Limitations of Proximity-Effect Correction for Electron-Beam Patterning of Photonic Crystals

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ABSTRACT

We investigate the patterning-accuracy limits of proximity-effect corrected (PEC) electron-beam lithography applied to the fabrication of photonic crystals (PhC's). Energy-intensity distribution simulations reveal that conventional dose-modulation PEC techniques present a lower limit of the best attainable hole-radius variation of \( \approx 1\% \) for a generic PhC structure, while a PEC method proposed by Watson theoretically should yield perfect correction. Simulation results were verified experimentally and additionally we introduce a new method to determine the beam-broadening parameter \( \alpha \). We analyzed the impact of geometrical key parameters of PhC’s on achievable patterning accuracy and showed that proximity effects impose severe limitations on the patterning of structures with large filling factors and/or small lattice constants. Furthermore, we performed a sensitivity analysis on the proximity parameters and showed that overestimation of the backscatter efficiency can actually improve the lithographic accuracy and mimic the Watson-PEC method to a certain degree.

Keywords: Photonic Crystal, Electron-Beam Lithography, Proximity-Effect Correction, Electron-Beam Simulation, Hole-Size Variation, Energy Intensity Distribution, Proximity-Effect Parameter-Measurement

1. INTRODUCTION

Photonic crystals have been the object of growing interest due to their peculiar optical dispersion relations that give rise, e.g., to a photonic bandgap or the superprism effect.\textsuperscript{1} These novel properties promise an increased capability to control light in photonic integrated circuits as well as novel functionalities for optical communications. A promising light waveguiding concept—especially for monolithic integration of PhC-based devices for TDM and WDM applications—is based on a semiconductor slab waveguide for vertical light confinement and a two-dimensional (2D) PhC structure of deeply etched holes to ensure lateral light control. For such planar 2D PhC's, theoretical studies show\textsuperscript{2} that fabrication tolerances must be tightly kept under control to yield certain targeted functionalities.

PhC devices for integrated-optics applications require fabrication techniques with nanometer-range patterning accuracy. Owing to its design flexibility, electron-beam lithography (EBL)—combined with dry-etching techniques for pattern transfer—is often the method of choice for rapid prototyping of such structures. A large number of studies (see Ref.\textsuperscript{3} and references therein) have shown that proximity-effect correction (PEC) via dose modulation offers a simple and effective technique to enhance lithographic accuracy. Photonic crystals (PhC’s) with their high structural density turn out to be ideal benchmark structures to test the accuracy of PEC methods.

Fabrication accuracy and process latitude of EBL can be addressed by the computation of the energy-intensity distribution (EID) in the resist. Extensive work in this direction has been performed that includes 2D simulations of grating structures\textsuperscript{4} and full 3D simulations of resist shape upon exposure and development.\textsuperscript{5} However, to limit computational efforts, the 3D investigations are restricted to small areas, thus allowing only a qualitative comparison to experiments. Furthermore, to the best of our knowledge, these investigations do not evaluate feature-size standard deviation versus applied dose and do not address the specific requirements of high structural-density photonic crystals.

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In this work a two-dimensional EID approach is pursued. It allows the evaluation of average hole radius and homogeneity for EBL of 2D PhC’s. In section 2, we present the methods of the analysis. The behavior of hole radius variation is analyzed in section 3 for three PEC techniques: no PEC, conventional energy-equalization PEC and a midpoint-equalization PEC proposed by Watson et al.6 It is shown that the Watson method theoretically allows a perfect accuracy. In section 4, the theoretical results are compared to exposed structures in order to validate our approach. Additionally, this method offers a simple mean to reliably measure the beam-broadening parameter $\alpha$. Applications of the EID technique in the context of PhC research are presented in section 5. We investigate the impact of geometrical parameters (i.e., lattice constant, filling factor) and of proximity-effect parameters on the quality of the correction.

2. PROXIMITY-EFFECT CORRECTION AND ENERGY-INTENSITY DISTRIBUTION

The overall methodology for PEC analysis using EID computations is shown in Fig. 1. The methodology will now be explained.

2.1. Proximity-Effect Correction in Photonic Crystals

In designs with strong structural-density variations on the scale of the backscatter range $\beta$, proximity effects degrade the ability of EBL to ensure an accurate pattern formation. Established PEC techniques employ structure fracturing and dose modulation to equalize the final energy deposition for all elements. As the beam-broadening parameter $\alpha$ is usually much smaller than the smallest feature sizes, these methods approximate the direct resist exposure by a delta function and correct only for the broad indirect exposure by the backscattered electrons.

The high structural density of PhC’s hinders a coarse design fracturing and efficient PEC of the design. In a previous work,7 we presented a method that takes advantage of the periodicity of PhC’s to yield a fast and accurate formulation of the self-consistent dose modulation approach. Moreover, because the lattice constant $a$ and the hole radius $R$ are larger than $\alpha$ but much smaller than $\beta$, we can assign a homogeneous dose for each circular element and treat the backscattering cross-contributions via a point dose at the corresponding lattice site. The computed PEC is used as a starting point for simulations of deposited energy in the resist.

2.2. Energy Intensity Distribution (EID) Simulation

The proximity function $f(r)$ gives the radial distribution of energy deposition $E(\vec{r})$ in the resist for a point exposure. It consists of two components: a narrow high peak representing the direct exposure and a broad background from backscattered electrons. The proximity function is often approximated by the sum of two gaussians:

$$f(r) = \frac{1}{\pi(1+\eta)} \left( \frac{1}{\alpha^2} \exp\left(-\frac{r^2}{\alpha^2}\right) + \frac{\eta}{\beta^2} \exp\left(-\frac{r^2}{\beta^2}\right) \right), \quad \text{with} \quad \int_0^\infty 2\pi f(r) r \, dr = 1 ,$$  

(1)
where $\alpha$ is the range of forward scattering in the resist, $\beta$ is the backscattering range and $\eta$ is the deposited energy ratio between direct-exposure and backscattered electrons.

The normalized deposited energy $\frac{E(x,y)}{E_{cl}}$ is calculated by summation (convolution in the continuous case) of the proximity function $f(r)$ weighted with the local dose $G \cdot \frac{D(x',y')}{D_{cl}}$ on a calculation grid:

$$G \int_{2D} \frac{D(x',y')}{D_{cl}} f(|\vec{r} - \vec{r}'|) d\vec{r} dx dy \approx G \cdot d^2 \sum_{l=1}^{N} \frac{D(x_l,y_l)}{D_{cl}} \cdot f \left( \sqrt{(x_l - x)^2 + (y_l - y)^2} \right) = \frac{E(x,y)}{E_{cl}},$$ (2)

where $D(x,y)$ is the spatial distribution of the applied dose, $D_{cl}$ is the normalization clearing-dose of the process, $G$ is an overall dose factor applied to all elements of the design, $E_{cl}$ is the clearing energy, i.e., the energy required to fully develop the resist, $d$ is the pixel size of the discretized computation grid, and $N$ is the total number of exposed pixels. It is assumed that $\frac{D(x,y)}{D_{cl}}$ is the number which is attributed to each element in the design file and $G$ can be used as a flexible scaling parameter. A typical deposited-energy surface computed using Eq. 2 is depicted in Fig. 2a.

For this computation, we make the following assumptions: (i) the energy deposition is constant along the resist thickness, (ii) the resist contrast curve is approximated by a step function. Therefore, the shape of the developed pattern can be extracted from an energy-intensity contour by nominally slicing the energy distribution at the height $E(x,y) = E_{cl}$, i.e., the energy for thorough resist development. From the resulting black-white image (Fig. 2b), the average radius $\bar{R}$ and its relative standard deviation $\sigma_R$ are extracted as a function of $G$. Only correctly resolved structures are evaluated, i.e., those structures for which all energy cones lie above the slicing threshold. We should mention that computing the EID anew for each $G$ is very time-consuming. However, thanks to the linear scaling properties of the EID, it is equivalent to varying the slicing threshold $T$ instead. $G$ is given by $G = \frac{1}{T}$.

It is important to notice that our approach presented in Fig. 1 uses two sets of proximity parameters: $(\beta_{corr}, \eta_{corr})$ that are used for the PEC and $(\beta_{sim}, \eta_{sim})$ that represent the physical values. Thus, a sensitivity analysis on the proximity parameters can be performed for a range of dose factors $G$ and insights can be gained on the PEC quality depending on the experimental accuracy of $\beta_{corr}$ and $\eta_{corr}$.

The discretization $E(x,y)$ of the continuous function $E(\vec{r})$ introduces systematic errors that result in altered $\sigma_R$. In order to estimate the error associated with the pixelization, we have computed $\sigma_R$ for three different
pixel sizes, as shown in Fig. 3a. A coarse pixel size results in increased scattering in \( \sigma_R \) but does not change the overall trend. A fine resolution results in a smooth curve, suggesting that a significant change of \( \sigma_R \) may not be expected for grid resolutions < 3nm.

We have investigated the impact of overall structure size on the pattern quality. Figure 3b shows the behavior of \( \sigma_R \) vs. the length \( L \) of a quadratic PhC structure. \( \sigma_R \) first increases dramatically from low values to a maximum for \( L \approx 3 \cdot \beta \) and then decreases slowly for larger corrected areas. This behavior can be understood as follows: proximity effects have only a marginal impact on tiny structures, while only affecting the edge of large designs, for which the surface-to-edge ratio decreases. Quantitative EID analysis is therefore unique to each set of chosen design parameters, although the qualitative insights gained with the EID technique remain valid for a large range of designs.

3. SIMULATION RESULTS

The following analysis is based on a generic double-bend design with a lattice constant of \( a = 300\,\text{nm} \) and a design hole-radius of \( R_D = 100\,\text{nm} \) as depicted in Fig. 2b. This particular design is meaningful in the context of PhC research and shows enough proximity effects for the intended analysis. The pixel size \( d \) of the computation grid is 3nm.

The EID method introduced in the previous section was applied to three cases: no PEC, conventional energy-equalization PEC and a midpoint-equalization PEC scheme proposed by Watson et al. In all three cases the proximity parameters for PEC (\( \eta_{\text{corr}}, \beta_{\text{corr}} \)) and for EID computation (\( \eta_{\text{sim}}, \beta_{\text{sim}} \)) were equal. These parameters correspond to the experiment to be described in section 4. To investigate the impact of beam broadening, three values of \( \alpha_{\text{sim}} \) were chosen (15nm, 35nm, 55nm).

3.1. No Proximity-Effect Correction

When no PEC is applied to the design, the relationship \( \frac{D(\vec{r})}{D_D} = 1 \) holds for all elements. A cross-section of the EID along cutline \( A - A' \) (see Fig. 2b) is shown in Fig. 4a for two dose factors \( G \). The broad background due to backscattering is clearly visible. The exposed elements have an equal height above the background but different maximal energy intensities \( E(\vec{r}) \).

Figure 4b shows \( \bar{R} \) and \( \sigma_R \) vs. \( G \). \( \alpha \) has a major impact on the quality of the EBL process in terms of: (i) the best achievable hole-radius variation \( \sigma_R \), (ii) the slope of the hole radius curve vs. dose factor \( \bar{R}(G) \), due to the increasingly gentler flanks of the energy cones for increasing \( \alpha \), (iii) the maximal useful dose interval \( I_G(\alpha) \),
due to the merging of the energy cones above the background for large \( \alpha \)'s. The minimum dose to properly resolve the structure is \( G \approx 2 \). The minimum \( \sigma_R \) lies in the range 2 – 7% for corresponding optimal dose factors \( G = 3 – 3.5 \). Independently of \( \alpha \), the slope minimum of the \( \bar{R}(G) \) curve occurs approximately at the design radius \( R_D \).

3.2. Energy-Equalization Proximity-Effect Correction

The energy-equalization PEC technique modulates the element doses in order to achieve a uniform energy deposition \( \frac{E(\bar{r})}{E_{cl}} = 1 \). This is illustrated in Fig. 5a, where the EID cross-section along cutline \( A – A' \) is shown for \( G = 1 \) and \( G = 1.5 \).

In Fig. 5b, we show \( \bar{R} \) and \( \sigma_R \) vs. \( G \). As in the case of no PEC, a strong influence of \( \alpha \) on \( \bar{R} \), \( \sigma_R \) and \( I_G \) is still observed. Whereas the \( \sigma_R \)-minimum is strongly reduced to a range of 0.5 – 3%, the slope of \( \bar{R}(G) \) still markedly increases with \( \alpha \). Dose factors for optimal hole-radius variation \( G_{\text{min}(\sigma_R)} \) are considerably lower than the dose factors \( G_{R_D} \) that yield the design radius and are optimal for process latitude (minimal slope of \( \bar{R}(G) \)).

**Figure 4.** Simulation: no PEC. a) Cross-section of EID for \( G = 1 \) and \( G = 2 \), \( \alpha_{\text{sim}} = 30\text{nm} \). b) Average radius \( \bar{R} \) and standard deviation \( \sigma_R \) vs. dose factor \( G \) for \( \alpha_{\text{sim}} = 15, 35, 55\text{nm} \).

**Figure 5.** Simulation: energy-equalization PEC. a) Cross-section of EID for \( G = 1, G = 1.5, \alpha_{\text{sim}} = 30\text{nm} \). b) Average radius \( \bar{R} \) and standard deviation \( \sigma_R \) vs. dose factor \( G \) for \( \alpha_{\text{sim}} = 15, 35, 55\text{nm} \).
3.3. Midpoint-Equalization Proximity-Effect Correction

Watson et al. proposed a midpoint-equalization PEC technique that inherently accounts for beam-broadening correction. In contrast to conventional energy-equalization PEC where the postulate “direct exposure + background = 1” equalizes the maximum energy deposition for all elements, the Watson technique equalizes the midpoint energy of the direct exposure above the background via \( \frac{1}{2} \cdot \text{direct exposure} + \text{background} = 1 \). This results in an EID (see Fig. 6a with \( G = 1 \)) where the development threshold \( E_{\text{cl}}(\vec{r}) = 1 \) intersects the EID curve halfway between background and maximum energy, i.e. for an \( \alpha/2 \) beam-broadening for all elements. Therefore, with \( G = 1 \) all elements develop at the design radius \( R_D \). Conversely, for the conventional energy-equalization PEC technique, the width of beam broadening at the threshold \( E_{\text{cl}}(\vec{r}) = 1 \) depends on the background strength i.e. the local structural density.

In Fig. 6b, we show \( \bar{R} \) and \( \sigma_R \) vs. \( G \) for the midpoint-equalization PEC technique. This technique results in increased element dose values compared to the conventional PEC, therefore lower overall dose factors \( G \) are necessary. \( \bar{R} \) behaves similarly to the previous case, but \( \sigma_R \) shows a zero for all values of \( \alpha \) (within numerical accuracy). This zero is reached for \( G \approx 1 \) where \( \bar{R} \approx R_D \) and the \( \bar{R}(G) \)-slope is smallest. The intervals for optimal hole-radius variation and optimal process latitude overlap. \( \alpha \) only affects the \( \bar{R}(G) \)-slope and the slope of the \( \sigma_R(G) \) curve.

3.4. Discussion of Simulation Results

EBL-patterning of photonic crystals without PEC is possible within an appropriate dose range, but patterning uniformity is rather poor. On the other hand, energy equalization—the most widespread PEC technique—improves the situation considerably but perfect pattern-transfer fidelity is not achievable with this method. This is due to the fact that no dose exists where all elements are properly developed at the same relative height of the beam-broadening gaussian. The midpoint-equalization PEC allows perfect accuracy at the design radius \( R_D \) for an overall dose factor \( G = 1 \). This important result is not affected by a variation of \( \alpha \).

Process latitude is—in the context of PhCs fabrication—related to the slope of the \( \bar{R}(G) \) curve (regarding exposure dose and development) and to \( \bar{R}(\alpha) \) (regarding sample planarity, beam focusing quality and beam stability). Thus, the optimum overall dose factor concerning process latitude \( (G_{\text{opt}}^\text{pl}) \) is given by the minimum of the \( \bar{R}(G) \)-slope and the independence of \( \bar{R} \) on \( \alpha \). This is—in all considered cases—satisfied where \( \bar{R} \approx R_D \). However when working with conventional PEC, \( G_{\text{opt}}^\text{pl} \) does not arise for the \( \sigma_R \) minimum, which occurs at lower doses. Working at an optimal dose \( G_{\text{opt}}^\text{pl} \) therefore results in a loss of accuracy. For the energy-midpoint equalization PEC, perfect pattern-formation accuracy is achievable at the optimal dose for process latitude \( G_{\text{opt}}^\text{pl} \).
4. EXPERIMENTAL VERIFICATION AND MEASUREMENT OF $\alpha$

The experimental determination of $\alpha$ is mostly done by spot exposure\(^{10}\) but suffers from beam instabilities and local resist inhomogeneities.\(^4\) To overcome this problem, statistical approaches have been proposed\(^3,9\) where measured resist-pattern sizes after development were fitted to EID simulation data. In the context of PhC, the image analysis of micrographs containing a large number of holes allows the statistical determination of the average radius in a relatively straightforward and elegant manner.

4.1. Exposure, Image Processing and Data Analysis

The generic double-bend structure was corrected for proximity effects using the PEC method for PhC’s (see 2.1) according to the two methods described in 3.2 and 3.3. A proximity function consisting of a double gaussian and an exponential term was used with previously measured backscatter parameters\(^7\): $\beta = 1.59\mu\text{m}$, $\eta = 0.72$, $\gamma = 0.76\mu\text{m}$, $\nu = 0.58$. Exposure of a 230nm-thick PMMA layer on an InP substrate was performed with a 30kV Raith150 EBL tool followed by development in MIBK:IPA (1:3) at 22°C for 60s. The overall dose factor $G$ was varied in an interval that did yield under- to overexposed structures. After development, micrographs were taken that included ca. 25% of the overall structure as seen in Fig. 7a in order to offer simultaneously sufficient resolution and enough objects for statistical analysis.

To estimate the hole-radius distribution for each structure, an automatic image-processing technique was developed to evaluate the area of each hole. The contrast of the pictures was improved by spatial filtering and brightness equalization followed by thresholding to obtain the hole areas in a black-white image. Subsequently, spurious objects were removed and loosely connected areas were separated. Statistics on individual objects revealed the hole-radius distribution ($\bar{R}_{\text{exp}}$, $\sigma_{\bar{R}}$) by comparing the calculated area of such circular objects in an analogous way as was described in section 2.2.

The EID for the exposed structure was computed with different beam-broadening parameters ($\alpha = 15\text{nm} \ldots 55\text{nm}$) and structure-development analysis was performed for the area included in the micrographs to obtain $\bar{R}_{\text{sim}}$ and $\sigma_{\bar{R}}$. The best estimate for $\alpha$ was obtained by performing a least-squares fit on the experimental and simulated values for $\bar{R}(G)$. Because the analysis of the SEM micrographs does not reveal the cleared area at the bottom of the holes, but only the top edge, the experimentally determined radii correspond to an energy $E_{\text{te}}$ instead of the clearing energy $E_{\text{cl}}$, as illustrated in Fig. 7b. Therefore, a second parameter $k = E_{\text{cl}} / E_{\text{te}}$, that accounts for resist contrast, was introduced into the fitting procedure.

4.2. Experimental Results and Discussion

The best fit between experimental and simulated radii is shown in Fig. 8 for both conventional and midpoint-equalization PEC techniques. It should be mentioned that because the SEM micrographs yield hole radii for

Figure 7. a) Image-processing analysis that yields experimental values for $\bar{R}$ and $\sigma_{\bar{R}}$; b) relationship between the clearing energy $E_{\text{cl}}$ and the top-edge energy $E_{\text{te}}$. 

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Figure 8. Best fit of experimental (symbols) and simulated (lines) $\bar{R}$ and $\sigma_R$ that yields $\alpha = 32.5\text{nm}$ and $k = \frac{E_{cl}}{E_{te}} = 1.53$ for a) energy-equalization PEC and b) midpoint-equalization PEC.

a deposited energy $E_{te}$, experimental dose factors $G_{exp}$ in the figure are scaled by the factor $k$. An excellent agreement between experimental and modelled radii was obtained with best fit values of $\alpha = 32.5\text{nm} \pm 3\text{nm}$ and $k = \frac{E_{cl}}{E_{te}} = 1.53 \pm 0.03$ for both sets of data independently.

Experimental values $\sigma_{R}^{\text{exp}}$ follow the trend of— but are somewhat offset from— $\sigma_{R}^{\text{sim}}$. Indeed, a poor contrast of the SEM micrographs is responsible for hole-radius variations during the extraction procedure. Because this process is random, it does negligibly affect $R_{\text{exp}}$ and the determination of $\alpha$. This effect is very large for underexposed structures. The upper dose limit for the evaluation procedure is set by the distorted hole shapes for high $G_{exp}$ close to overexposure. Overall, better results are obtained for the midpoint-equalization PEC technique with an excellent minimal hole-radius variation of $\sigma_R = 1.4\%$.

Limitations of the method arise because of trade-offs between number of objects per micrograph and range of fitted dose factors on the one hand and micrograph resolution and minimum feature size on the other hand. The SEM-micrograph analysis requires good resolution and contrast, as well as enough objects for statistical analysis.

5. EID SIMULATIONS APPLIED TO PHOTONIC CRYSTALS

We have applied the EID method to photonic crystals and investigated the impact of geometrical and proximity parameters on the quality of the lithography. This study is based on conventional PEC, because most of the PhC research is performed with this method.

5.1. Geometrical Parameters

The physics of PhC’s is dominated by its geometrical parameters: lattice constant $a$ and hole radius $R$. EID simulations are performed with the generic double-bend design by changing structural dimensions. The proximity parameters are those extracted in section 4.

5.1.1. Filling Factor $\frac{R}{a}$

For a triangular lattice of airholes, the bandgap for TE-polarized light widens considerably for increased $\frac{R}{a}$ and even exhibits a complete bandgap for TE- and TM-polarized light for $\frac{R}{a} \geq 0.4$.\(^1\) Although structures with $\frac{R}{a} \geq 0.4$ are highly desirable, they present a real challenge for EBL as will be presented below.

The EID simulations were performed for different values of $\frac{R_{D}}{a}$ and $\alpha$. The lattice constant was $a = 300\text{nm}$ and $R_D$ represents the design radius. In Fig. 9a, we show $G_D$—the dose at the design radius—and the maximum dose ($G_{\text{max}}$) on the brink of overexposure. $G_D$ decreases slightly when $\frac{R_{D}}{a}$ grows due to the raised background.

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level but shows a weak dependence on $\alpha$. However, $G_{\text{max}}$ drops dramatically because of the merging of the energy cones above the raised background, and the gap between $G_D$ and $G_{\text{max}}$ gets narrower for large values of $R_D/a$. In Fig. 9b, the standard deviation $\sigma_{R_D}$ and the slope of $\bar{R}(G)$ curve at design radius are shown. Both values increase by $\approx 50\%$ with increasing $R_D/a$ and show a strong dependence on $\alpha$. The observed behavior can be understood as follows: the increased filling factor degrades the energy contrast (background-to-direct exposure ratio) that in turn leads to gentler energy-cone flanks [$\bar{R}(G)$ slope].

The dose window between $G_D$ and $G_{\text{max}}$ as well as the slope of $\bar{R}(G)$ characterize the process latitude. This means that the patterning of PhC’s with $R_D/a > 0.4$ is difficult, very sensitive to process-parameter variations and shows a low accuracy. This is especially true for non-optimal values of $\alpha$ and — as $G_{\text{max}}$ depends on $\eta$ via the background level — for material systems with a large backscatter efficiency $\eta$, as e.g. InP. It should be pointed out here, that experimentally measured maximal useful doses are lower than $G_{\text{max}}$ which is determined by EID simulations. This is due to resist development effects. Therefore the above given analysis presents an upper boundary on lithographic performance.

5.1.2. Lattice Constant $a$

As PhC characteristics are determined by the reduced frequency $u = \frac{\lambda}{a}$, a given PhC property—such as the bandgap—scales with the wavelength $\lambda$ by a corresponding scaling of the lattice constant $a$. EID simulations and structure analysis for different lattice constants and $\alpha$ parameters were performed to investigate the limits of this scaling. The filling factor was kept constant at $R_D/a = 1/3$.

In Fig. 10a, we show $G_D$ and $G_{\text{max}}$. $G_D$ remains roughly constant, the slight increase towards lower $a$ being due to the decreasing overall size of the analyzed structure. Furthermore, $G_D$ shows a weak dependence on $\alpha$ whereas $G_{\text{max}}$ drops sharply when the lattice constant reaches $a \approx 10 \cdot \alpha$, i.e., when the distance between hole edges is less than $3 \cdot \alpha$ and the energy cones start merging. Thus, the process window gets narrower for small $a$. In Fig. 10b, $\sigma_{R_D}$ and the slope of the $\bar{R}(G)$ curve at design radius are shown. The slope of $\bar{R}(G)$ does not change much because for constant filling factor, the direct-exposure-to-background ratio remains unchanged. However, $\sigma_{R_D}$ increases by up to 5 times when reducing the lattice constant from 0.5$\mu m$ to 0.15$\mu m$.

The dose window between $G_D$ and $G_{\text{max}}$ as well as $\sigma_{R_D}$ depend substantially on $\alpha$. This implies that fabrication of PhC’s with small $a$ and reasonable accuracy is a challenging task, requiring excellent control of the lithographic step. Thus, a thin resist layer should be used in order to reduce forward scattering, however at the cost of reduced process latitude for, e.g., subsequent etching steps.
5.2. Proximity Parameters

In this section, we evaluate the influence of proximity parameters on the pattern quality. For this study, we proceed as follows: (i) Using the parameters $\beta_{corr}$ and $\eta_{corr}$, we correct the generic double-bend structure ($a = 300\text{nm}$, $R_D = 100\text{nm}$) and applying different values, we study the effect of inaccuracies in their determination. (ii) The parameter set $[\beta_{sim}, \eta_{sim}, \alpha_{sim}]$ is the set of “exact” parameters and is used to model the resist exposure and development.

5.2.1. Beam Voltage

For submicron EBL the influence of proximity effects may be reduced with increased acceleration voltages, as $\beta$ increases and $\alpha$ is reduced. In the literature, we found the following proximity parameters$^{11}$ of InP substrates for $50kV$ acceleration voltage: $\beta_{corr} = \beta_{sim} = 3.7\text{µm}$, $\eta_{corr} = \eta_{sim} = 1.4$, for the double-gaussian proximity function. $\bar{R}$ and $\sigma_R$ were simulated and compared to the results obtained with a $30kV$ acceleration voltage. The results are shown in Fig. 11a and b for no PEC and conventional energy-equalization PEC, respectively.

In both cases, a similar qualitative behavior compared to the $30kV$ case is observed. However, the hole-radius uniformity is improved and the dose interval ($I_G$) is increased. One can understand this behavior by the reduction

![Figure 11. $\bar{R}$ and $\sigma_R$ for 50kV acceleration voltage, with a) no PEC applied and b) energy-equalization PEC.](image-url)
of the overall relative structure size compared to $\beta$ and therefore a lower background dose. Thus, increasing the acceleration voltage is an effective measure to improve pattern quality only if the overall structure size is of the same order of magnitude as the backscatter range $\beta$. However, as $\eta$ is not reduced, the principal limitations of dose-equalization PEC remain. On the other hand the reduced $\alpha$ lowers $\sigma_R$ and may allow the use of a thicker resist layer.

5.2.2. Proximity-Parameter Sensitivity Analysis

Even though various methods are presented in the literature that allow the measurement or simulation of the backscatter parameters,$^{12}$ an accurate determination of these parameters is no simple task, especially in the case of highly insulating top layers or complicated multilayer structures.

EID simulations offer a straightforward method to perform a sensitivity analysis of $\sigma_R$ on proximity parameters. In order to simplify the interpretation, the double-gaussian proximity function was used and the values for $\eta_{corr}$ and $\beta_{corr}$ were varied, while $\alpha_{sim} = 35\text{nm}$, $\eta_{sim} = 1.05$ and $\beta_{sim} = 1.72\mu\text{m}$ were held constant at the “best fit to measurement”-values for InP.

In Fig. 12a the minimum of $\sigma_R$ was plotted against $\Delta \eta = \eta_{corr} - \eta_{sim}$ and $\Delta \beta = \beta_{corr} - \beta_{sim}$. For $\eta_{corr} = \eta_{sim}$ the minimum of $\sigma_R$ is 1.4%, consistent with the results of section 3.2. A decrease of $\eta_{corr}$ and a deviation of $\beta_{corr}$ from $\beta_{sim}$ result in an increase of $\sigma_R$. On the other hand, when $\eta_{corr}$ is increased, min($\sigma_R$) $\approx 0$ (within numerical accuracy). Thus, for all $\eta_{corr} > \eta_{sim}$ a dose factor $G$ and a corresponding average radius $\bar{R}$ can be found, for which perfect hole-radius homogeneity can be achieved. The strategy for identifying $\eta_{corr}$ that yields simultaneously min($\sigma_R$) $= 0$ and $R = R_D$ is depicted in Fig. 12b where $\sigma_{RD}$ is plotted against $\Delta \eta$ and $\Delta \beta$. A single point exists at $\eta_{corr} = 2.2 \times \eta_{sim}$ and $\beta_{corr} = \beta_{sim}$ that fulfills both conditions.

Form these findings we can draw the following conclusion: it is possible to achieve perfect accuracy with the conventional energy-equalization PEC technique by considerably increasing $\eta_{corr}$ compared to the experimentally determined value. Hence, overestimating $\eta_{corr}$ mimics the effects of the “midpoint-equalization” PEC: the energy deposition in the regions of low structural density (e.g., the edges and corners) is artificially enhanced. However, it has to be mentioned, that the exact values of $\eta_{corr}$ and $G$ for which $\sigma_{RD}$ is zero, depend on the particular design topology. Therefore “midpoint equalization” PEC is superior as it inherently accounts for beam-broadening effect and yields $\sigma_{RD} = 0$ for every corrected structure.

6. CONCLUSION

In this paper, we have presented an analysis of the patterning-accuracy limits by electron-beam lithography in the context of photonic crystals. Based on a fast proximity-effects correction solver and energy-intensity distribution (EID) simulations, we have evaluated the best attainable hole-size uniformity of photonic-crystal devices, using three different correction strategies: (i) no PEC, (ii) a conventional energy-equalization PEC, and (iii) a new
midpoint-equalization PEC technique which inherently accounts for the beam broadening. We showed that, while
the conventional strategy imposes a lower limit on the best attainable uniformity, the midpoint-equalization PEC
theoretically yields a perfect correction.

Based on statistical analysis of SEM micrographs and least-squares fit with EID simulations, we developed a
new method to determine the beams-broadening parameter \( \alpha \). We analyzed the impact of geometrical parameters
of PhC’s and showed that the proximity effects impose severe limitations for the patterning of structures with large
filling factor and/or small lattice constant. A sensitivity analysis on the proximity-effect correction parameters
\( \eta_{corr} \) and \( \beta_{corr} \) reveals that overestimation of \( \eta_{corr} \) mimics the “midpoint-equalization” PEC and theoretically
improves the lithographic result to the point of perfect accuracy. However for a given value of \( R_D \), the dose \( G \)
and \( \eta_{corr} \) to achieve \( \sigma_{R_D} = 0 \) depend on the exact design topology.

We should mention that although this study was performed in the context of photonic crystals, the insights
are in no way limited to this particular kind of structures but remain valid for the EBL patterning of high
structural-density designs. Because the EID method does not deal with resist-development effects, it defines an
upper boundary of lithographic performance. In a next step, the investigation of the impact of geometrical and
proximity-related parameters should be extended to the “midpoint-equalization” PEC.

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