Effects of stochastic exposure on critical dimension in electron-beam lithography

Hyesung Ji, Soo-Young Lee, Jin Choi, Seom-Beom Kim, In-Kyun Shin, and Chan-Uk Jeon

Citation: Journal of Vacuum Science & Technology B, Nanotechnology and Microelectronics: Materials, Processing, Measurement, and Phenomena **35**, 06G503 (2017);

View online: https://doi.org/10.1116/1.4995445

Effects of stochastic exposure on critical dimension in electron-beam lithography

Hyesung Ji and Soo-Young Lee[a)]
Department of Electrical and Computer Engineering, Auburn University, Auburn, Alabama 36849

Jin Choi, Seom-Beom Kim, In-Kyun Shin, and Chan-Uk Jeon
Samsung Electronics, Mask Development Team, 16 Banwol-Dong, Hwasung, Kyunggi-Do 445-701, South Korea

(Received 11 July 2017; accepted 4 October 2017; published 26 October 2017)

The computational lithography is a common approach to various optimizations of the electron-beam lithographic process. An essential step in most of the optimization problems is to estimate the exposure distribution in the resist, which is typically done through the convolution of the dose distribution of a circuit pattern with a point spread function (PSF). Although most of the computational lithographic methods employ a deterministic PSF, a PSF is stochastic in reality due to the shot noise and electron scattering. The feature size estimated from the stochastic exposure can be substantially different from that of the corresponding deterministic exposure. This difference stems from the fact that the rough development-front caused by the stochastic exposure makes the developing rate effectively larger. In this study, the effects of stochastic exposure on the critical dimension (linewidth) and their dependency on the lithographic parameters are analyzed in detail. Results obtained through an extensive simulation are presented and thoroughly discussed in this paper. © *2017 American Vacuum Society*. https://doi.org/10.1116/1.4995445

I. INTRODUCTION

Electron-beam (e-beam) has been widely used in the pattern transfer, especially for a pattern of fine features. However, the electron scattering during the process of exposing a pattern leads to the undesirable shape-distortion of written features, i.e., the proximity effect.[1–4] There have been many methods developed for reducing the proximity effect, most of which take a computational approach.[1,5–7] One of the essential components of the computational lithography needed for the proximity effect correction is the point spread function (PSF), which describes the exposure (energy deposited in the resist) distribution when a point is exposed. The exposure fluctuates, i.e., is stochastic, in reality due to the random nature of electron scattering and shot noise. Nevertheless, the PSF employed in the computational lithography is assumed to be deterministic, equivalently, the average PSF is used, in most cases. In this study, the discrepancy in computational-lithography results, which could be caused by using a deterministic PSF, is investigated.

The fluctuation of exposure, coupled with the randomness in the resist-development process, causes the roughness in the feature boundaries, e.g., line edge roughness (LER). The LER, which is independent of the feature size, limits the minimum feature size and maximum feature density and has been and is being extensively studied.[8] Another effect of exposure fluctuation, which has not received much attention, is on the size of a written feature. Due to the exposure fluctuation, the actual size of a written feature can be substantially different from that estimated based on the deterministic exposure. The reason for this effect is that a point with a lower exposure is helped by the neighboring points with higher exposures in the development process. That is, the effective developing rate at such a point is higher than the nominal value and there can be more such points in the stochastic exposure than in the deterministic exposure. Therefore, the stochastic exposure tends to make the size of a written feature larger compared to the deterministic exposure.

Lithographic parameters such as resist thickness, beam energy, etc., affect the exposure fluctuation. Also, the exposure fluctuation varies with the layer of resist. The main objectives of this study are to show that the stochastic exposure can have a substantial effect on the critical dimension (CD) of a line, i.e., linewidth, and analyze the dependency of the effect on the lithographic parameters through an extensive simulation. The effect of stochastic exposure tends to be larger for a thicker resist, a lower layer and a lower beam energy. In order to obtain realistic results, a computational lithographic method needs to take this effect into account.

The remainder of this paper is organized as follows. The model assumed in this study is depicted in Sec. II. The simulation method employed in analyzing the effect of stochastic exposure is described in Sec. III. The comparison between the deterministic and stochastic exposures and the dependency on the lithographic parameters are discussed in Sec. IV. The results from the simulation are provided with the detailed discussion in Sec. V, followed by a summary in Sec. VI.

II. MODEL

In order to focus on the effect of stochastic exposure on the CD of a feature excluding the interfeature proximity effect, the case of a single line is considered where the line length is much larger than the linewidth. A typical substrate

---

[a)] Electronic mail: leesooy@eng.auburn.edu

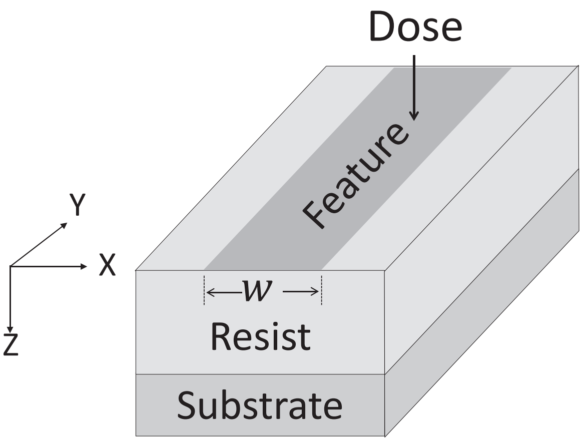


FIG. 1. Typical substrate system where a long line along the Y-dimension is exposed with a uniform dose considered.

system is employed which is composed of a resist layer on a substrate as illustrated in Fig. 1. The line feature is transferred into the resist layer through the e-beam lithographic process where the feature is exposed with a uniform dose D.

In most of the previous studies, the PSF is assumed to be deterministic and space-invariant. As a result, the exposure is also deterministic. In such a case, the exposure distribution, $e(x, y, z)$, in the resist layer, when the line feature is exposed, can be computed as follows:

$$e(x,y,z) = \int\int d(x',y')p(x-x',y-y',z)dx'dy', \quad (1)$$

where $d(x, y)$ is the dose distribution, i.e., D inside the feature and 0 outside, and $p(x, y, z)$ is a PSF.

Suppose that an infinitely long line with a certain width is exposed with a uniform dose. The length dimension of the line is aligned with the Y-axis as shown in Fig. 1. Let $e_d(x, y, z)$ represent the deterministic exposure distribution when such a line is exposed. Then, $e_d(x, Y_1, z) = e_d(x, Y_2, z)$ where $Y_1 \neq Y_2$, i.e., the exposure does not vary along the Y-dimension as shown in Fig. 2(a).

In reality, the PSF $p(x, y, z)$ is not deterministic but stochastic due to the shot noise in the e-beam source and electron scattering in the resist. Therefore, $p(x,y,z) \neq p'(x,y,z)$, where $p(x, y, z)$ and $p'(x,y,z)$ are the instances of PSF for two different points exposed, i.e., the PSF is space-variant. The exposure distribution cannot be obtained through the space-invariant convolution with a single instance of PSF in Eq. (1). Let $e_s(x, y, z)$ represent the stochastic exposure distribution for an infinitely long line in Fig. 1. Unlike the deterministic exposure, $e_s(x, Y_1, z) \neq e_s(x, Y_2, z)$, where $Y_1 \neq Y_2$ as shown in Fig. 2(b).

With the same dose for both deterministic and stochastic exposures, $e_d(x, y, z) = E[e_s(x, y, z)]$ which may be computed by averaging $e_s(x, y, z)$ along the Y-dimension in the case of an infinitely long line. In this study, the effect which the stochastic exposure has on the linewidth realized through the e-beam lithographic process is analyzed in detail, compared to the deterministic exposure which is assumed in most cases.

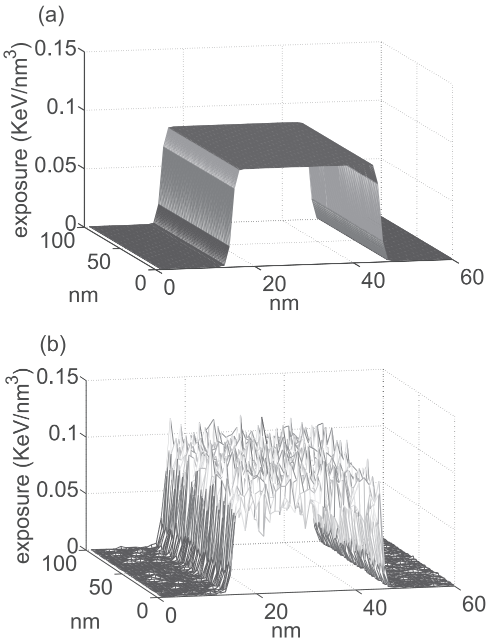


FIG. 2. (a) Deterministic exposure and (b) stochastic exposure for a line feature.

III. SIMULATION METHOD

The effect of stochastic exposure is analyzed through the simulation where a typical e-beam lithographic process is followed. In this simulation study, "lithographic parameters" which affect the exposure distribution are considered, e.g., resist thickness, resist layer, beam energy, and target linewidth. With the lithographic parameters set, the stochastic and deterministic exposure distributions are generated. The exposure is converted into the developing rate. Then, the resist-development simulation is carried out to obtain the remaining resist profile from which the actual linewidth is measured (computed).

A. Exposure distribution

The PSF is generated through a Monte Carlo simulation. In order to compute the stochastic exposure distribution, $e_s(x, y, z)$, an instance of PSF needs to be generated for every point exposed. Since the Monte Carlo simulation is computationally intensive and the number of points exposed is large, such an approach would be too time-consuming to be practical. A practical method for generating the stochastic exposure distribution was previously developed.[9] In this method, a certain number of the instances of a stochastic PSF is generated and, given a circuit pattern, an instance of the PSF is randomly selected for each point exposed in the pattern. Although each instance is used multiple times, it has been shown that the statistical properties of the stochastic exposure generated in such a way are sufficiently close to those obtained by generating an instance of stochastic PSF for every point. Hence, $e_s(x, y, z)$ is generated by this method.

To ensure that the deterministic exposure is equivalent to the stochastic exposure, i.e., $e_d(x, y, z) = E[e_s(x, y, z)]$ (refer to Sec. II), the deterministic exposure distribution is generated as follows. In order to reduce the fluctuation of exposure, a PSF is generated with a large number of electrons through the Monte Carlo simulation. The exposure, $e_{d0}(x, y, z)$, computed using the PSF, is not completely deterministic. Therefore, the deterministic exposure is obtained by integrating $e_{d0}(x, y, z)$ along the length dimension of a line feature (Y-dimension: see Fig. 1) and replicating the integration result along the same dimension. That is,

$$e_d(x,y,z) = \frac{1}{L}\int_0^L e_{d0}(x,y,z)dy, \tag{2}$$

where L is the length of the line feature.

B. Development simulation

The developing speed of resist is not linearly proportional to the exposure, and therefore, the exposure is converted into the developing rate, $r(x, y, z)$, before the development simulation. The relationship between the exposure and developing rate, referred to as "conversion formula," may be derived through an experiment. In this study, the conversion formula shown in Fig. 3, which was obtained in a previous study,[6] is employed.

The remaining resist profile may be obtained from the distribution of developing rate through a simulation. There are many methods designed for the development simulation such as the cell-removal[10] and fast-marching methods.[11] However, they are often computationally intensive and therefore time-consuming. Therefore, a fast development-simulation method[12] is utilized, which was designed mainly for simple shapes such as lines, but was shown to be accurate even for more general shapes.

C. Minimum dose

Given a target linewidth and a resist layer, the "minimum dose" required for the actual linewidth at the resist layer to be the target linewidth is derived through an iterative procedure using the deterministic exposure distribution. In order to avoid the resist-development simulation in each iteration, a L-shaped development path[12] is utilized, which starts at a point on the top surface of resist within the line feature, follows a vertical path segment down, and turns onto a lateral path segment to the line edge on the specified resist layer. Since a long line is exposed with a uniform dose, the exposure is the largest at the line center, monotonically decreases toward both edges of the line, and does not vary along the length dimension. For each of the L-shaped paths starting at different points (from the line center to the line edge), the dose required for the path to end at the target edge location is computed as illustrated in Fig. 4. The L-shaped path for which such dose is lowest is the "critical path" (for the deterministic exposure) and the lowest dose is the minimum dose.

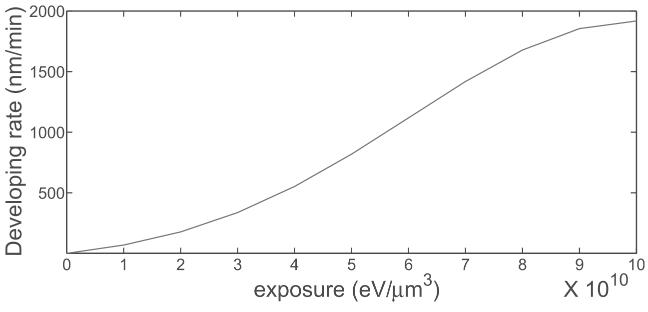


FIG. 3. Conversion formula maps the exposure to the developing rate.

The same minimum dose is used in computing both deterministic and stochastic exposures for the resist-development simulation. In the case of deterministic exposure, the actual linewidth measured from the remaining resist profile must be the same as the target linewidth since the minimum dose is derived with the deterministic exposure. However, the actual linewidth obtained from the stochastic exposure may not be the same as that from the deterministic exposure. Hereafter, the former is referred to as "stochastic linewidth" and the latter as "deterministic linewidth." Note that the stochastic linewidth varies and therefore is averaged along the length dimension of a line.

IV. DEPENDENCY ON LITHOGRAPHIC PARAMETERS

In this section, why the stochastic linewidth can be different from the deterministic linewidth is explained and the general dependency of stochastic linewidth on each of the lithographic parameters is discussed.

A. Deterministic versus stochastic

The developing rate, $r(x, y, z)$, obtained from the exposure, $e(x, y, z)$, through the conversion formula (see Fig. 3) is a point-by-point developing rate, referred to as the "nominal developing rate." The actual developing rate at a point, referred to as the "effective developing rate," can be significantly different from the nominal developing rate depending on the states of its neighboring points. Suppose that the resist layer is modeled by a 3D array of cubic voxels. When at least one of six sides (faces) of a voxel is exposed to the developer (i.e., one of the six neighboring voxels is completely developed), the voxel starts to be developed. The more sides are exposed to the developer, the faster the voxel is developed. That is, the effective developing rate of such a voxel is higher than its nominal developing rate (which can be considered to be the developing rate when only one side is exposed to the developer).

When a long line along the Y-axis (refer to the model described in Sec. II) is exposed with a uniform dose, $r(x, y, z)$

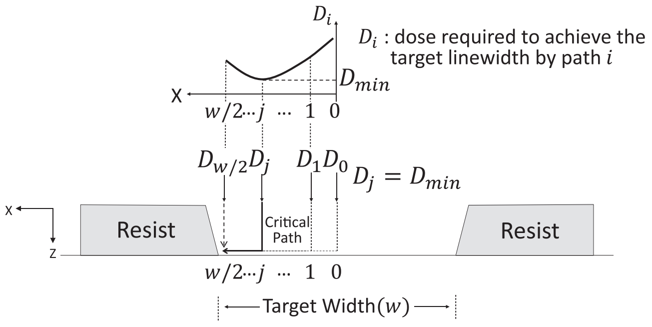
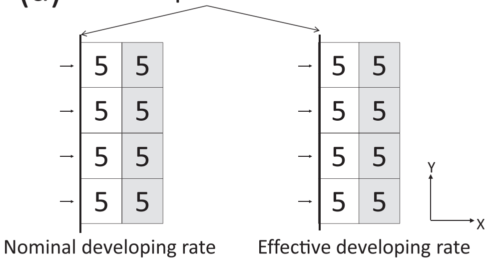


FIG. 4. Minimum dose is found through an iterative procedure which looks for the L-shaped path requiring the lowest dose to reach the target edge location.

does not vary with *y* and decreases from the center of the line toward the edges. Therefore, the development process progresses from the top surface of resist down (along the Z-dimension) and from the center of the line outward (along the X-dimension). For the convenience of description, let us define "developing path" to be a path along which the resist gets developed. In the case of deterministic exposure, the front of development process remains straight during the development process as illustrated in Fig. 5(a) since all developing paths advance at the same speed and therefore in phase. As a result, all voxels on the front of development process are at the same state, i.e., no voxel is developed more or less than its neighboring voxels (equivalently, adjacent developing paths do not interact). Hence, the effective developing rate of each voxel (point) is equal or very close to its nominal developing rate.

On the other hand, in the case of stochastic exposure, it is highly likely that adjacent developing paths advance out of phase, i.e., a developing path is ahead of or behind its neighboring paths, since the distribution of developing rate along a developing path varies with the path. As a result, the front of developing process is not straight but rough [see Fig. 5(b)]. Some voxels are exposed more to the developer than others, making their effective developing rates higher than their nominal developing rates. That is, a developing path ahead of others helps (pulls) those behind. Also, a developing path currently behind others may get ahead later. Through this interaction among developing paths, the effective developing rate becomes higher than the nominal developing rate for most voxels in the case of stochastic exposure. Therefore, the stochastic linewidth is larger in general than the deterministic linewidth.

(a) Development front



(b) Development front

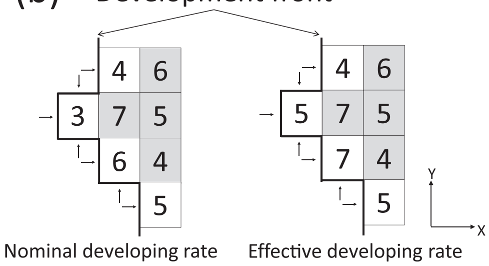


Fig. 5. Illustration of nominal and effective developing rates for (a) the deterministic exposure and (b) the stochastic exposure when a long line is exposed with a uniform dose. The number in each voxel is an illustrative developing rate. In the illustration, it is assumed that the effective developing rate of a voxel with one side exposed to the developer is the same as the nominal developing rate. The more sides of a voxel are exposed to the developer, the larger the increase in the effective developing rate is. Note that for the voxels (in gray) not exposed to the developer yet the effective developing rates, the same as the nominal developing rates, are shown.

B. Resist layer

As electrons enter the resist, they start to interact with resist molecules depositing their energy and being scattered. In most cases, they deposit more energy at an upper layer of resist than at a lower layer, i.e., the exposure level is higher at an upper layer. The random nature of electron scattering is one of the main reasons why the exposure is stochastic. It is more likely for electrons to be scattered at a lower layer of resist than at an upper layer since they become weaker as they travel down in the resist. This tends to make the relative fluctuation (randomness) of exposure to increase from the top layer to the bottom layer though the absolute fluctuation is smaller at a lower layer. Therefore, it is expected that the stochastic linewidth becomes larger for a lower layer.

The absolute fluctuation of exposure is defined as the standard deviation of exposure and the relative fluctuation of exposure as the absolute fluctuation of exposure divided by the average exposure.

C. Resist thickness

When the resist is thinner, the exposure distribution and the stochastic property of exposure show a smaller difference between the top and bottom layers. However, the fluctuation of exposure becomes larger at a lower layer, compared to an upper layer, as the resist thickness increases. Note that for a thicker resist, there is more room for electrons to lose their energy being scattered more as they travel down. Hence, the stochastic linewidth tends to be larger at lower layer for a thicker resist.

D. Beam energy

An electron with a higher energy is less likely to interact with resist molecules. Therefore, when the beam energy is higher, electrons are scattered less and the fluctuation of exposure is smaller. This makes the stochastic linewidth smaller for a higher beam energy.

E. Feature size

In most cases, the stochastic property of exposure is not significantly affected by the feature size (linewidth in this study). Therefore, it is expected that the amount of linewidth increase due to the stochastic exposure is independent of the linewidth. That is, as the linewidth increases, the stochastic linewidth increases only by the amount of linewidth increase.

V. RESULTS AND DISCUSSION

A. Simulation and results

The substrate system employed in this study is composed of PMMA on Si. The thickness of PMMA is varied from 100 to 500 nm and the beam energy from 10 to 50 keV. For each case (combination of resist thickness and beam energy), a set

TABLE I. ΔCD at the top, middle and bottom layers for the resist thickness of 100 nm.

		ΔCD (nm)		
Beam energy (keV)	Feature size (nm)	Top	Middle	Bottom
10	30	0.92	4.28	8.23
	50	0.96	4.46	8.64
	100	0.93	4.65	9.23
30	30	0.78	2.47	4.18
	50	0.77	2.48	4.25
	100	0.73	2.46	4.21
50	30	0.78	2.27	3.35
	50	0.77	2.28	3.30
	100	0.79	2.26	3.19

TABLE II. ΔCD at the top, middle, and bottom layers for the resist thickness of 300 nm.

		ΔCD (nm)		
Beam energy (keV)	Feature size (nm)	Top	Middle	Bottom
10	30	1.62	13.09	20.06
	50	1.73	14.29	19.06
	100	1.73	15.01	21.98
30	30	1.16	7.65	13.89
	50	1.22	7.58	14.07
	100	1.16	7.60	14.50
50	30	1.02	5.31	10.27
	50	1.08	5.34	10.35
	100	1.07	5.39	10.67

TABLE III. ΔCD at the top, middle, and bottom layers for the resist thickness of 500 nm.

		ΔCD (nm)		
Beam energy (keV)	Feature size (nm)	Top	Middle	Bottom
10	30	2.56	14.43	10.36
	50	2.70	17.58	10.29
	100	2.73	20.22	14.06
30	30	1.75	11.13	16.92
	50	1.81	11.73	17.45
	100	1.78	11.74	19.19
50	30	1.57	9.81	16.59
	50	1.63	10.13	18.30
	100	1.61	10.19	18.37

of 80 instances of the corresponding PSF is generated by a Monte Carlo simulation [CASINO (Ref. 13)] with 40 electrons (640 μC/cm^2 for the pixel interval of 1 nm). Three different linewidths, 30, 50, and 100 nm, are considered where the line-length is 300 nm in all cases. Given a linewidth (resist thickness and beam energy), the stochastic exposure distribution is computed using the corresponding set of PSF instances. Then, the remaining resist profile is obtained through the development simulation and the linewidth (i.e., stochastic linewidth) is measured at the top, middle, and bottom layers of the profile. In each case, a (stochastic) PSF is generated with a large number of electrons (10 000) to minimize the fluctuation of exposure. Then, the deterministic exposure distribution is derived from the stochastic exposure distribution obtained from this PSF as described in Sec. III A. The same procedures are followed with the deterministic exposure distribution to obtain the deterministic linewidth. The steps in the simulation procedures are described below.

(1) Generate the stochastic and deterministic PSF's using the Monte Carlo simulation software (CASINO).

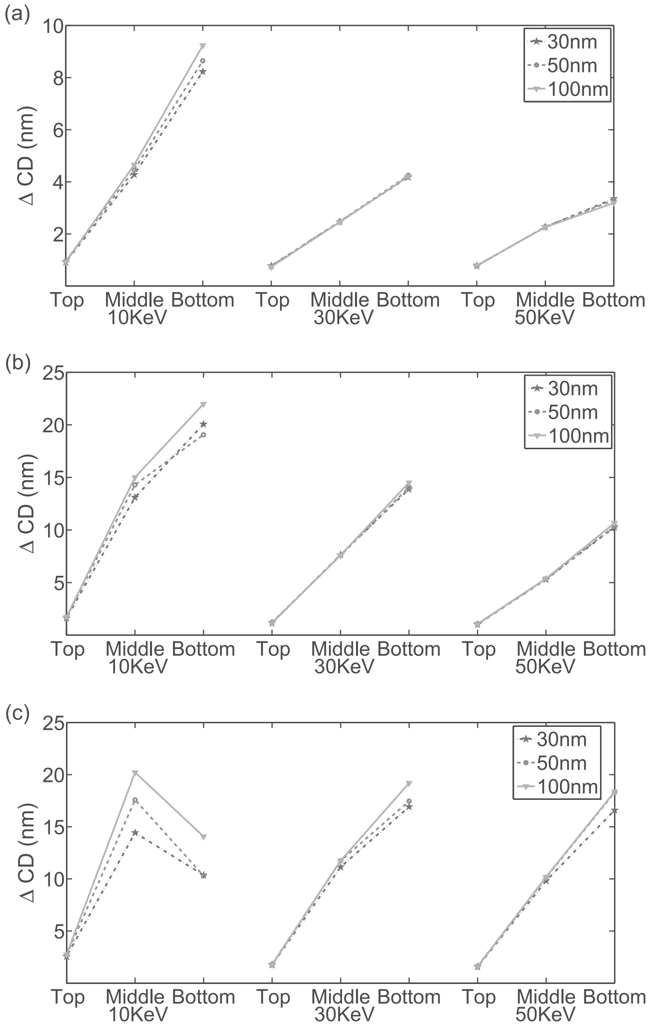


FIG. 6. Dependency of ΔCD on the resist layer with the resist thickness of (a) 100 nm, (b) 300 nm, and (c) 500 nm (for the feature size of 30, 50, and 100 nm and the beam energy of 10, 30, and 50 keV).

(2) Compute the stochastic and deterministic exposures through the convolution of the pattern of a long line with the PSF. A base dose is assumed.
(3) Normalize the stochastic exposure to the deterministic exposure.
(4) Find the minimum dose, $D_{\min}$, using the deterministic exposure.
(5) Scale the deterministic and stochastic exposures by $D_{\min}$.
(6) Perform the resist-development simulation with each of the deterministic and stochastic exposures.
(7) Calculate the CD and LER from the remaining resist profiles.

In the analysis of the results in Sec. V B, the focus is placed on the difference between the stochastic and deterministic linewidths, which is denoted by ΔCD,

$$\Delta\mathrm{CD} = \mathrm{stochastic\,linewidth} - \mathrm{deterministic\,linewidth}. \quad (3)$$

Note that ΔCD is a quantification of the possible estimation error of linewidth when the deterministic exposure is assumed in the estimation.

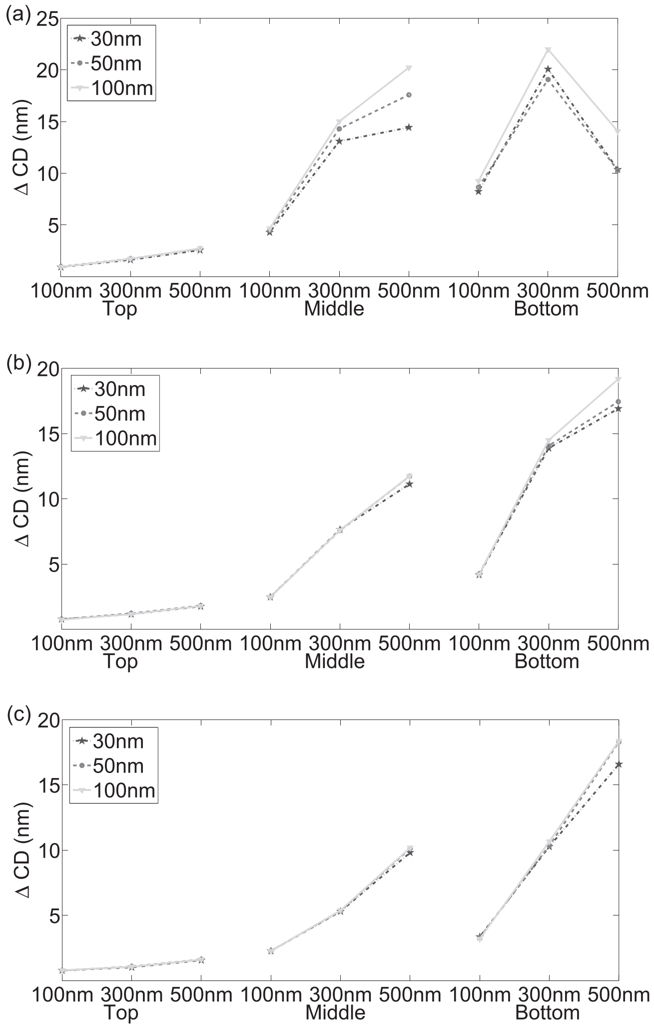


Fig. 7. Dependency of ΔCD on the resist thickness with the beam energy of (a) 10 keV, (b) 30 keV, and (c) 50 keV (for the feature size of 30, 50, and 100 nm and at the top, middle, and bottom layers).

The results of ΔCD obtained through an extensive simulation are provided in three tables, one for each thickness of resist (Tables I–III). Also, they are plotted as a function of each of the four lithographic parameters in order to analyze the dependency of ΔCD on the parameters. The graphs are presented in Figs. 6–9. Each figure will be referred to in the corresponding section of discussion.

B. Discussion

From Tables I to III and Figs. 6 to 9, it is seen that the difference (ΔCD) between the stochastic and deterministic linewidths can be significant. The value of ΔCD may be affected to some extent by the specific set-up of simulation, e.g., the absolute level of dose, developer (i.e., the exposure-to-rate conversion), etc. However, the results obtained in this study clearly indicate that the effect of stochastic exposure on the CD of a feature would not be negligible and therefore must be considered in the computational lithography. The dependency of ΔCD on each lithographic parameter is analyzed below, which shows a consistent trend in most cases.

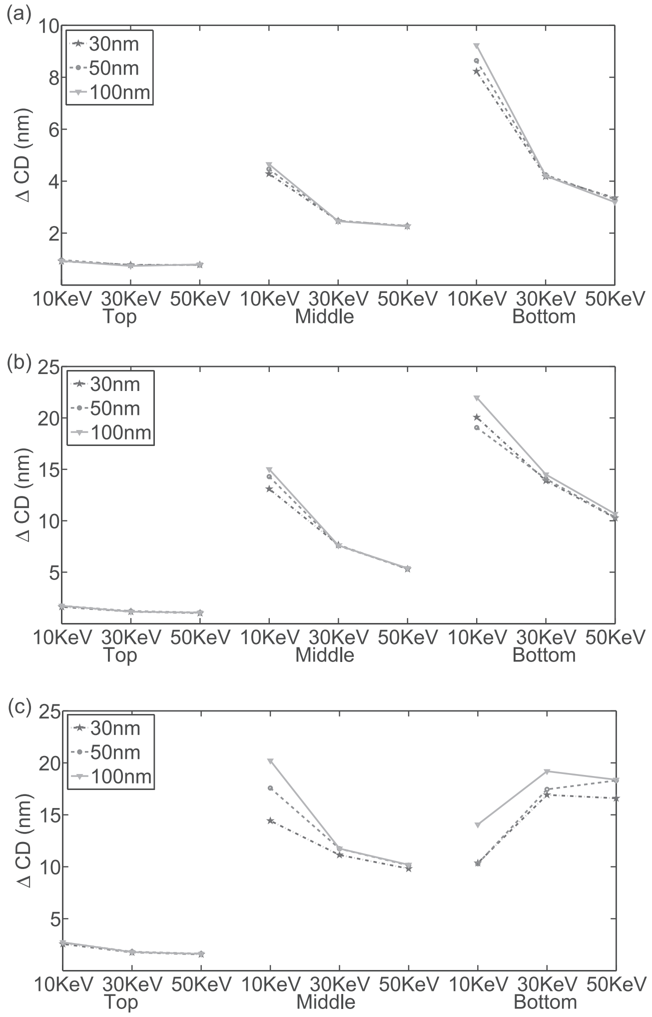


Fig. 8. Dependency of ΔCD on the beam energy with the resist thickness of (a) 100 nm, (b) 300 nm, and (c) 500 nm (for the feature size of 30, 50, and 100 nm and at the top, middle, and bottom layers).

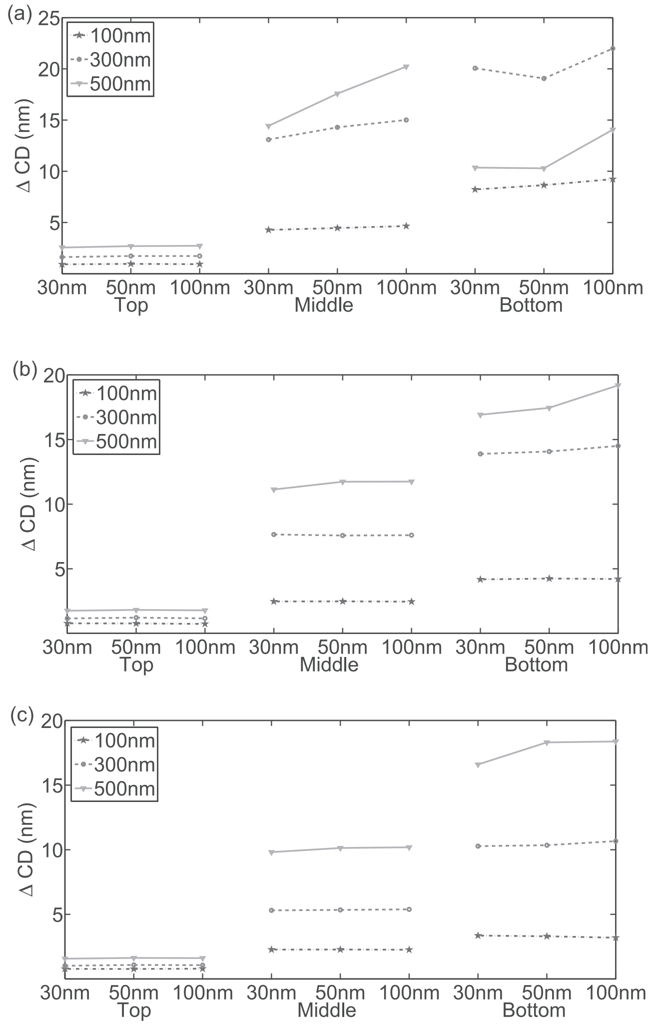


FIG. 9. Dependency of ΔCD on the feature size with the beam energy of (a) 10 keV, (b) 30 keV, and (c) 50 keV (for the resist thickness of 100, 300, and 500 nm and at the top, middle, and bottom layers).

1. Resist layer

At a lower layer of resist, ΔCD is larger as can be seen in Tables I–III and Fig. 6. As explained in Sec. IV B, at a lower layer, the relative fluctuation of exposure is larger though the absolute fluctuation of exposure is smaller (see Fig. 10). This makes the stochastic linewidth larger and therefore ΔCD larger. Also, the PSF is broader at a lower layer, which makes the exposure contrast lower, i.e., the exposure decreases spatially slower from the inside of a feature to the outside. In other words, the exposure outside a feature is comparable to the exposure inside. The actual edge of a feature is outside the feature in the case of stochastic exposure (when it is at the target edge in the case of deterministic exposure). Therefore, the higher exposure contrast at a lower layer helps enlarging ΔCD.

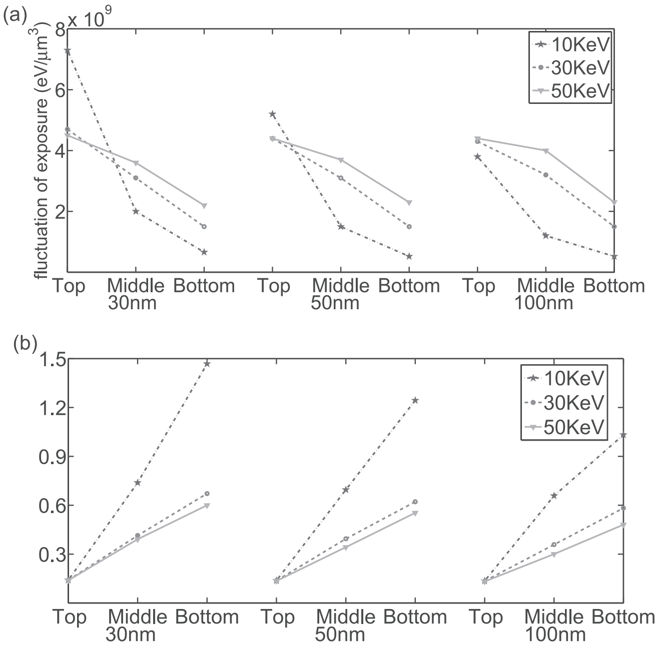


FIG. 10. (a) Absolute and (b) relative fluctuations of exposure at the top, middle, and bottom layers and for the feature size of 30, 50, and 100 nm (for the resist thickness of 500 nm). The absolute and relative fluctuations of exposure averaged within the domain of developed resist on each layer are plotted.

One deviation from the general trend (a larger ΔCD for a lower layer) occurs when the beam energy is 10 keV for the resist thickness of 500 nm [see Fig. 6(c)]. Note that ΔCD is smaller at the bottom layer than at the middle layer. When the beam energy is low for a thicker resist, electrons are less likely to reach a lower layer. As a result, in this particular case, the "external exposure," defined as the total exposure outside a feature as illustrated in Fig. 11, is much lower at the bottom layer than at the middle layer (see Fig. 12). The effect of this much-lower external exposure becomes dominant, compared to that of the larger relative fluctuation of exposure, at the bottom layer, resulting in the decrease in ΔCD from the middle layer to the bottom layer.

2. Resist thickness

It can be seen in Tables I–III and Fig. 7 that for a thicker resist, ΔCD is larger. As the resist thickness increases, the PSF becomes broader (see Fig. 13) and the relative fluctuation of exposure increases at each layer. Therefore, ΔCD at a certain layer becomes larger for a thicker resist. Another way to understand this trend is to realize that increasing the resist thickness is equivalent to considering a lower layer. One can see that ΔCD at a layer for a thickness is similar to ΔCD at a lower layer for a thinner resist. It is also seen that the increase of ΔCD for increasing the resist thickness is very minimal at the top layer. The reason for this is that the

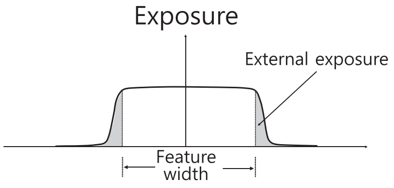


FIG. 11. External exposure is the total exposure outside a feature.

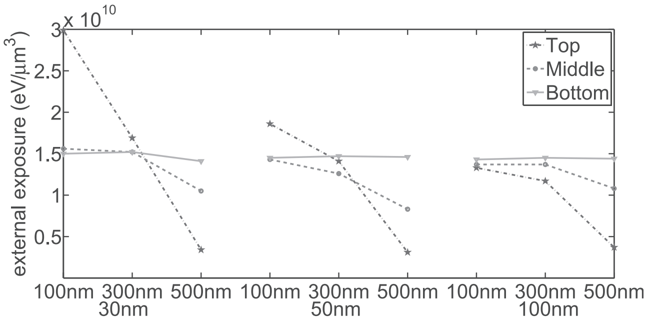


Fig. 12. External exposure for the resist thickness of 500 nm (at the top, middle, and bottom layers, and for the feature size of 30, 50, and 100 nm).

exposure at the top layer is not affected significantly by increasing the resist thickness.

A different observation is that ΔCD decreases at the bottom layer when the resist thickness increases from 300 to 500 nm with the beam energy of 10 keV [see Fig. 7(a)]. At a low beam-energy of 10 keV, the exposure level, accordingly the external exposure, decreases greatly at the bottom layer though the relative fluctuation of exposure increases as the

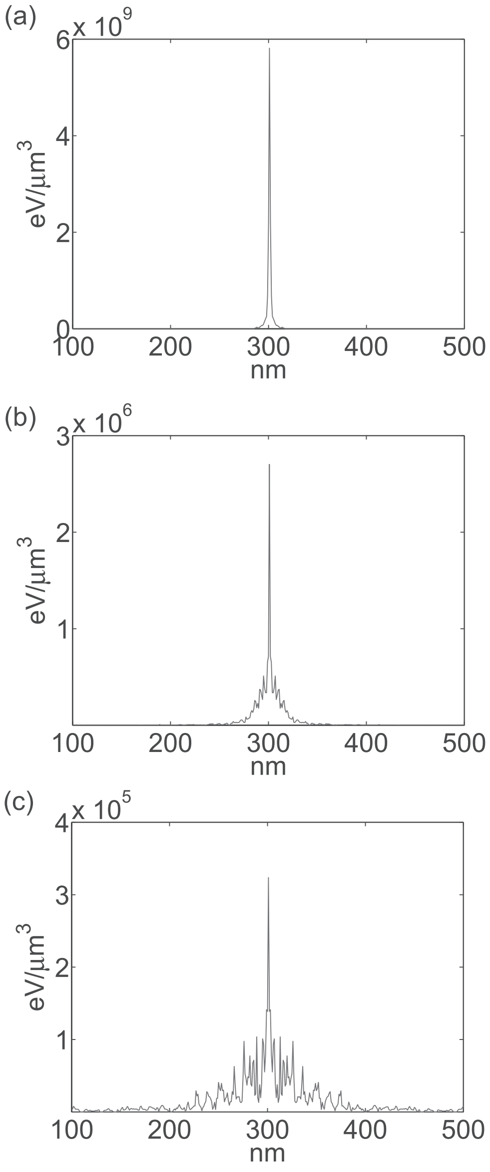


Fig. 13. PSF at the bottom layer for the beam energy of 10 keV, and the resist thickness of (a) 100 nm, (b) 300 nm, and (c) 500 nm.

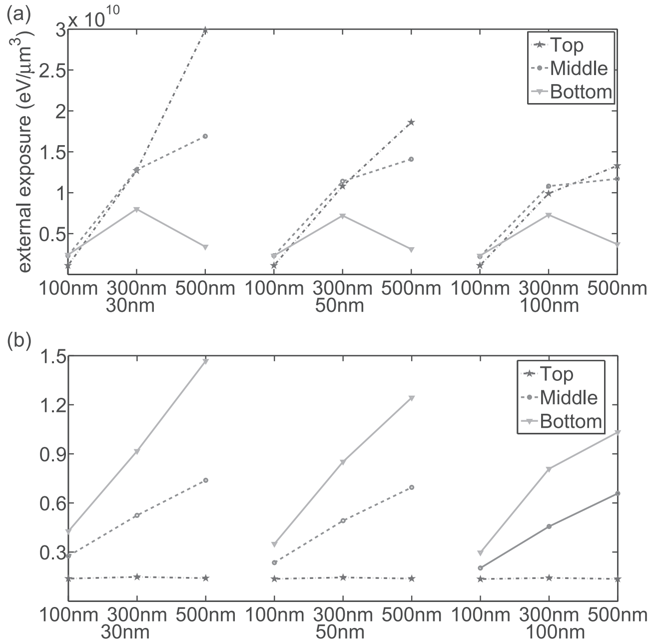


Fig. 14. (a) External exposure and (b) the relative fluctuation of exposure for the beam energy of 10 keV (for the resist thickness of 100, 300, and 500 nm and the feature size of 30, 50, and 100 nm). The relative fluctuation of exposure averaged within the domain of developed resist on each layer is plotted.

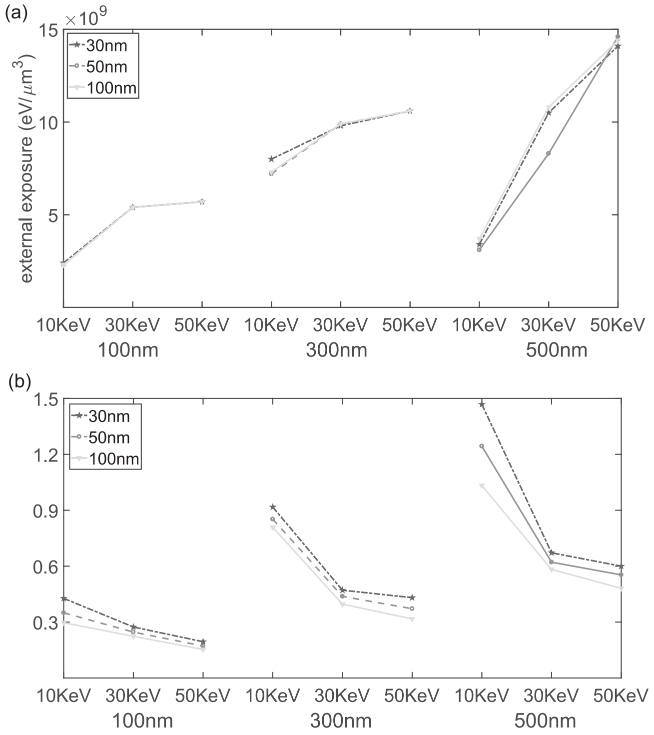


Fig. 15. (a) External exposure and (b) the relative fluctuation of exposure for the beam energy of 10, 30, and 50 keV and for the resist thickness of 100, 300, and 500 nm (a case at the bottom layer). The relative fluctuation of exposure averaged within the domain of developed resist on each layer is plotted.

resist becomes thicker from 300 to 500 nm (see Fig. 14). This leads to a smaller ΔCD for the resist thickness of 500 nm.

3. Beam energy

Tables I–III and Fig. 8 show that Δ*CD* is larger for a lower beam energy. As the beam energy increases, electrons scatter less in the resist, making the exposure fluctuation smaller [see Fig. 15(b)] and therefore ΔCD smaller. Also, for a higher beam energy, the PSF is sharper, which makes the external exposure lower and therefore ΔCD smaller (see Fig. 16). In addition, the dose needs to be higher for a higher beam energy since higher-energy electrons deposit their energy less in the resist. A higher dose leads to a smaller relative fluctuation of exposure, making ΔCD smaller.

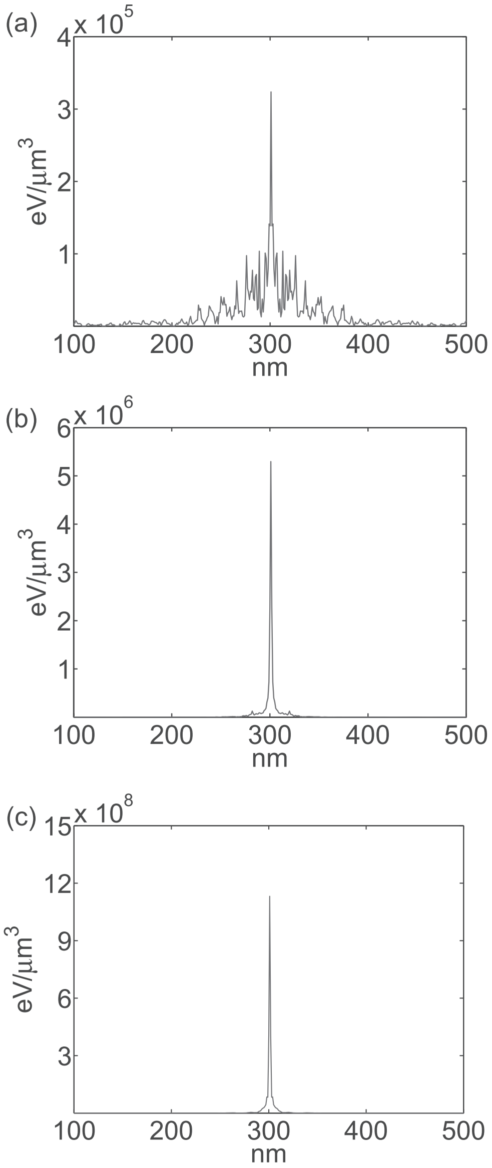


FIG. 16. PSF at the bottom layer for the resist thickness of 500 nm: beam energy of (a) 10 keV, (b) 30 keV, and (c) 50 keV.

A different behavior is observed at the bottom layer when the resist thickness is 500 nm, i.e., ΔCD does not always monotonically decrease as the beam energy increases from 10 to 50 keV [see Fig. 8(c)]. Specifically, ΔCD increases with the increase in the beam energy from 10 to 30 keV. This is most probably due to the relatively larger increase in the external exposure in these cases [see Fig. 15(a)].

4. Feature size

The PSF, specifically its sharpness and randomness which affect ΔCD, is independent of the feature size (linewidth). Therefore, as can be seen in Tables I–III and Fig. 9, ΔCD remains almost the same as the feature size changes in most cases. However, in some cases, ΔCD increases slightly as the feature size increases. This may be explained as follows. In general, a higher dose is required for a smaller feature due to the proximity effect. The variation of the required dose for different feature sizes is larger when the PSF is broader, e.g., a lower beam energy, a lower layer, or a thicker resist as seen in Fig. 17. A lower dose, required for a larger

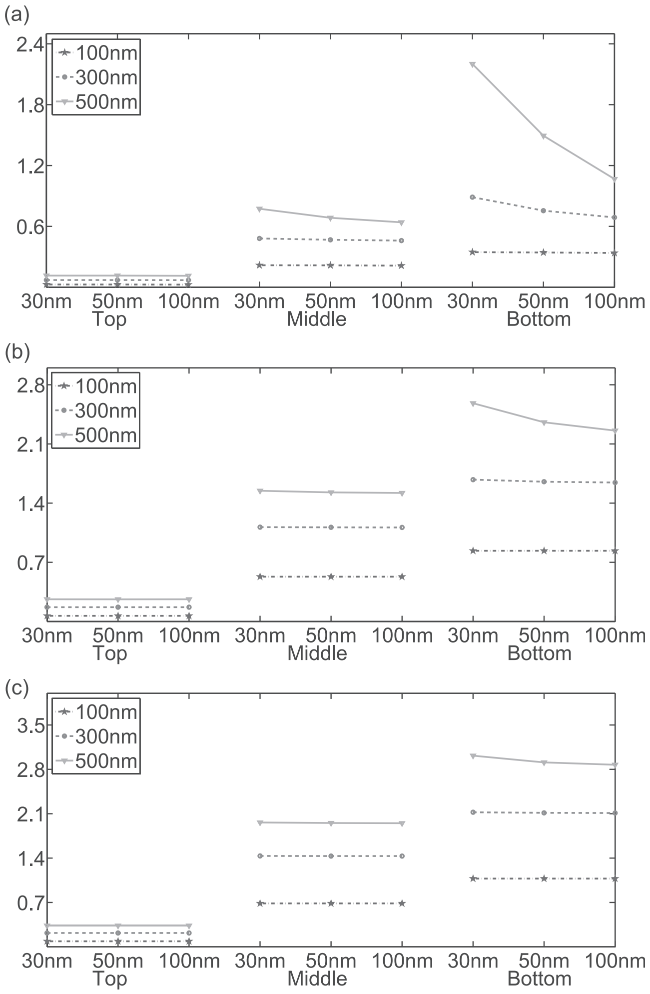


FIG. 17. Normalized dose for varying feature size for the beam energy of (a) 10 keV, (b) 30 keV, and (c) 50 keV (for the resist thickness of 100, 300, and 500 nm). The base dose is 640 μC/cm^2.

feature, leads to a larger fluctuation of exposure and therefore a larger ΔCD.

VI. SUMMARY

The exposure in the resist is inherently stochastic, while most of the studies in the computational lithography assume a deterministic exposure distribution. In the case of stochastic exposure, a faster developing path pulls a slower one and can become a slower one later. This interaction among adjacent developing paths tends to make the effective developing rate at a point larger than its nominal developing rate. Therefore, the CD of a feature, estimated based on the stochastic exposure, can be larger than the CD based on the deterministic exposure. In this study, the effect of the stochastic exposure on the CD has been analyzed through an extensive simulation study. The general trend is that the difference between the stochastic and deterministic linewidths is larger for a thicker resist, a lower beam energy, or a lower layer of resist. Because of this difference, results based on the deterministic exposure in the computational lithography, such as the results from the proximity effect correction, might not be realistic. Therefore, in order to obtain realistic results in the computational lithography, it is necessary to use the stochastic exposure or compensate results from the deterministic exposure for the difference.

ACKNOWLEDGMENT

This work was supported in part by a research grant from Samsung Electronics Co., Ltd.

[1] S.-Y. Lee and B. D. Cook, IEEE Trans. Semicond. Manuf. **11**, 108 (1998).

[2] R. Rau, J. McClellan, and T. Drabik, J. Vac. Sci. Technol., B **14**, 2445 (1996).

[3] G. P. Watson, L. A. Fetter, and J. A. Liddle, J. Vac. Sci. Technol., B **15**, 2309 (1997).

[4] G. P. Watson, S. D. Berger, and J. A. Liddle, J. Vac. Sci. Technol., B **16**, 3256 (1998).

[5] M. Osawa, K. Takahashi, M. Sato, and H. Arimoto, J. Vac. Sci. Technol., B **19**, 2483 (2001).

[6] Q. Dai, S.-Y. Lee, S.-H. Lee, B.-G. Kim, and H.-K. Cho, Microelectron. Eng. **88**, 902 (2011).

[7] Q. Dai, S.-Y. Lee, S.-H. Lee, B.-G. Kim, and H.-K. Cho, J. Vac. Sci. Technol., B **30**, 06F307 (2012).

[8] M. Nagase, H. Namatsu, K. Kurihara, K. Iwadate, K. Murase, and T. Makino, Jpn. J. Appl. Phys., Part 1 **35**, 4166 (1996).

[9] X. Zhao, S.-Y. Lee, S.-H. Lee, B.-G. Kim, and H.-K. Cho, J. Vac. Sci. Technol., B **30**, 06F308 (2012).

[10] Y. Hirai, S. Tomida, K. Ikeda, M. Sasago, M. Endo, S. Hayama, and N. Nomura, IEEE Trans. Comput.-Aided Des. **10**, 802 (1991).

[11] J. Sethian, Proc. Natl. Acad. Sci. U. S. A. **93**, 1591 (1996).

[12] Q. Dai, R. Guo, S.-Y. Lee, J. Choi, S.-H. Lee, I.-K. Shin, C.-U. Jeon, B.-G. Kim, and H.-K. Cho, Microelectron. Eng. **127**, 86 (2014).

[13] D. Drouin, A. R. Couture, D. Joly, X. Tastet, V. Aimez, and R. Gauvin, Scanning **29**, 92 (2007).