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SOI Waveguides Fabricated by Wet-Etching Method*

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Abstract: SOI waveguides fabricated by wet-etching method are demonstrated. The single mode waveguide and 1 × 2 3dB MMI splitter are analyzed and designed by three dimensional beam propagation method to correct the error of effective index method and guided mode method. The devices are fabricated. Excellent performances, such as low propagation loss of − 1.37dB/cm, low excess loss of − 2.2dB, and good uniformity of 0.3dB, are achieved.

Key words: SOI; wet-etching; multimode interference; single mode waveguide
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1 Introduction

The unique optical properties owing to large refractive index difference between the core ($n_{Si} = 3.5$) and the cladding ($n_{SiO_2} = 1.45$) have caused the emergency of silicon-on-insulator (SOI) as a platform for both photonic integrated circuits (PIC's) as well as VLSI. This promising trend has led to in-depth investigation of the characteristic and application of SOI waveguides[1,2] and silicon based photonic devices[3~5] in the past tens of years. Comparing with other channel waveguides such as SiO_2[6], most SOI single-mode waveguides with core dimensions comparable with single-mode fibers are rib structure, planar wafers have to be etched by dry-etching, such as reactive ion etching (RIE) and inductively coupled plasma (ICP), or wet-etching.

In comparison, wet-etching method has several significant advantages over dry etching method. Firstly, it requires no expensive equipments. The constant temperature box can be easily found in a common chemical laboratory. Secondly, unlike ICP or RIE, it can be easily carried out and can be repeated exactly, avoiding huge number of samples to be tested for etching condition. Thirdly, this method can provide very smooth bottom surface and sidewalls, thus yield surprising propagation loss as low as 0.1dB/cm[7]. Unfortunately, the cross-section of the waveguides is trapezoidal with side angle at 54.74° because of the anisotropic etching speed along different crystal orientations, resulting in inconvenience for designing various devices. In this paper, we present the design of single mode SOI waveguide and 1 × 2 3dB multimode mode interference (MMI) splitters by three dimensional beam propagation method (3-D BPM). Also, these devices are fabricated and tested, showing excellent performance.

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2 Design

The slope side walls of the rib waveguides as shown in Fig. 1 make effective index method (EIM) unworkable to obtain single mode curve as rib waveguides with vertical side walls stated as[1]

$$t \leqslant 0.3+\frac{r}{\sqrt{1-r^{2}}},\ t=\frac{w}{H},\ r=\frac{h}{H},\ r \leqslant 0.5 \quad (1)$$

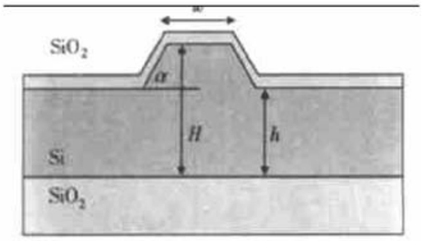

Fig. 1 Cross section of trapezoidal SOI waveguide

Some other analytical methods as transfer matrix method to calculate trapezoidal cross section waveguides[8] are studied. However, more accurate method such as 3-D BPM have to be employed especially when dealing with MMI couplers due to the uncertainty of effective width of multimode waveguide including Goos-Hahnchen extension. Figure 2 represents the schematic diagram of a 1 × 2 MMI splitter based on the self-imaging property[9] of a multimode waveguide. The minimum length of the multimode waveguide to form two-fold image cannot be determined by

$$L=\frac{n_{\mathrm{r}} W_{\mathrm{eff}}^{2}}{2 \lambda} \quad (2)$$

where n_{r} is the refractive index of the multimode section and W_{eff} is the effective width of the multimode waveguide, since it is difficult to determine W_{eff}.

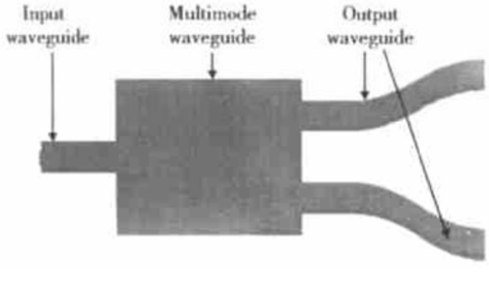

Fig. 2 Schematic diagram of 1 × 2 MMI splitter

Our numerical simulation by 3-D BPM employed perfect match layer (PML) boundary condition and alternating direction implicit (ADI) method. The program was executed on Matlab platform. The default wavelength was set to 1.55μm. For the single mode waveguide, $H=5$, $w=3$, $h=3.2$ and the computation window was 16 × 16 plus 2 × 2 PML layer, and the default unit was micrometer. The input Gaussian field had a radius of 4μm representing optical field of the single mode fiber. Figure 3 (a) illustrates the outfield after propagating 2000μm and Figure 3 (b) shows the total energy in the computation window as a function of the propagation length. The base TE mode contour map would keep steady after 1000μm and no more than 62.24% energy would remain in the waveguide, representing the couple efficiency between single mode fiber and the SOI waveguide.

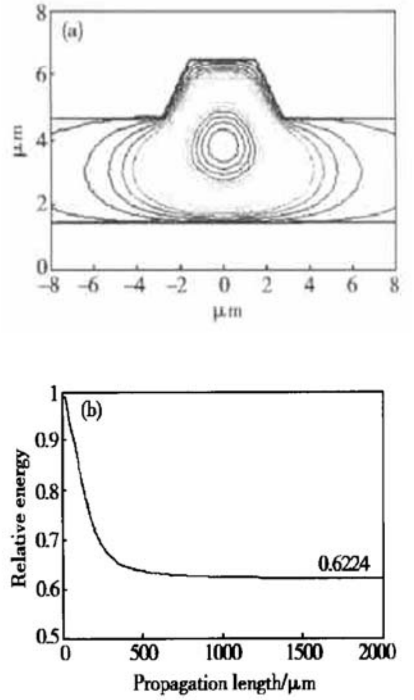

Fig. 3 (a) Contour map of TE mode in cross section; (b) Remaining energy in computation window

The MMI splitter in this paper consisted of one input waveguide located at the center of the multimode waveguide and two symmetrical output waveguides with $W_{\mathrm{eff}}/2$ spacing. The widths of these waveguides were 3μm and 50μm respectively. During the process of simulation, to seek the best length for the MMI splitter, there were only one input waveguide with 1000μm in length and one multimode waveguide of 3700μm. The computation window was 70μm × 20μm including 2μm × 2μm PML layer. Figures 4 (a) and (b) show the contour map of TE mode in the propagation plane and cross section at the optimum length of the multimode waveguide. It can be seen that the best length is 3262μm, while the length derived by Eq. (2) is 3151μm considering Goos-Hahnchen extension. The two output waveguides should be located ± 13.7μm offset the center axis to receive maximum power, while ± 13.2μm according to guided mode theory[8]. To evaluate the performance of the MMI splitter, power uniformity (UF) and excess loss (EL) are defined as:

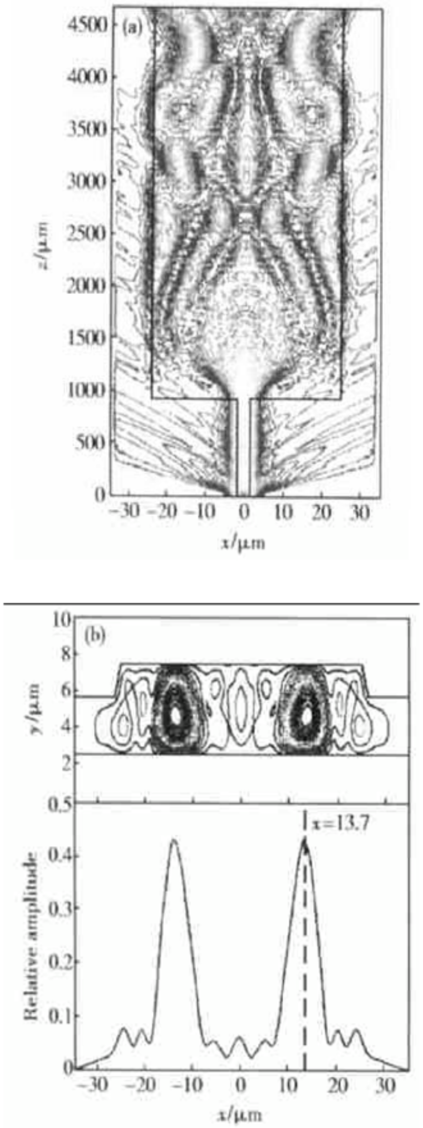

Fig. 4 (a) Contour map of TE mode in the propagation plane; (b) Contour map of TE mode in the cross section at the optimum length

$$\mathrm{UF} = 10\lg(P_1/P_2)$$

$$\mathrm{EL} = 10\lg\left(\frac{P_1 + P_2}{P_0}\right) \qquad (4)$$

P_1 and P_2 ($P_1 > P_2$) are the output powers in the two branches respectively. P_0 is the output power from the straight single mode waveguide under the same testing circumstance.

3 Fabrication

The bond and etch-back SOI (BESOI) wafer which had a SiO_2 thickness of 1μm and an Si thickness of 5μm was used to fabricate the single mode waveguide and the MMI splitter by conventional Si process. The rib waveguides were wet chemically etched to a depth of 1.8μm using a mixture of KOH, $CH_3(CH_2)_2OH$ and H_2O in the mass ratio of 23.4∶13.3∶63.3. The width of SiO_2 lithography mask for the single mode waveguide was 3μm since the undercutting of the mask by anisotropic etching process was so small as to be omitted. This case could also be true with respect to multimode waveguide. The multimode waveguide was 3262μm in length and 50μm in top width. The smooth side wall surface could be clearly seen from the SEM graph as Fig. 5, which is indispensable for low propagation loss. A 0.3μm SiO_2 covering layer was deposited by plasma enhanced chemical vapor deposition (PECVD) on top of the silicon layer to protect the surface. Also, tapered waveguides were used to connect the multimode section with the output waveguide to reduce loss and enlarge power uniformity[3]. The wafer was thinned and cleaved at last.

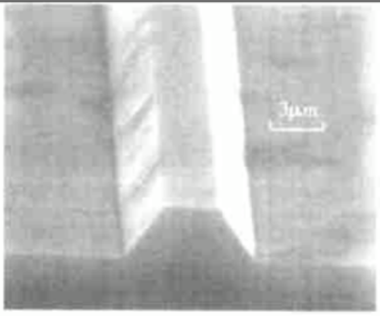

Fig. 5 SEM graph of SOI waveguide

4 Experimental result

The wafer was located on the MELLES GRIOT six-dimension adjusting platform to couple with the single mode fiber, from which the laser at wavelength of 1.55μm was launched to the cleaved facet of the input waveguide. The light through the output waveguides was collected by a lens and then projected onto an infrared sensitive CCD. With the help of PC laser beam analyzer (a software running on a PC), the image could be displayed on the PC monitor. If another single mode fiber connecting with a power meter was aligned to the output waveguides in place of the convex, the outcome powers were directly measured. To measure the propagation loss of the straight single mode wave-guide, multi-reflecting method using HP 8504B precision reflectometer was employed, showing excellent veracity and iteration. The propagation loss coefficient can be derived by

$$\alpha = -\frac{1}{2L}\ln\left[\frac{1}{R^2} \times \frac{P_3}{P_2}\right] = -\frac{1}{2L}\ln\left[\frac{1}{R^2} \times \frac{P_4}{P_3}\right] \quad (5)$$

or

$$\delta = 10\alpha \lg e \quad (6)$$

here L represents the length of the waveguide, $R = 0.31$ is the Fresnel reflective coefficient, and P_i ($i = 2, 3, 4 \cdots$) is the power of the ith reflective peak that can be read from the reflectometer. Figures 6 (a) and (b) are the measured near field images of the single mode waveguide and 1 × 2 MMI splitter respectively. The propagation loss coefficient of the single mode waveguide measured by multi-reflecting method is 1.37dB/cm. The uniformity of the splitter is as low as 0.3dB and excess loss of −2.2dB. The total insertion loss for one port of the splitter is −15.7dB, including −2.8dB propagation loss, 3dB splitting loss, −3.5dB Fresnel reflecting loss and −4.2dB coupling loss between two end surfaces and single mode fibers.

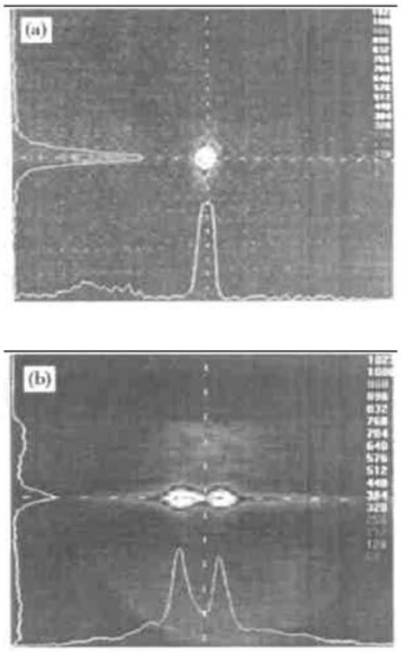

Fig.6 (a) Near field image of single mode waveguide; (b) Near field image of 1 × 2 MMI splitter

5 Conclusion

In this paper, we demonstrated the single mode waveguide and 3dB MMI splitter based on BESOI wafer fabricated by wet chemical etching method that can be easily carried out. The output near-field images were obtained and output powers were directly measured by power meter. Also, the multi-reflecting method was applied to get propagation loss coefficient as 1.37dB/cm for the single mode waveguide. The excess loss and power uniformity of the splitter were −2.2dB and 0.3dB respectively.

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湿法腐蚀制备的SOI光波导*

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摘要: 用化学湿法腐蚀的方法制作了SOI光波导,并且用三维波束传播方法分析和设计了单模波导和1×2 3dB多模干涉分束器,修正了有效折射率和导模传输方法的误差.制作的器件具有低传输损耗(-1.37dB/cm)、低附加损耗(-2.2dB)、良好的均衡性(0.3dB)等优良性能.

关键词: SOI; 湿法腐蚀; 多模干涉; 单模波导

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