 (2013) 282–286

Contents lists available at SciVerse ScienceDirect

Microelectronic Engineering

journal homepage: www.elsevier.com/locate/mee

PSF calibration patterns selection based on sensitivity analysis

Thiago Figueiro [a,b,*], Mohamed Saib [a], Jean-Herve Tortai [b], Patrick Schiavone [a]

[a] Aselta Nanographics, MINATEC-BHT, 7 Parvis Louis Néel–BP50, 38040 Grenoble, France
[b] CNRS/UJF-Grenoble1/CEA LTM, 17 Avenue des Martyrs, 38054 Grenoble, France

ARTICLE INFO

Article history:
Available online 28 March 2013

Keywords:
Model calibration
Sensitivity analysis
PSF
E-beam proximity effect correction
Calibration patterns
Electron beam lithography
Electron microscopy
Point spread function
Global sensitivity analysis

ABSTRACT

Proximity effects in electron beam lithography impact feature dimensions, pattern fidelity and uniformity. These effects are addressed using a mathematical model representing the effect of the electron exposure and the subsequent effect of the resist. Therefore, one of the key steps of any proximity effect correction procedure is to determine properly the parameters of the model. However, the approach of extracting the parameters of a model based on measurements requires that the patterns measured are sensitive enough to the characteristics of the process that are described by the model. In this work it is presented a sensitivity analysis technique that allows the evaluation of the capability of a given test pattern to provide information over every parameter of a proposed model. Finally, a test pattern is presented in order to validate this approach. The proposed pattern is evaluated by the sensitivity analysis techniques described on this paper and then a calibration procedure is executed based on simulation results (with and without noise). Results shows accurate model calibration when the pattern set presents sensitivity to all its parameters.

1. Introduction

E-beam lithography has being proposed to allow industry to achieve better resolution and continue to advance for new technology nodes. However, structures may always be affected by its surroundings, making it difficult to hit target resolution. One main source of these effects is the contrast loss in the absorbed energy in the resist due to proximity effects. In order to compensate these effects, dose and geometry modulations have being used in order to hit critical dimension (CD) and end of lines (EOL) targets by compensating the impact of surrounding shapes [1]. In order to perform these proximity effects corrections (PECs), it is necessary to estimate the energy distribution due to electron scattering. In order to obtain a fast model which could actually be evaluated in an entire design, empirical models have being proposed [2–6]. Those mathematical models are called point spread function (PSF). Therefore, one of the key steps of any PEC procedure is to determine properly the parameters of the PSF, since all corrections that will be executed afterwards is based on its predictions. Eq. (1) shows an example of multiple Gaussians PSF.

$$\mathrm{PSF}(r) = \frac{1}{\pi\left(1+\sum_{i=1}^{i=n}\eta_i\right)}\left[\frac{1}{\alpha^2}e^{-\frac{r^2}{\alpha^2}} + \sum_{i=1}^{i=n}\frac{\eta_i}{\beta_i^2}e^{-\frac{r^2}{\beta_i^2}}\right] \quad (1)$$

With α the short range contribution of incident electrons, β_i the ith component of the middle or long range length due to backscattered electrons and η_i is the weight of this ith component.

There are several industrial tools that perform PEC for e-beam lithography, such as Inscale®, from Aselta Nanographics [7]. Inscale provides a complete environment for determining a model from a set of measurements. The methodology for obtaining the parameters of the model is general enough to be applied for any test pattern and for any model. However, the approach of extracting the parameters of a model based in measurements requires that the measured patterns are sensitive enough to the characteristics of the process that are described by the model (for instance, measuring only isolated features will provide a poor approximation of long range effects). In this work it is presented a sensitivity analysis technique [8–10] that allows the evaluation of the capability of a given test pattern to provide information over every parameter of a proposed model.

Finally, a test pattern is proposed. It is the traditional line/space (L/S) Grating with different CDs and densities. The originality of this approach is to perform the measurements in lines close to the border of the L/S Grating. The evaluation of the resulting CD in different parts of the block provides information over the long range effects.

2. Sensitivity analysis methodology

Sensitivity analysis is the study of how the uncertainty (change of value) in the output of a model can be portioned to different sources of variation in the model inputs [8]. This method indicates

* Corresponding author at: Aselta Nanographics, MINATEC-BHT, 7 Parvis Louis Néel–BP50, 38040 Grenoble, France. Tel.: +33 4 38 78 04 95.
E-mail address: thiago.figueiro@aselta.com (T. Figueiro).

0167-9317/$ - see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.mee.2013.03.113

the importance of individual parameters' contribution to the model result. Consider a given model, represented as $y = f(X)$, where $X = (x_1, x_2, \ldots, x_k)$ is the set of the parameters of the model. In this work, f is the model (presented in Fig. 1), x_i are the parameters, such as α, β_i and η_i, and the result y is the output CD/EOL of the model applied to a given pattern. Fig. 1 represents the model and which parameters variation is being considered to obtain the sensitivity to the output variation. The model consists in evaluating the aerial image of a given pattern by convolving it with a PSF with the parameters presented in the input set. In this paper, for sake of simplicity, we do not use any resist model other than considering a fixed threshold. The CD value is obtained from the Aerial Image contour extracted at a fixed threshold value (0.5) in the indicated metrology point. Please notice that if the same pattern provides several metrology points (the case of the proposed pattern in this work) each metrology point is considered as a distinct pattern for sensitivity analysis calculation purposes. In this sense, considering as the output the CD value and as the input the PSF parameters, the sensitivity analysis result would indicate how changes in the parameters of the PSF impact the pattern under evaluation. The higher the impact, the more sensitive the pattern is to the given parameter and, therefore, the more suitable to helping calibrating it.

The sensitivity analysis method used was the calculation of Sobol' Global sensitivity indices [9], which were presented with improved formulas for the same methodology at [10]. This work shows that Global sensitivity indices can be efficiently computed by Variance-based methods, implemented using quasi-Random sampling algorithms. These indices estimate how the variation of each input impacts the overall output of the model. This method is based on the expansion of the output as a sum of functions, each function depending on the combination of the inputs. For instance, a function depending on three parameters could be decomposed as presented in (2):

$$f(X) = f_0 + f_1(x_1) + f_2(x_2) + f_3(x_3) + f_12(x_1, x_2) + f_{13}(x_1, x_3) + f_{23}(x_2, x_3) + f_{123}(x_1, x_2, x_3) \quad (2)$$

where f_0 is the portion that does not depend on any parameter, f_1 is the portion that depends only on x_1, f_{23} is the portion that depends both in x_2 and x_3,and so on.

Based on this decomposition, it is possible to determine the total variance, as presented in (3) and the partial variance of each portion as presented in (4):

$$D = \int f(x)^2 dx - f_0^2 \quad (3)$$

where $f(X)$ is the model function applied to the input set X for a given test pattern and f_0 is the mean value.

$$D_i = \int f_i(x_i)^2 dx_i \quad (4)$$

where $f_i(x_i)$ is the contribution x_i to the model function $f(X)$.

Finally, the Global sensitivity indices can be calculated as presented in (5)

$$S_{i_1,\ldots,i_k} = \frac{D_{i_1,\ldots,i_k}}{D} \quad (5)$$

Notice that the larger the Global sensitivity index of a parameter is, the more a variation on the parameter's value affects the output value.

According to the model characteristics, analytical calculation of these parameters can be prohibitive. This is exactly the case of PSF models convoluted to different calibration patterns. However, there are several ways to estimate the sensitivity indices values based on quasi-Random sampling and Variance-based techniques. Methods for estimating those indices are presented in [9,11].

3. Proposed calibration pattern

A calibration pattern is proposed to evaluate the described procedure. It consists of finite extension line/space (L/S) grating or block, with different CDs and densities (see example in Fig. 2(a)). The originality of this approach is to perform the measurements in lines close to the border of the block (see detail in Fig. 2(b)). The evaluation of the resulting CD in different parts of the block provides information over the mid-range and long range effects. Fig. 3 shows the simulation of the dose exposed over a portion of the L/S Grating. It is possible to notice the reduction of the dose received (and consequently, a reduction on the CD value) as lines are closer to the border of the block.

It is known that the way the CDs are impacted in this case is directly related to the characteristics of the PSF and, therefore, indicates that this information may be useful to perform PSF model calibration.

Therefore, to sample the impact of any PSF in every range, it is necessary to explore the L/S Grating from the border up to 20 μm away from the border (which is usually larger than the range of the PSF), plus the center line (which is a reference as no long range effects, since it is compensated by the surroundings).

Some lines can be skipped to reduce the total number of measurements that may be required. This can be seen as a logarithmic sampling from the border, as presented in Fig. 2.

The evaluation of the quality of this pattern is presented in the results chapter of this paper.

4. Results

4.1. Sensitivity analysis evaluation

In order to evaluate the benefits of using the proposed calibration pattern, the computation of the sensitivity indices of all the five parameters of a 3 Gaussian PSF model was performed. The choice of a 3 Gaussians PSF was based on the fact that it presents short, middle and long range components. However, notice that any other model with different parameters would require the same

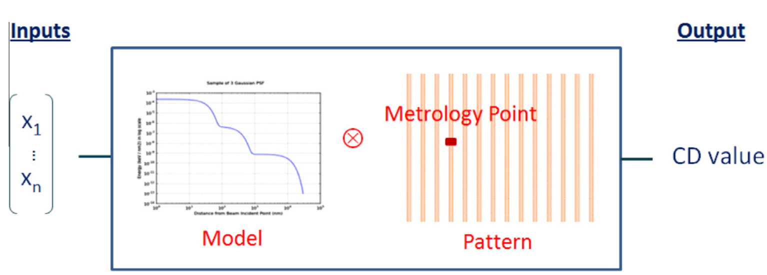

Fig. 1. The model being considered as the convolution of a PSF with a given pattern (and the PSF parameters $X_1 \ldots X_n$ and the test pattern being considered as its inputs).