Fast Simulation of Stochastic Exposure Distribution in Electron-beam Lithography

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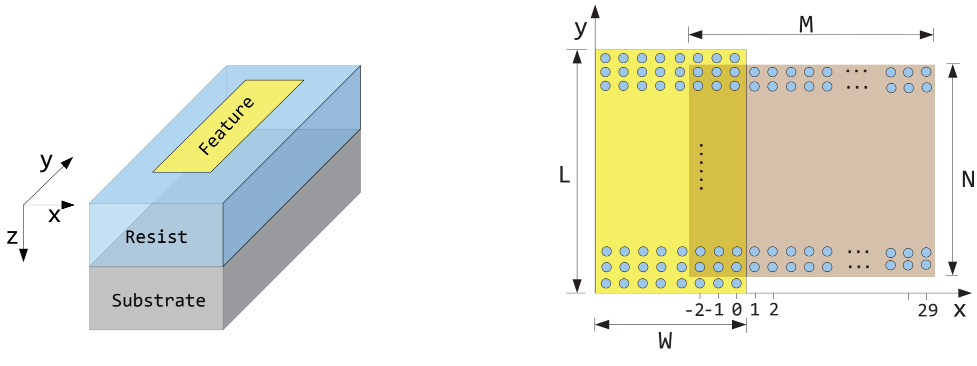
As the feature size is reduced well below 100 nm, the relative CD (critical dimension) variation becomes so large that it can have a significant effect on the minimum feature size and maximum circuit density realizable in most lithographic processes. One source of such variation which has been actively investigated is the line edge roughness (LER). One of the major factors which affect the LER in the electron-beam lithographic process is the fluctuation of exposure (energy deposited) in the resist. In order to develop an effective method to reduce the LER, it is critical to estimate it accurately. One may formulate an analytic model for the estimation. However, accuracy of the parameters required in such a model is not guaranteed. Another common method is to rely on the Monte Carlo simulation in computing the exposure distribution in a circuit pattern, i.e., generating a point spread function (PSF) for each point to be exposed, where the PSF is stochastic, to be referred to as *direct* Monte Carlo method ("DMC"). While this approach can lead to a more realistic estimation, it is not practical since the number of points (or PSF's to be generated) is tremendous and generating a PSF requires a long computation time. In this study, a new method to reduce the number of PSF's to be generated by several orders of magnitude without sacrificing the accuracy of estimating the exposure fluctuation has been investigated.

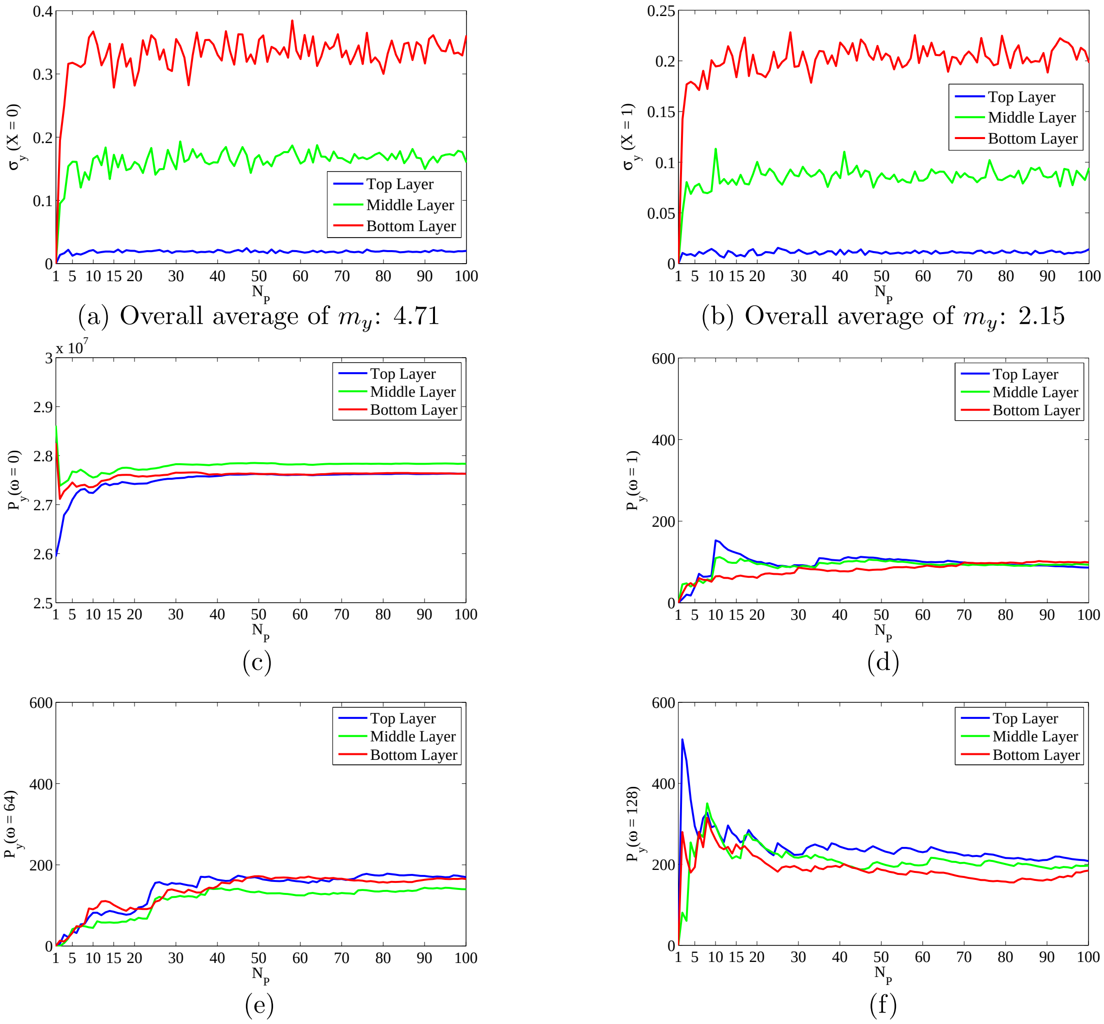
The key idea of the new method is to generate only a small number of (stochastic) PSF's and use them randomly in the exposure calculation for a circuit pattern, to be referred to as *simplified* Monte Carlo method ("SMC"). The validity of the method is verified by analyzing the behaviors of certain measures of exposure fluctuation as functions of the number (N_p) of PSF's used. The two measures employed in this study are the standard deviation (σ) and power spectral density ($P(\omega)$) of exposure distribution. The exposure at point (x, y, z) is denoted by $E(x, y, z)$ which is computed through convolution within a window of size $M \times N$ ("exposure window"), shown in Fig. 1, selecting a PSF randomly out of N_p PSF's for each point exposed by the electron beam. A line feature of size $W \times L$ is considered as shown in Fig. 1. The two measures are computed along the length (Y) dimension of the line. That is, given X and Z, $\sigma_y = \sqrt{\frac{1}{N}\sum_y (E(X, y, Z) - m_y)^2}$ where $m_y = \frac{1}{N}\sum_y E(X, y, Z)$, and $P_y(\omega) = |F_y(\omega)|^2$ where $F_y(\omega) = \frac{1}{N}\sum_y E(X, y, Z)e^{-j\omega y}$. Note that X can be interpreted as the relative distance from the line edge and Z as the index of resist layer.

In the simulation, the size of line feature is set to $W \times L = 8 \times 300$ where the pixel interval is 5 nm, i.e., the width of line is 40 nm. The exposure window of which size is $M \times N = 32 \times 256$ is overlapped with the feature 3 pixels in the X dimension where $X = 0$ corresponds to the edge of line feature. In order to obtain statistically stable results, σ_y and $P_y(\omega)$ are computed multiple times (up to 5) and averaged for each value of N_p with N_p varied from 1 to 100 (note that the DMC would require generation of 2400 PSF's). Each PSF is generated tracing 1000 electrons, i.e., 640 $\mu C/cm^2$ for the pixel size of 5 nm, for the substrate system of 300 nm PMMA on Si with the acceleration voltage of 50 keV. Some of the typical simulation results are provided in Fig. 2. It is seen that the standard deviation, σ_y, of exposure distribution quickly levels out (converges) as N_p, is increased beyond 10 at the bottom layer of resist, and even quicker at the top and middle layers. The convergence of the power spectral density varies with the frequency at all three layers. It appears that a higher frequency component requires a larger N_p to converge, where the maximum frequency component ($\omega = 128$) tends to become stable beyond around N_p=50. Hence, the proposed SMC can achieve the σ_y and $P_y(\omega)$ statistically equivalent to those by the DMC while using a very small fraction of the PSF's that would be required by the DMC. In this paper, the proposed method will be described in detail with a comprehensive set of simulation results.



(a) (b)

Figure 1: Simulation Model: (a) substrate system consisting of 300 nm PMMA on Si, and (b) a rectangular feature of $W \times L$ and a window of $M \times N$ within which the exposure distribution is analyzed.



(a) Overall average of m_y: 4.71

(b) Overall average of m_y: 2.15

(c) (d) (e) (f)

Figure 2: Standard deviation σ_y of exposure distribution (a) on the edge of feature, i.e., along the line $X = 0$ (refer to Fig. 1-(b)) and (b) right outside of the feature, i.e., along the line $X = 1$. Power spectral density $P_y(\omega)$ of exposure distribution along the line $X = 1$: (c) $\omega = 0$, (d) $\omega = 1$, (e) $\omega = 64$ and (f) $\omega = 128$ where $\omega = 1$ and $\omega = 128$ are the fundamental and maximum frequency components, respectively. The units of σ_y and $P_y(\omega)$ are eV/nm^3 and $(eV/nm^3)^2$, respectively.