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An All-E-Beam Lithography Process for the Patterning of 2D Photonic Crystal Waveguide Devices*

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Abstract: We present an all-e-beam lithography (EBL) process for the patterning of photonic crystal waveguides. The whole device structures are exposed in two steps. Holes constituting the photonic crystal lattice and defects are first exposed with a small exposure step size (less than 10nm). With the introduction of the additional proximity effect to compensate the original proximity effect, the shape, size, and position of the holes can be well controlled. The second step is the exposure of the access waveguides at a larger step size (about 30nm) to improve the scan speed of the EBL. The influence of write-field stitching error can be alleviated by replacing the original waveguides with tapered waveguides at the joint of adjacent write-fields. It is found experimentally that a higher exposure efficiency is achieved with a larger step size; however, a larger step size requires a higher dose.

Key words: photonic crystal; e-beam lithography; stitching problem; proximity effect correction
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1　Introduction

Photonic crystals[1,2] (Ph. C.) are photonic structures with periodic variations of the refractive index over wavelength-scale periods, which have various unique properties and are hailed as promising platforms for ultra-small high-density photonic integrated circuits (PIC). However, because of some difficulties in fabricating three dimensional (3D) devices, most experimental research focuses on two dimensional (2D) photonic crystal devices based on photonic crystal slabs[3,4], in which light is confined by a sufficiently large photonic band-gap (PBG) within the 2D plane and vertical light confinement is realized by the refractive index contrast between the core and the cladding.

Generally, in the near infrared wavelength range, 2D photonic crystal devices consist of an air-hole area with the smallest feature size of about 200nm and long access waveguides for measurement. Owing to its flexibility and accuracy, EBL is frequently adopted to pattern these wavelength-scale nanophotonic devices. However, because the scan speed of EBL is too slow, conventional optical lithography is often used to define the long access waveguides to improve the production yield. The combination of EBL and optical lithography is effective in patterning photonic crystal devices, but it has two main drawbacks. First, there is a need to fabricate a photomask for the access waveguides, which adds to the complexity of the process; and second, misalignment between the EBL and successive optical lithography is hard to be avoided and leads to a significant reduction of coupling efficiency between the access waveguides and the photonic crystal structures. Aiming at solving the above problems, we developed an all-EBL solution for the patterning of 2D photonic crystal devices.

2　Solution description and existing problems

The all-EBL method presented here is simple in principle. With this method, the whole device structure is separated into two parts (two layers in the layout). One part is the photonic crystal area exposed with sufficiently precise pixels in the first

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lithography step. The other part is composed of input and output waveguides connected to the photonic crystal area, the fabrication of which does not require ultra high accuracy, so it can be exposed at a larger exposure step size. With this treatment, both the accuracy of the holes and a relatively high patterning efficiency can be achieved. However, two problems still exist.

A phenomenon called the proximity effect[5] must be taken into account when fabricating a photonic crystal lattice with period and hole-size in the range of 100 to 500nm. The proximity effect is due to the scattering of electrons in the resist and substrate, which leads to an undesired influence in the regions adjacent to those exposed by the e-beam. The resulting lattice holes become larger or smaller than the target size. An example of this is shown in Fig.1, in which the holes at the center of the pattern are larger than those at the border of the lattice. The reason is that the peripheral holes receive a lower dose than the central holes because of the proximity effect and are printed smaller. Many correction methods have already been developed in the field of microelectronics, but for a photonic crystal with a dense lattice, these methods are usually computationally intensive. A special correction method for photonic crystals also was proposed in Ref.[6]; however, it requires the solution of a complex dose matrix equation, which still costs a considerable amount of time. Therefore, correcting the proximity effect with high efficiency is essential for patterning a homogeneous photonic crystal lattice.

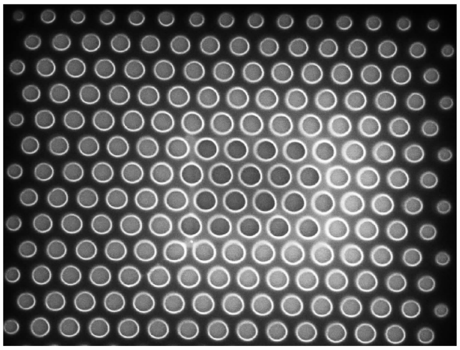

Fig. 1 Photonic crystal lattice without proximity effect correction

Another problem, called write-field stitching error, is due to the unique working mechanism of the EBL system[7]. During the lithography process, an area of a hundred or several hundreds microns is exposed using the electron optics of the e-beam column, and then the stage holding the sample is moved so that the next area can be exposed. The adjacent exposure fields have to be properly lined up or stitched in order to maintain the continuity of the exposure pattern. Hence, if a pattern has an exposure area larger than one write-field, the stitching problem will arise even if the sample-stage is controlled by the most precise interferometric feedback system. On the other hand, if the size of the write-field is increased, the dynamic range of the digital-to-analog converters and amplifiers is limited, and the nonlinear distortion will deform the pattern[8]. For most photonic crystal devices, including hole-area and access waveguides, the hole-area can be confined to a single write-field; but the input and output access waveguides always have a length of 1mm or longer to facilitate measurement, so they have to cross several write-fields and the stitching problem is introduced. The effect of the stitching error on waveguide patterning is shown in Fig.2. The access waveguide is formed by exposing and etching two rectangular areas (the wide gray zone in Fig.2) with their space W_0 as the waveguide width. One can see that there is a serious offset of about 209nm at the joint of the two adjacent write-fields of the waveguide. Light transmitted through the discontinuous region will be scattered, and the energy will be lost.

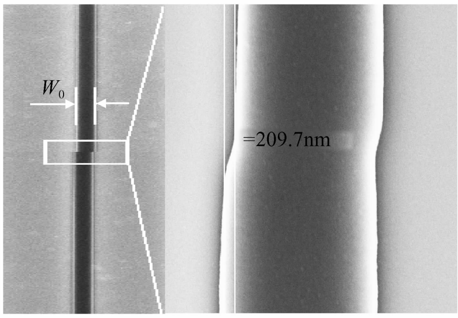

Fig.2 Stitching error causes waveguide discontinuity at the joint of adjacent write-fields

3 Proximity effect correction

EBL can print the bulk holes of the lattice correctly, but due to the proximity effect, air holes near the borders of the defects will be printed smaller since they are made less susceptible by the neighboring holes. However, though the proximity effect is generally harmful for patterning dense components, its applications can be developed. The use of an extra proximity effect to compensate for the original proximity effect in patterning a photonic crystal lattice was demonstrated effectively and efficiently in our experiments.

Take for example the patterning of a photonic crystal Fabry-Perot cavity, which is formed by adding two groups of holes separated by a certain distance into the single line-defect waveguide acting as frontal and back reflectors. To compensate for the proximity effect, two rectangular areas near the photonic crystal lattice are also exposed with high dose. According to the original proximity effect, from the center to the border, the electron dose that the holes receive gradually decreases. When there is an extra proximity introduced by the nearby rectangles' exposure, the holes in different rows from the border to the center will receive decreasing doses. Therefore, if the dose and location of the extra features are chosen properly, the original proximity effect can be compensated by the extra proximity effect, and uniform lattice structures can be defined.

The fabricated FP cavity with the above correction method is shown in Fig. 3, in which the extra exposed rectangles represented by the gray zones at the left and right sides are not totally included. The lithography was done using a Raith150 system at a 10kV acceleration voltage and a 30μm aperture with 400nm-thick PMMA as a resist. The target hole-size was 135nm in radius, and the lattice period was 400nm. The exposure dose for all the holes was 70μA · s/cm^2, while various doses of the rectangles and their space d to the outermost holes of the lattice were tried in order to find the best conditions. After exposure, the structures were developed in a MIBK : IPA = 1 : 3 solution for 15s and subsequently rinsed in IPA for 15s. Figure 3(b) shows the experimental results of the outermost hole-size versus dose of the rectangles for d of 200 and 300nm, respectively. It is apparent that with increased dose, the outermost hole-size increases approximately linearly, and the larger the distance d, the smaller the holes will be because of the weaker influence of this extra proximity effect on the holes. Therefore, to achieve a hole diameter of 270nm, nearby rectangles should be exposed at the doses of 180 and 158μA · s/cm^2 for d of 300 and 200nm, respectively. For comparison, if there is no extra dose compensation, the diameter of the outermost holes is about 230nm. If the holes are exposed directly at the above two dose values, their diameters are 375 and 360nm, respectively. Quantitative hole-size measurements demonstrate that the hole-size difference across the whole structures is limited to 5%, as can be seen from the homogeneity of the lattice shown in Fig. 3(a).

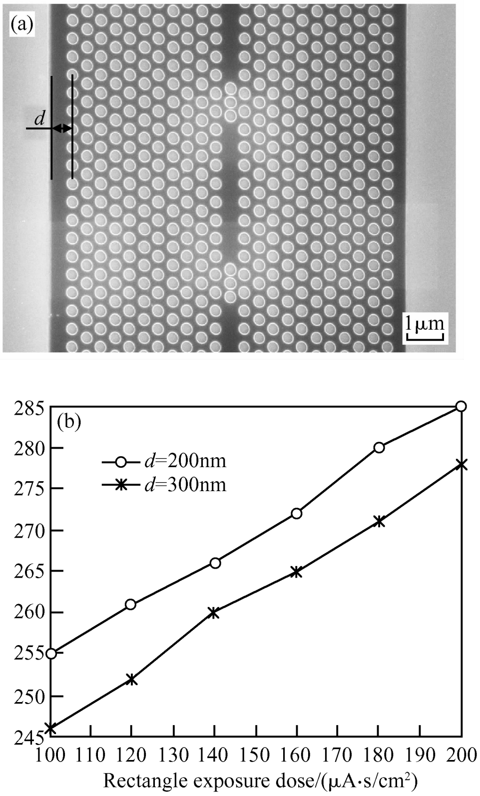

Fig. 3 (a) SEM image of the patterned FP cavity with extra proximity effect compensation; (b) Variation of the diameter of the outmost holes with electron dose at the rectangles

4 Alleviation of stitching error

As has been described, the stitching error of adjacent write-fields deforms the resulting access waveguides across the write-fields. Therefore, light transmitted through these waveguides will be scattered by the discontinuity, and energy will be lost. Though many researchers have tried to solve this problem[9], the best achievable stitching accuracy is on the order of 100nm. Using multiple scans with different field sizes, the stitching offset in the longitudinal direction of the waveguide could be avoided, but in the transverse direction it has a typical value of 200nm according to our experiments.

Since the stitching problem cannot be fully solved for EBL, an extra waveguide taper is inserted into the write-field transition section of the waveguide to alleviate the impact of the stitching offset. The fabricated access waveguide without taper and the tapered waveguide structure are shown in Fig. 4. The taper length was optimized to prevent extra light energy loss.

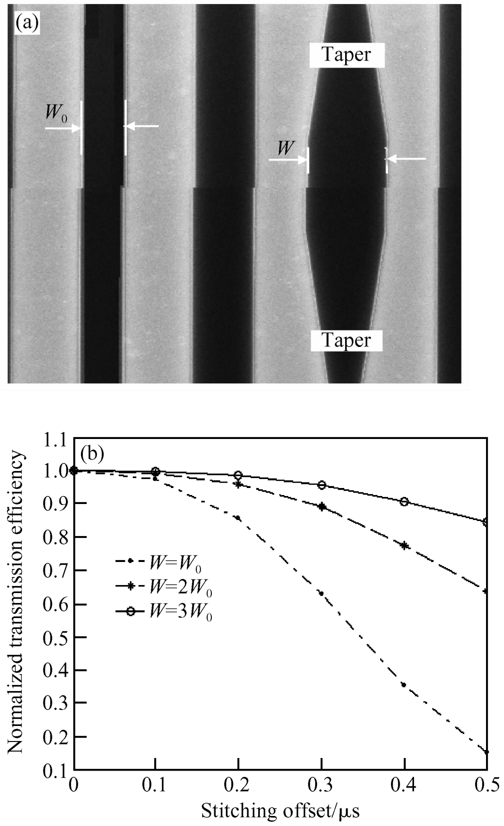

Fig. 4　(a) SEM image of the original straight waveguide and the tapered waveguide; (b) Influence of stitching offset on propagation efficiency for the original waveguide ($W = W_0 = 700$nm) and two tapered waveguides($W = 2W_0$, $W = 3W_0$)

The semi-vectorial Runge-Kutta beam propagation method (RK-BPM)[10] was adopted to simulate the influence of stitching offset on light transmission efficiency for the original waveguide and two tapered waveguides with maximum widths (W) 2 and 3 times the original width (W_0), respectively. When W_0 equals $\sqrt{3}a$, where a is the photonic crystal period, the maximum coupling efficiency between the line-defect waveguide and the access waveguide is achieved for the wavelength of 1550nm, so the value of W_0 chosen in simulation was 700nm, corresponding to the lattice period of about 400nm. Assuming that the whole device is fabricated in SOI substrate with a core thickness of 250nm, the normalized transmission efficiency of light in the access waveguides with different stitching offsets is plotted in Fig. 4(b). The propagation efficiency decreases with the increase of stitching offset, but the light intensity in the tapered waveguides decreases much more slowly than in the unmodified waveguide. For example, if the stitching offset is 200nm, the transmission efficiencies of the three waveguides are 98%, 96%, and 85%, respectively. Therefore, the introduction of a wider taper to the access waveguide at the transition section of adjacent write-fields can greatly improve the light transmission efficiency when there is stitching error.

5　Speeding up the exposure

To estimate the patterning speed of EBL for different step sizes, 10 samples of photonic crystal FP cavities together with input and output waveguides were fabricated. All the process conditions were the same as those of Fig. 3, with the only exception of varied step sizes or pixels. The total exposure area for the waveguide is about 0. 1mm^2.

Figure 5 shows the change of exposure time and optimal dose for different step sizes. The curve marked with circles demonstrates that a larger step size can improve the patterning speed. As the step size goes from 5 to 30nm, the time cost for exposure decreases from 68 to 20min, greatly enhancing the EBL efficiency. However, although higher throughput can be achieved by increasing the step size further, the patterning accuracy will worsen accordingly. For example, the position of the access waveguides will deviate from the central axes of the line-defect waveguide, giving rise to coupling loss between the access waveguides and the line-defect waveguides. It is demonstrated in our experiments that the largest step size for patterning the access waveguides with acceptable shape and position is 35nm.

The curve marked with stars in Fig. 5 shows the relationship between optimal dose and step size for proper waveguide exposure. For the same development and rinse time, the dose increases a bit as the step size becomes larger. A dose of $70\mu A \cdot s/cm^2$, which is suitable for a 5nm step size, is not enough for a step size of 20nm. The reason may be that the dose implemented during the exposure process is lower than the designed dose at a large step size, which is essentially because of the decrease of patterning accuracy.

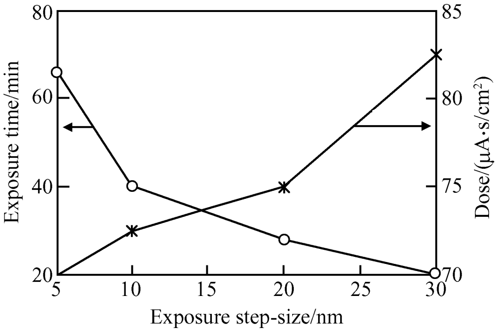

Fig. 5 Time cost for waveguide exposure (the curve marked with circles) and electron dose (the curve marked with stars) as a function of area step-size

6 Conclusion

We have developed an all-EBL process for the patterning of 2D photonic crystal waveguides. To define the air-holes precisely, a small exposure step size (less than 10nm) should be used and the proximity effect must be corrected. The original proximity effect is compensated through the introduction of an additional proximity effect. A waveguide taper is added at the joint of adjacent write-fields to alleviate the impact of the stitching problem, with the result that light transmission efficiency in the access waveguides is improved. Larger exposure step size can enhance the production yield of EBL, but higher dose is needed. This lithography process can be adopted to pattern almost any type of passive photonic crystal device based on a 2D slab, such as directional couplers, polarization or power splitters, Mach-Zehnder interferometers, and resonators.

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全电子束光刻制造二维光子晶体波导器件解决方案*

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摘要：以光子晶体 Fabry-Perot 腔为例，提出了全电子束光刻制作光子晶体波导器件的解决方案．曝光光子晶体区域时采用较小的曝光步长，同时引入额外的邻近效应补偿本征邻近效应，从而获得高质量的掩模图形．曝光较长的输入、输出波导时，采用较大的曝光步长以提高电子束扫描速度，同时在波导的写场（write-field）过渡区引入一个锥形波导以减小写场拼接误差对光传输效率的影响．实验结果证明，这种方法既能保持小孔制作需要的高精度，也能很大程度上提高光刻效率．

关键词：光子晶体；电子束光刻；写场拼接；邻近效应校正

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