Fabrication and Evaluation of Bragg Gratings on Optimally Designed Silicon-on-Insulator Rib Waveguides Using Electron-Beam Lithography*

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Abstract: The fabrication of Bragg gratings on silicon-on-insulator (SOI) rib waveguides using electron-beam lithography is presented. The grating waveguide is optimally designed for actual photonic integration. Experimental and theoretical evaluations of the Bragg grating are demonstrated. By thinning the SOI device layer and deeply etching the Bragg grating, a large grating coupling coefficient of $30\mathrm{cm}^{-1}$ is obtained.

Key words: integrated optics; Bragg grating; silicon-on-insulator; rib waveguide
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1 Introduction

Bragg gratings are essential components in optical communication systems and have found many applications in reflectors, wavelength filters, dispersion compensators, and other devices. Much research on fabricating Bragg gratings by physically corrugating the waveguide surface in such materials as InP/InGaAsP, silica, and polymer has been reported. However, little has been reported on grating fabrication on silicon-on-insulator (SOI) wafers, even though SOI has become a popular substrate for use in photonic integration[1].

Rib waveguides on SOI wafers have attracted significant attention due to their design flexibility, lower transmission loss, low polarization dependence, and high tolerance for fabrication errors[2]. Furthermore, a rib waveguide can support a single-mode operation even if it has a large cross section[3]. Much research on silicon rib waveguides has been reported[4~6]. Murphy *et al*. presented the first experimental demonstration of a narrow-band Bragg-reflection filter in SOI rib waveguides using interference lithography[4].

Here we report another method for forming Bragg gratings on SOI rib waveguides using electron-beam (EB) lithography. Compared with conventional interference lithography, direct-write EB lithography has many advantages in grating fabrication[7]. For example, it is easy to form a very narrow pitch grating, a chirped Bragg grating, and a phase shift grating. The grating waveguide is optimally designed for the actual photonic integration[8].

As an important evaluation parameter of Bragg grating performance, the coupling coefficient is basically determined by the spatial periodic index perturbation. In order to obtain a large index perturbation, we thinned the SOI device layer and deeply etched the grating. The deep etching of a silicon grating is technically challenging because a silicon grating has a smaller grating period due to a larger refractive index than other materials such as SiO_2 and polymer. In order to implement deep etching, we selected chromium (Cr) as a mask to etch the SOI device layer because there is a larger selective etching ratio. The Cr grating pattern was formed by a lift-off process, as using EB lithography to define the grating pattern ensures good pattern transference from the resist to the Cr layer.

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With these technical considerations, we obtained a large grating coupling coefficient of $30cm^{-1}$, which is the largest to date among works on SOI rib waveguides.

2 Design and fabrication

The SOI wafers we used were prepared by the bond and etch back technique (BESOI). The thickness of the buried SiO_2 was 1.0μm, and that of the silicon device layer was 2.1μm. The design of the rib waveguide is a natural tradeoff between waveguide single-mode conditions, transmission loss and bending loss of curved waveguides. The transmission loss is mainly from the roughness in the etched waveguide surface[9], so a rib waveguide with a large cross section has less transmission loss under the same level of the surface roughness. However, there is a large bending loss for a rib waveguide with such a large cross section because of the weak confinement of the propagating modes. With a judicious choice of these dimensions, a reasonable compromise can be obtained.

The consideration of SOI device layer thickness is critical in designing the rib waveguide, as shown in Fig. 1, where the waveguide width, and the thicknesses inside and outside of the waveguide are denoted by W, H and h, respectively. In the cal-

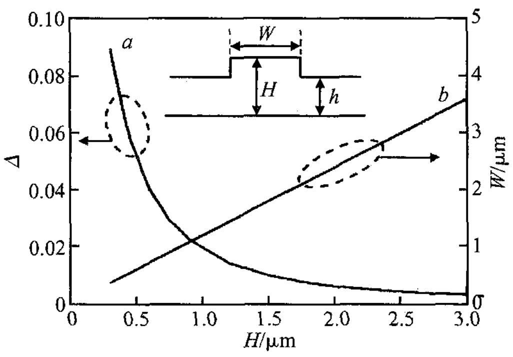

Fig. 1 Dependence of refractive index difference (Δ) and waveguide width (W) on substrate thickness (H) for h/H = 2/3

culations of Fig. 1, a condition of $h/H = 2/3$ is assumed, and it is used in the following discussions. Plot a shows the dependence of the relative refractive index difference (Δ) on device layer thickness. Δ is defined as $(n_{co} - n_{cl})/n_{co}$, where n_{co} and n_{cl} are the effective refractive indexes in the core and the clad of the waveguide, and it relates directly to the bending loss of the curved waveguides. Therefore a thinner device layer leads to less bending loss under the same widths of the waveguide. Also, a strong grating coupling can be easily obtained for a thin device layer. However, a thin device layer would lead to a narrow waveguide width according to the single-mode conditions of rib waveguides, as shown by plot b. The area below plot b is a single-mode zone. Usually, a narrow waveguide is difficult to fabricate. In this work, considering that the waveguide is patterned by standard photolithography, we first selected a waveguide width of 2μm. Based on the results in Fig. 1, the SOI device layer was thinned to 1.6μm by a wet oxidation step with H_2O and O_2 at 1000 ℃, and the etched depth was selected to be 0.53μm.

The grating fabrication on the SOI rib waveguide comprised two steps. First was the grating fabrication on the SOI surface, as shown in Figs. 2(a) and (b). Second was the formation of the waveguide on the grating patterns, as shown in Figs. 2(c)～(f). In order to form a Bragg grating on the SOI wafer, the wafer was coated by an EB resist, ZEP520, and patterned by EB exposure. After development, a Cr-layer with a thickness of

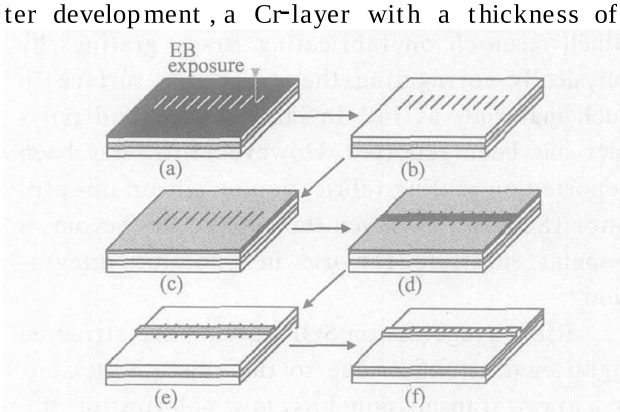

Fig. 2 Fabrication process of Bragg gratings on rib waveguides

60nm was deposited on the wafer, and a grating Cr pattern was formed by a lift-off process. Then a silicon grating was formed by etching the SOI device layer to a depth of 200nm in an inductively coupled plasma-reactive ion etching (ICP-RIE) process, where the Cr pattern served as a mask. The length, period and the duty circle of the silicon Bragg grating are 500μm, 230nm, and 40%, respectively. A gas mixture of C_3F_8, O_2 and Ar in a ratio of 5∶1∶20 was used in the RIE process.

The ICP power and the bias were 600W and 250W, respectively. Under the RIE conditions, the etching ratio of Cr and Si is about 1 : 4.5.

Forming the grating waveguide is a very important process. In the process, we aimed at two things. One was not to damage the fine grating pattern, and the other was to make a smooth, vertically-etched wall of the grating waveguide. Using a two-step-etching method, we formed the grating waveguide. In the first etching step, a SiO_2 pattern was formed. Then the SiO_2 pattern served as mask, and the silicon waveguide was formed in the second etching process. The fabrication details are as follows. First, the wafer with grating patterns was deposited with a layer of SiO_2 as shown in Fig. 2(c). After the deposition, the wafer was coated by a photoresist, TSMR, and was exposed by a standard photolithography process as shown in Fig. 2(d). Then the photo-mask pattern was transferred to the SiO_2 layer by the first RIE step utilizing a C_3F_8-O_2-Ar gas mixture as shown in Fig. 2(e). Next we etched the SOI device layer in the second RIE step, utilizing a Cl_2-Ar gas mixture to form the silicon waveguide, as shown in Fig. 2(f). A SEM picture of a waveguide with a Bragg grating is shown in Fig. 3. Then, we deposited a thick SiO_2 layer on the SOI wafer to protect the silicon patterns. Finally, the SOI wafer was cleaved for measurement after lapping by chemical mechanical polishing (CMP).

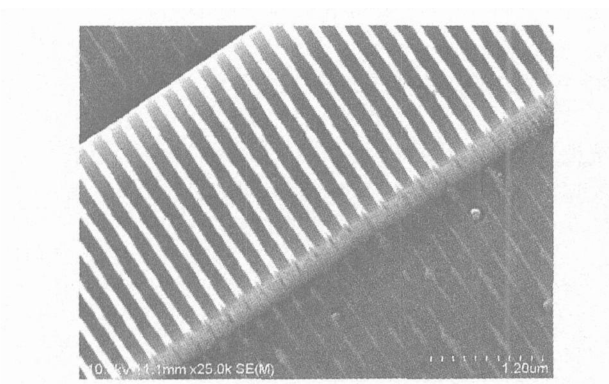

Fig. 3　Bragg grating on an SOI rib waveguide

3　Results and discussion

The measurement was carried out as follows. An amplified spontaneous emission (ASE) source was input into a polarization controller, and the output of the polarization controller was launched into the grating waveguide by lensed-fiber. The waveguide output was collected by lensed-fiber that connected with an optical spectrum analyzer. The reflection from the grating waveguide was received by an optical circulator. The measured transmission and reflection of a Bragg grating for the TE mode are shown by the solid lines in Figs. 4(a) and (b), respectively. Figure 4(a) shows that there are some resonant peaks on the right side of the center wavelength, which is likely due to the poor uniformity of the EB resist pattern. For example, if a resist defect were transferred into a grating pattern, it would lead to grating spectrum asymmetry because of local resonant modes[10].

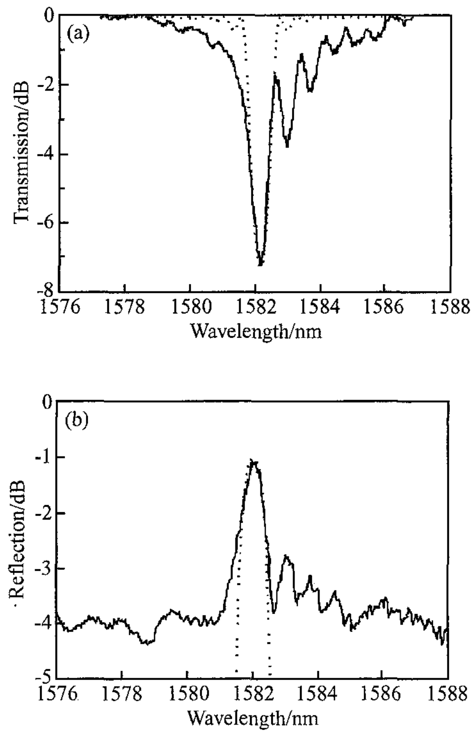

Fig. 4　Measurement and simulated results of transmission (a) and reflection (b) for TE mode of a Bragg grating

Using coupled mode theory, we simulated the transmission and reflection of the grating. The results are shown by the dotted lines in Figs. 4(a) and (b). From Fig. 4(a), we know that the calculated results basically agree with the experimental data, though there is a disagreement around the center wavelength. This is mainly from the grating scattering loss due to the surface roughness of the etched grating teeth. In Fig. 4(b), the spectrum away from the peak is inconsistent between the experiment and simulation results because we did not consider the measurement background, the reflected light from the input facet of the grating waveguide, in the theoretical simulation. From the measured grating spectra, the grating coupling coefficient is theoretically evaluated to be about $30cm^{-1}$.

The propagation loss of the grating waveguide is about 3dB/cm for the TE mode, as measured by the cut-back method. The coupling loss between a fiber and the grating waveguide was evaluated to be about 4dB/facet.

4 Conclusion

We have presented a new method for fabricating Bragg gratings on SOI rib waveguides using EB lithography. A grating waveguide was optimally designed for actual photonic integration. By thinning the SOI device layer and deeply etching the grating, a grating coupling coefficient as large as $30cm^{-1}$ was obtained.

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用电子束曝光方法在优化设计的绝缘体上硅脊状波导上实现布拉格光栅的制作和评价*

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摘要: 报道了一种用电子束曝光的方法在绝缘体上硅的脊状光波导上制做布拉格光栅的技术. 考虑到实际的光子学集成的应用, 讨论了这个带有布拉格光栅的脊状光波导的优化设计, 给出了该布拉格光栅的测试和理论模拟结果. 通过薄化绝缘体上硅的波导层的厚度和光栅的深腐蚀加工, 获得了高达 $30cm^{-1}$ 的光栅耦合系数.

关键词: 集成光学; 布拉格光栅; 绝缘体上硅; 脊状光波导

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