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Systematic considerations for the patterning of photonic crystal devices by electron beam lithography

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Abstract

Photonic crystal devices with feature sizes of a few hundred nanometers are often fabricated by electron beam lithography. The proximity effect, stitching error and resist profiles have significant influence on the pattern quality, and therefore determine the optical properties of the devices. In this paper, detailed analyses and simple solutions to these problems are presented. The proximity effect is corrected by the introduction of a compensating dose. The influence of the stitching error is alleviated by replacing the original access waveguides with taper-added waveguides, and the taper parameters are also discussed to get the optimal choice. It is demonstrated experimentally that patterns exposed with different doses have almost the same edge-profiles in the resist for the same development time, and that optimized etching conditions can improve the wall angle of the holes in the substrate remarkably.

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Keywords: Photonic crystal; E-beam lithography; Resist; Stitching error; Proximity effect correction

1. Introduction

Photonic crystals [1,2] (PCs) are optical materials with periodic changes in the dielectric constant on the wavelength scale, analogous to the crystal structure of a semiconductor, in which photonic band gaps (PBGs) can be created for certain ranges of photon energies. Various applications have been predicted and are expected to be realized by PCs, including ultra small optical circuits or photonic integrated circuits (PICs). Ideally, such PICs should be realized using a three-dimensional (3D) system, but an alternative system using a dielectric slab with a two-dimensional (2D) PC, called a 2D PC slab [3,4], is also very attractive for its relatively easy fabrication. It uses the effect of the 2D PC to confine light in the in-plane direction, and the refractive index contrast to confine light in the vertical direction.

Owing to its flexibility and high precision, EBL is frequently adopted to pattern nanophotonic devices in integrated optics, and many PC devices such as directional couplers [5], power or beam splitters [6,7], Mach-Zehnder interferometers [8] and resonators [9–11] based on a variety of microcavities have been experimentally achieved by common or modified EBL processes. While some researchers have conducted useful investigations on the proximity effect and the etching process related to PC fabrication [12,13], in this paper we will aim at overcoming the main technical challenges in patterning PC devices with common EBL, and some effective and efficient methods will be proposed to simplify the PC fabrication process.

In Section 2, the proximity effect and the corresponding correction method are analyzed. The stitching problem is then discussed in Section 3. In Section 4, we investigate the effects of dose variation on resist profiles and demonstrate that high selectivity of etching improves the profile transfer to the wafer. Finally, conclusions are drawn in Section 5.

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2. Proximity effect

In EBL, resist is exposed through beam-material interactions. When the electron beam strikes the resist solid, many of the electrons experience small-angle forward scattering, and some of the electrons penetrating into the substrate undergo large-angle scattering leading to backscattering [14]. Also, the secondary electrons powered by the primary electrons through collisions may have significant energy and contribute to the bulk of the resist exposure. The effect of forward scattering and backward scattering of the electrons in the resist and substrate giving rise to exposure on an undesired region is known as the e-beam proximity effect. An example of the result of the proximity effect on PC patterning is shown in Fig. 1. The beam can be targeted to print the bulk holes of a lattice correctly, but near the border (or the defects) of the lattice some of the holes will be printed smaller even though the same dose is applied to the entire structure. Since the functionality of a PC structure is often determined by the precise geometry of the lattice holes and defects, the influence of this proximity effect should be minimized.

To correct the proximity effect, the electron energy deposition profile or the point spread function (PSF) on the resist should first be calculated. Traditionally it is approximated by the sum of two Gaussian distributions [15]

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

where α is the forward scattering range parameter, β is the backscattering range parameter, and η is the ratio of backscattered energy to forward scattered energy. By normalizing the Fourier transformation of Eq. (1), the modulation transfer function (MTF) [16] for quantitatively characterizing the proximity effect is presented,

$$M = \frac{1}{1+\eta}\left[\exp\left(\frac{-\pi^2\alpha^2}{p^2}\right) + \eta\exp\left(\frac{-\pi^2\beta^2}{p^2}\right)\right]. \qquad (2)$$

Here p is the spatial period. Ideally M should be 1 for all p. However, in the presence of electron scattering, M is less than 1 and is dependent on p. If the proximity effect is corrected, M is independent of p and the curve of MTF is flat, which corresponds to $M = 1/(1+\eta)$. For comparison, a spatial pass-band is defined in which M varies by no more than $\pm 15\%$.

The proximity parameters are experimentally evaluated via a fitting method before the measurement procedure [17]. It is found that when $\alpha = 0.087$ µm, $\beta = 0.76$ µm and $\eta = 0.72$, the computational predictions agree best with the tested devices with 400 nm PMMA and 10 kV voltage used in our experiments. When the voltage is kept constant but the resist thickness varies from 100 nm to 500 nm, the corresponding α increases from 0.05 µm to 0.11 µm; however, β and η remain constant. The MTF curves for different resist (PMMA) thickness under the same voltage 10 kV for SOI substrate are shown in Fig. 2. As can be seen, the range (0.49, 0.66) represented by the dashed lines is the pass-band for the absence of the proximity effect. The upper part of the curves ($M > 0.57$), which depends mainly on the back scattering of electrons, coincide due to the unchanged β for the same voltage. However, when M is less than 0.57 the curves are separated. The reason is that the forward scattering range changes significantly with the change of resist thickness. Moreover, the thinner the resist is, the wider the spatial pass-band will be. For example, the spatial pass-band for 100 nm and 500 nm resist are (400 nm, 2000 nm) and (900 nm, 2000 nm), respectively. It is also demonstrated that the effect of 100 nm resist is the same as that of resist with thickness less than 100 nm unless the voltage is increased, so the MTF curves for the resist with thickness less than 100 nm are not shown. The MTF decreases rapidly when the spatial period is less than 500 nm, which means the pattern quality is deteriorated because of the proximity effect. Therefore, for precise patterning of PC devices in optical communications whose periods and feature sizes are in the range of 100 nm to 500 nm, the proximity effect is a bottleneck that must be solved effectively and efficiently.

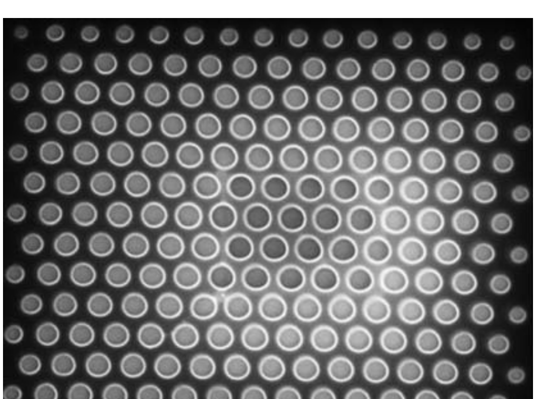

Fig. 1. Fabricated PC lattice without the proximity effect correction.

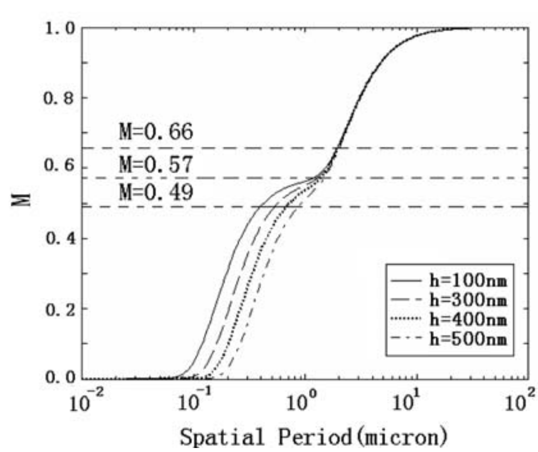

Fig. 2. MTF for different resist (PMMA) thicknesses with the same voltage of 10 kV.