An efficient dose-compensation method for proximity effect correction*

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Abstract: A novel simple dose-compensation method is developed for proximity effect correction in electron-beam lithography. The sizes of exposed patterns depend on dose factors while other exposure parameters (including accelerate voltage, resist thickness, exposing step size, substrate material, and so on) remain constant. This method is based on two reasonable assumptions in the evaluation of the compensated dose factor: one is that the relation between dose factors and circle-diameters is linear in the range under consideration; the other is that the compensated dose factor is only affected by the nearest neighbors for simplicity. Four-layer-hexagon photonic crystal structures were fabricated as test patterns to demonstrate this method. Compared to the uncorrected structures, the homogeneity of the corrected hole-size in photonic crystal structures was clearly improved.

Key words: proximity effect; electron beam lithography; photonic crystal structure; compensated dose factor
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1. Introduction

Electron-beam lithography (EBL) has been widely used in nano-fabrication for its high resolution. However, the proximity effect, which results from the combination of forward and backward scattering of electrons, plays an essential role in determining the resolution and actual structures obtained on the resist. Therefore, correction of the proximity effect is indispensable. Some efficient methods have already been proposed and developed for this purpose[1−4], among which basic methods include pattern biasing[3], dose compensation or a combination of both[4]. The dose compensation method is the most widely used of all. It typically models the exposure effect for each incident spot in terms of a double Gaussian function. This function can be written as[5]:

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

where α is the standard deviation of forward scattered electron distribution, β is the standard deviation of backward scattered electron distribution, and η is the ratio of energy deposited by backward scattered electrons to the energy deposited by forward scattered electrons. This model has been extensively used, and many different experimental methods have been proposed to determine α, β, and η[3, 6]. However, these methods to extract α, β, and η need complex test patterns, data base handling and complicated computational algorithms. In addition, special software is essential to achieve the correction.

In this work, a simple method to correct the proximity effect was proposed, in which the interaction of electron scattering is not involved. The relation between dose factors and sizes of object was obtained through the fitting way in the range under consideration. Finally an optimized dose setting of the pattern can be achieved by a series of simple calculations. A hexagonal photonic crystal structure was successfully exposed on poly-methyl methacrylate (PMMA) resist as a comparison result by this method.

This method can be widely used, and is especially suited to symmetric structures such as photonic crystal devices.

2. Basic principles of the method

Firstly, a series of single 200-nm-diameter-circle structures were exposed with different doses while other parameters were kept the same, such as electron-beam accelerate voltage, resist thickness, exposing step size, and kind of substrate and resist. The distances between each circle were far enough to avoid interactions. After exposure and development, different doses caused the diameters of circles to be different. The experimental data of the relation between diameter d_x and the corresponding dose factor D_x are shown in Fig. 1. In order to reduce the error, five circles with identical electron dose were measured respectively, and the final value of the diameter was the mean value of these five measured values.

A 3×3 circle-lattice pattern is used as an example to elucidate this method (as shown in Fig. 2). Distances between circles in the lattice are within the range of the backscattering of electrons. Consequently the actual gross doses of individual circles are different from the prior assigned values, with additional contributions from backscattered electrons. In fact,

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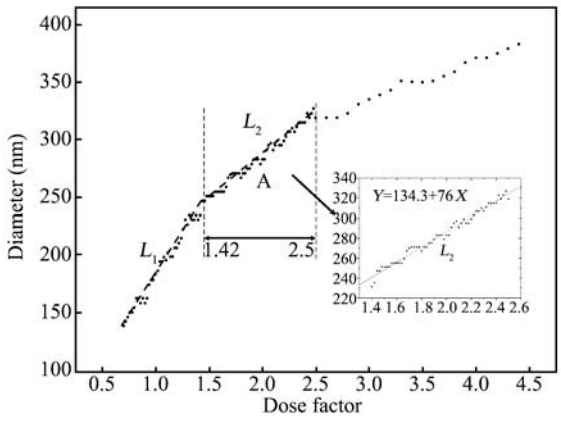

Fig. 1. Diameters of circles versus different dose values measured by SEM. In some range, the relation between diameters and dose factors can be assumed to be linear (L_1, L_2). A is the slope of L_2 in the dose factor range from 1.4 to 2.5.

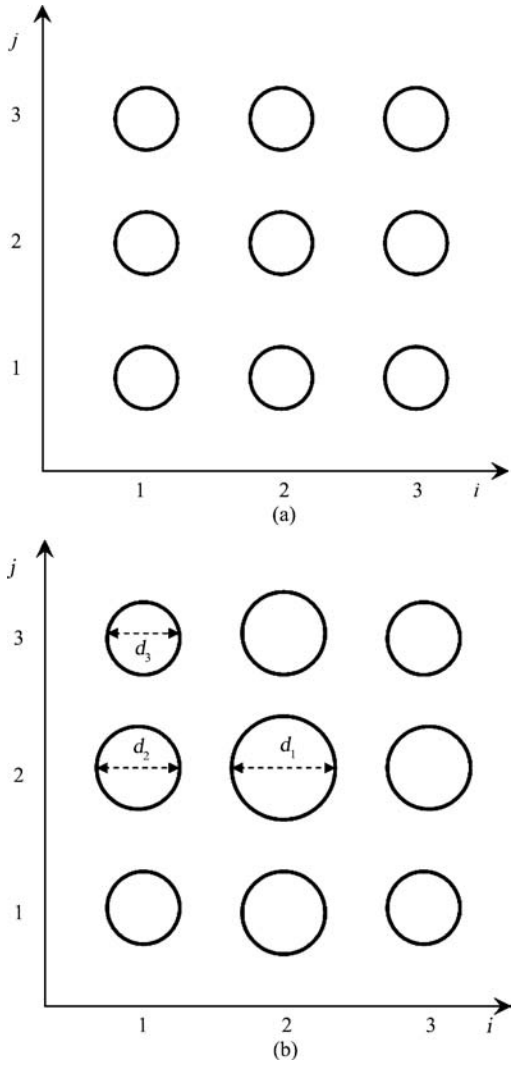

Fig. 2. Schematic of the 3×3 circle-lattice pattern. The dose of circles in pattern (a) is assigned to be identical. Due to the proximity effect, the diameters of circle pattern (b) are not the same size after exposure.

the amount of dose added is location-dependent.

Initially, the dose factors of circles in this 3×3 circle-lattice are all set to D_0 (the base dose is 100 μC/cm^2, and the actual dose value equals the dose factor multiplied by the base dose) as shown in Fig. 2(a). Each circle in the 3×3 circle-lattice is denoted as $C(i, j)$ $(1 \leqslant i, j \leqslant 3)$, where i represents the row number, and j represents the column number.

After exposure and development, the circles in the pattern are different in size due to the proximity effect. Ideally, the diameter d_1 of C(2, 2) is the largest. It results from the greatest gross dose factor D_1, taking into account all the contributions from the proximity effect. Owing to their symmetric positions, C(1, 2), C(2, 1), C(2, 3) and C(3, 2) have the same gross dose factor D_2 and diameter designated by d_2, while C(1, 1), C(1, 3), C(3, 1) and C(3, 3) also have the same gross dose factor D_3 and diameter designated by d_3 (as shown in Fig. 2(b)). The values of d_1, d_2 and d_3 can be obtained via scanning electron microscopic measurement (SEM).

In order to correct the proximity effect effectively and efficiently, two assumptions are taken into account. Assumption 1 is that the relation between dose factors and circle- diameters is considered as linear in the range under consideration (as L_2 which is the linear fitting line in Fig. 1). Assumption 2 is that when determining ΔD, which is named the compensated dose factor, the contributions from nearest neighbor circles are considered only. Contributions from more distant ones are neglected in order to simplify the correction process. Although the results are not accurate, the approximated value has reached the required accuracy.

Two steps are needed to implement the proximity effect correction. Specifically, the dose factors of symmetric circles in the 3×3 circle-lattice in Fig. 2(a) are adjusted as follows:

C(2, 2):

$$D'_{\mathrm{f1}} = D_0 - (D_1 - D_0) = 2D_0 - D_1, \tag{2}$$

$$D_{\mathrm{f1}} = D'_{f1} + \Delta D_1. \tag{3}$$

C(1, 2), C(2, 1), C(2, 3), C(3, 2):

$$D'_{\mathrm{f2}} = D_0 - (D_2 - D_0) = 2D_0 - D_2, \tag{4}$$

$$D_{\mathrm{f2}} = D'_{\mathrm{f2}} + \Delta D_2. \tag{5}$$

C(1, 1), C(1, 3), C(3, 1), C(3, 3):

$$D'_{\mathrm{f3}} = D_0 - (D_3 - D_0) = 2D_0 - D_3, \tag{6}$$

$$D_{\mathrm{f3}} = D'_{\mathrm{f3}} + \Delta D_3. \tag{7}$$

The dose factors used in the experiment are all in the range from 1.4 to 1.5 and belong to L_2. Accordingly, gross dose factors (D_1, D_2, D_3) can be calculated from the linear fitting equation of L_2 in Fig. 1:

$$Y = 134.3 + 76X, \tag{8}$$

where X represents the dose factor, and Y represents the diameters of circles. In Eq. (2), $D_1 - D_0$ is the difference between the designed dose factor and the actual gross dose factor resulting from the proximity effect. Correction-step-1, which is indicated by Eq. (2), is to subtract $D_1 - D_0$ from the designed value D_0. Correction-step-2, which is indicated by Eq. (3), is D'_{f1} plus ΔD_1. The meaning of ΔD is the compensation of the impact caused by the surrounding circles which make the main

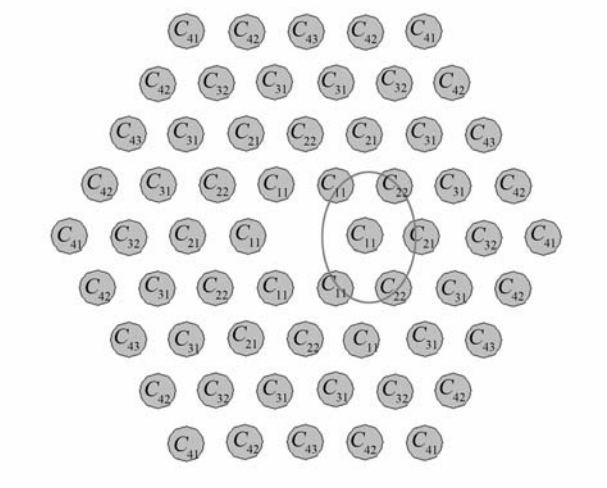

Fig. 3. Schematic of four-layer-hexagonal photonic crystal structures. The pattern is symmetric, and 8 circles are enough to cover the whole 60 circle characteristic. C_{11} is an example; only the nearest holes are considered in the process of correction-step-2.

contribution after correction-step-1. The determination of ΔD based on the two assumptions is explained by using a four-layer-hexagonal photonic crystal structures, which is the pattern used in Section 3 of this paper. The same explanations also apply to Eqs. (4)–(7).

Four-layer-hexagonal photonic crystal structures are used to explain how to determine the compensated dose factor ΔD described above. Although there are sixty circles in Fig. 3, due to the symmetry of the structure, it is only necessary to consider eight separate groups of circles, which are denoted by $C_{11}, C_{21}, C_{22}, C_{31}, C_{32}, C_{41}, C_{42}$ and C_{43} respectively.

One circle in the C_{11} group is taken as an example to illustrate how to evaluate the compensated dose factor ΔD (as shown in Fig. 3). In correction-step-1, the C_{11}' dose factor value is corrected as $2D_0 - D_{11}$. In correction-step-2, according to assumption 2 when determining the value of ΔD_{11}, only the five closest circles to C_{11} are considered (as shown in Fig. 3). The average value of the influence from the surrounding five closest circles is approximately written as

$$D_{\text{average}} = (D'_{\text{f11}} + D'_{\text{f11}} + D'_{\text{f21}} + D'_{\text{f22}} + D'_{\text{f22}})/5. \quad (9)$$

$D'_{\text{f11}}, D'_{\text{f11}}, D'_{\text{f21}}, D'_{\text{f22}}$ and D'_{f22} are the values of dose factors of the five circles after correction-step-1. The values of the compensated dose factor ΔD of the five circles are neglected. Although this calculation is not accurate, the estimated value has reached the required accuracy. Therefore, the equations can be deduced from the linear fitting Eq. (8) and shown as follows:

$$\Delta D_{11} = A \cdot \Delta d_{11}, \quad (10)$$

$$D_0/D_{\text{average}} = (D_{11} - D_0)/W, \quad (11)$$

$$\Delta D_{11} = (D_{11} - D_0) - W, \quad (12)$$

$$D_{\text{f11}} = (2D_0 - D_{11}) + \Delta D_{11}. \quad (13)$$

In Eq. (10), A equals 76 which is the slope of L_2 as shown in Fig. 1. Equation (11) is valid as long as the following approximations are applied: the intra-pattern proximity effect is neglected; the relation between the dose value of the surrounding environment and the increment caused by the surrounding environment is linear. According to Eqs. (6)–(13), $D_{11} - D_0$ is the increment for C_{11} caused by the surrounding environment of dose factor value 1.3. Similar to $D_{11} - D_0$, W can be assumed as the increment caused by the environment of dose factor value D_{average}. Therefore, compensated dose factor ΔD_{11} and the final result D_{f11} can be easily obtained by Eqs. (12) and (13). Series of data of C_{11}, C_{21}, C_{22}, C_{31}, C_{32}, C_{41}, C_{42} and C_{43} are calculated in the same way.

3. Experiment

In this section, four-layer-hexagon photonic crystal structures are fabricated as test patterns to demonstrate the method. The center-to-center distance in the hexagonal photonic crystal structure was designed to be 350 nm and the diameter of the circles was designed to be 200 nm in the layout.

A poly-methyl methacrylate (PMMA) resist (950 K, 4.0 in ethyl lactate) was spin-coated on a (SOI) substrate with a spinning speed of 3000 rpm. Subsequently, the sample was baked on a hot plate at 180 ℃ for 10 min. The exposure was carried out on a Raith150 electron-beam lithography system at an acceleration voltage of 10 kV. After exposure, the sample was developed for 20 s in a mixture solution of methyl isobutyl ketone (MIBK)/isopropyl alcohol (IPA) at the ratio of 1 : 3, and then rinsed in IPA and blow-dried with nitrogen. All the structures observed by SEM were under the same conditions. Due to the thin resist, low acceleration voltage and good conductivity-substrate, the image changes were not significant.

4. Results and discussion

SEM images of the uncorrected and corrected hexagonal photonic crystal structure after exposure and development are shown in Figs. 4(a) and 4(b), respectively. The dose factor of the uncorrected pattern was set to 1.3. Diameters are measured in the SEM image of Fig. 4(a). The corresponding dose factors were calculated by linear fitting of Eq. (8) and Eqs. (10)–(13). The results are shown in Table 1.

As shown in Fig. 4(a), a severe proximity effect was observed in the inner layers of the hexagonal photonic crystals due to a significant dose influence. In contrast, holes in the outermost layer of the structure were not completely exposed owing to lack of dose influence. As shown in Fig. 4(b), this proximity correction method could efficiently improve the uniformity of the hole-sizes. Holes both in uncorrected and corrected patterns were measured by SEM. The results of the relation between numbers of holes and diameters are illustrated in Fig. 5. The standard deviation σ decreased from 7.514 (for the uncorrected pattern) to 1.372 (for the corrected pattern). The hole-diameter variation in the corrected pattern was about ± 3 nm, which was a good result for structures with such dimensions exposed by EBL. Here, four-layer-hexagon photonic crystal structures were just taken as an example to explain this method. This method can naturally be adopted in the exposure of complex structures of photonic crystals.

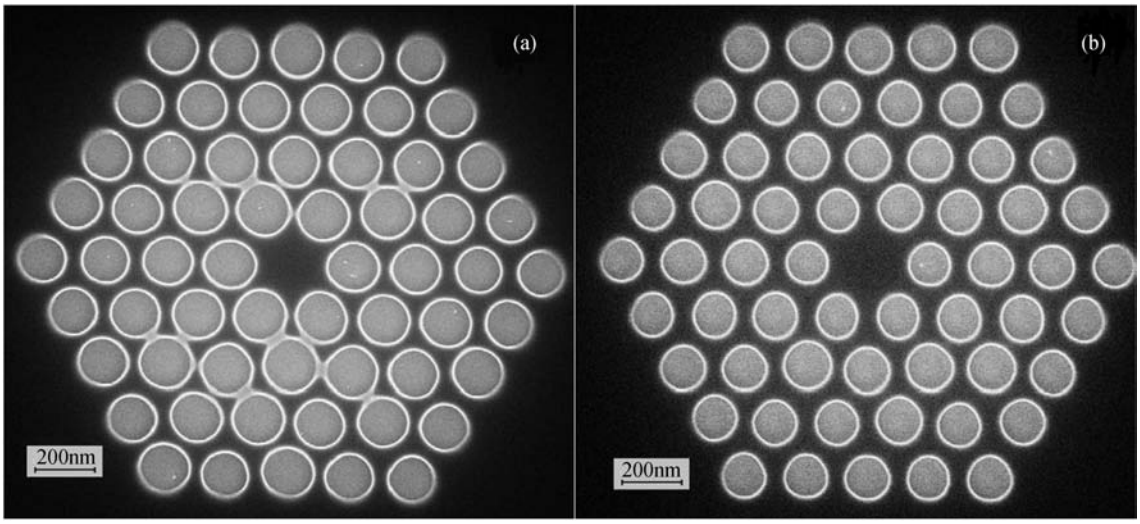

Fig. 4. SEM images of (a) uncorrected and (b) corrected patterns.

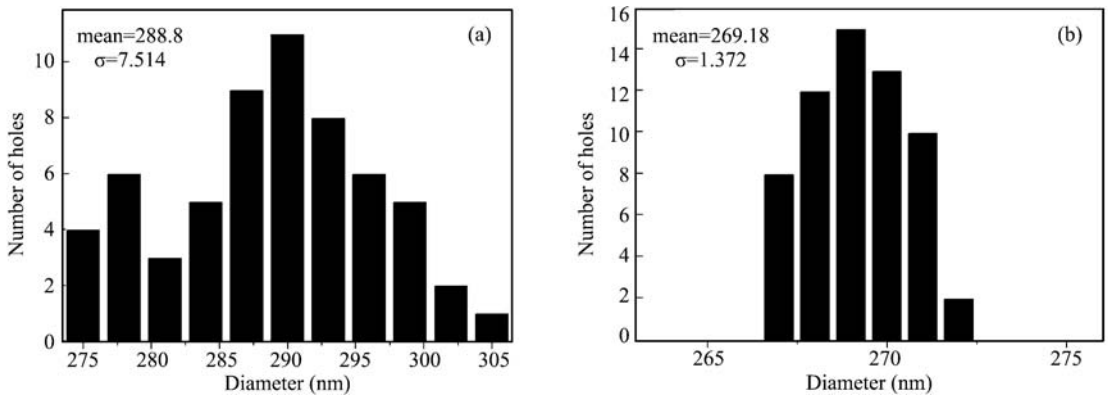

Fig. 5. Analysis of (a) uncorrected and (b) corrected hole sizes for consistency.

Table 1. Basic values of the holes in four-layer-hexagon crystal structures for correction by this proximity effect method.

Layer		d_{xx} (nm)	D_{xx}	$D'_{\mathrm{f}xx}$	W	ΔD_{xx}	$D_{\mathrm{f}xx}$
1	H11	303	2.25	0.35	0.35	0.6	0.95
2	H21	291	1.99	0.61	0.28	0.41	1.02
	H22	287	2.05	0.55	0.29	0.46	1.01
3	H31	283	1.93	0.67	0.34	0.29	0.96
	H32	291	2.05	0.55	0.37	0.38	0.93
4	H41	271	1.77	0.9	0.27	0.2	1.1
	H42	275	1.8	0.8	0.27	0.23	1.03
	H43	283	1.93	0.67	0.33	0.30	0.97

5. Conclusion

In this article an efficient dose-compensation method for proximity effect correction is presented. The method is based on two reasonable assumptions. An easy way was adopted to estimate the compensated dose factor ΔD. The holes' standard deviation was 1.372 and the diameter variation was about ± 3 nm, which is acceptable in a variety of applications.

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