Low-loss amorphous Si waveguides with gradient refractive index cladding structure

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Amorphous Si waveguides with gradient refractive index cladding structure are proposed and fabricated using plasma-enhanced chemical vapor deposition method. Compared with 6 dB/cm for ridge waveguide without gradient cladding, the propagation loss of the gradient cladding waveguides is less than 1 dB/cm with both TE and TM polarizations.

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Semiconductor waveguides are basic components in modern optical networks. In improving the performance of waveguides, coupling loss is one of the fundamental issues in device fabrication process. Aside from it, the total loss of the semiconductor optical waveguide is mainly due to the propagation loss, which includes the scattering loss, material absorption and structure loss, such as bending radii. The latter two sources of losses can be eliminated by improving the martial growth improvement and structure optimization[1,2].

Scattering loss in waveguide structures originates from the sidewall roughness, which is due to the line edge roughness of lithography process and the subsequent etching process. Radiation induced by the index contrast between the waveguide core materials and the cladding is the physical origin of this effect. The scattering loss is proportional to $\Delta n^2 = n^2_{\text{core}} - n^2_{\text{cladding}}$[3]. The electron beam-defined waveguide patterning followed by optimized dry etching process has been proposed to improve the waveguide loss[4]. However, this method is expensive and time consuming. Teo *et al.*[5,6] used oxidation process to reduce the index contrast between the Si waveguide core and the air cladding; both obtained low loss of less than 1 dB/cm in both TE and TM polarizations.

In this letter, we propose amorphous Si waveguides with symmetric quasi-continuous index distribution claddings. Figure 1 presents the schematic, which indicates that the core layer of the waveguide is sandwiched by gradient index distributed layer stacks from the core to the background material. As long as the index contrast between the adjacent layers in the stack is small enough, the scattering loss of the waveguide induced by the line edge roughness can be neglected. As a result, the total propagation loss of the waveguide is improved. We have achieved quasi-continuous index control from 3.33 to 1.45 by modifying the deposition parameters of plasma enhanced chemical vapor deposition (PECVD) in amorphous Si-SiN_x-SiO_xN_y-SiO_2 system using Surface Technology Systems (STS) Mesc Multiplex PECVD and PlasmaLab PECVD systems[7]. We also obtained ultralow reflectivity and broad band antireflective coating with a quasi-continuous index distribution dielectric stack. In the proposed waveguide structure, the cladding materials can be gradually modified from the surrounding material, i.e., SiO_2 to the core material amorphous Si. Based on the above analysis, the scattering loss of the fabricated waveguide can be eliminated with this gradient index stack.

Single dielectric layers were deposited on individual Si wafers and then characterized using a Woollam variable angle spectroscopic ellipsometer (VASE) to determine the thickness and refractive index by employing a Bruggeman effective medium approximation (EMA) ellipsometry model. The details have already been presented in another published work[7]. To fabricate the waveguide devices, a thin layer from SiO_2, SiN_xO_y, SiN_x to amorphous Si with 150-nm designed thickness was deposited on the (100) Si substrate with 6-μm oxide, followed by a 300-nm amorphous Si layer as the core. Then, the sample was patterned by conventional photolithography to define the waveguides with a width of 2 μm. Reactive ion etching (RIE) with CHF_3 plasma was carried out to etch the 300-nm core layer with photoresist as the mask. After removing the remaining photoresist, another 150-nm-thick gradient index distribution layer from amorphous silicon to SiO_2 was deposited on the whole wafer to obtain the gradient upper cladding. Finally, a 2-μm SiO_2 layer was deposited to obtain the symmetric index distribution. For comparison, we also fabricated a 300-nm-thick amorphous Si waveguide on 6-μm oxide

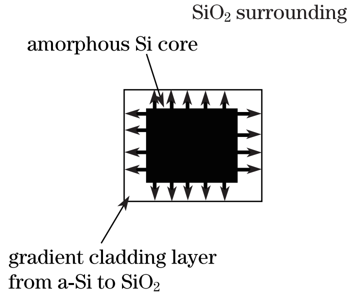

Fig. 1. Schematic figure of the proposed waveguide structure with a gradient index distribution cladding. The gradient layer is quasi continuously modified from amorphous silicon, SiN_x, SiN_xO_y, to SiO_2, i.e., the index decreases from 3.22 of amorphous Si to 1.44 of SiO_2 quasi continuously.

without gradient cladding layer. Figure 2 shows the scan electronic microscopy (SEM) and the photo picture of the cross-sectional and top views of the gradient index cladding waveguides, respectively. The interface of the waveguide core layer and the cladding layers is blurred due to the fact that the components of the layers have been quasi continuously modified. The optical mode profiles collected by CCD IR camera from the end facets of both the gradient cladding waveguide and the ridge waveguide with the same length are described in Fig. 3. It is brighter in the gradient cladding waveguide than in the ridge waveguide, which suggest that the scattering loss in the gradient cladding waveguide is smaller than that in the ridge waveguide.

The fabricated waveguides were cut into 2, 1.5, 1.0, 0.5, and 0.2-cm lengths for coupling measurement. The propagation loss and the coupling loss of 1.55-μm light were obtained using the cutback method[5]. Figure 4 shows the total loss as a function of the waveguide length. We can see that the slopes of the curves denoting the propagation loss are 0.95±0.6 and 0.89±0.04 dB/cm for TE and TM polarizations, respectively. These results are comparable with other experimental results[2,6,8]. Coupling losses of TE and TM polarizations are 17.3 and 15.3 dB, respectively, which can also be extracted from the curves. On the other hand, the propagation and coupling losses of the ridge waveguides are 6.5±0.8 and 5.7±0.5 dB/cm for the TE polarization, and 24.6±0.8 and 22.1±0.7 dB/cm for the TM polarization, respectively. We can conclude that the scattering loss of the waveguides is significantly reduced by reducing the index contrast Δn, which has

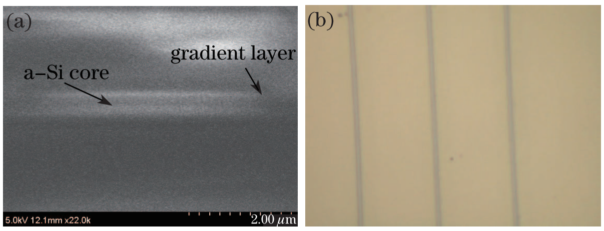

Fig. 2. (a) SEM picture of the cross-sectional and (b) the top views of the gradient cladding waveguides. The width is 2 μm, and the edge of the waveguide is blurred due to the continuously modified materials.

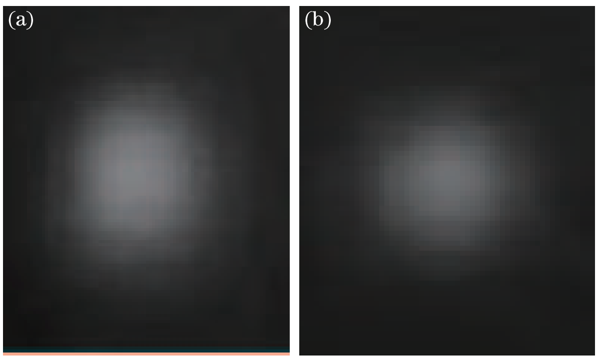

Fig. 3. CCD pictures of the optical modes from the facets of both (a) the gradient cladding waveguide and (b) ridge waveguide at the same magnification.

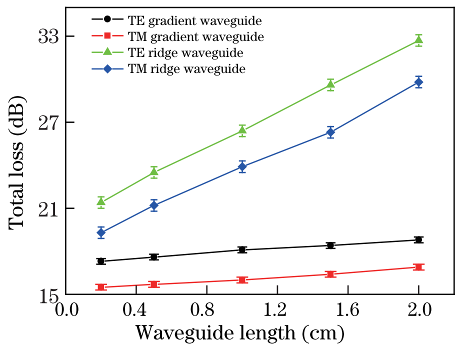

Fig. 4. Total coupling loss of the gradient cladding waveguides and the conventional ridge waveguide structure as a function of waveguide length for both TE and TM polarizations. The slope of the line suggests the improvement of the gradient claddings in the proposed structure. Furthermore, the coupling efficiency is improved by the mode expansion effect of the gradient layers.

been eliminated by the gradient layer stack. Furthermore, the continuous index distribution cladding layers enhance the optical mode expansion, and finally improve the coupling efficiency between the fiber and the amorphous silicon waveguides. Note that the propagation loss of the waveguide can be improved further by annealing the process, by which to eliminate the absorption loss of hydrogen, which can be further improved through the annealing process.

In conclusion, the low-loss amorphous Si core waveguides with quasi-continuous index distribution of cladding layers is proposed in this letter. The propagation losses of the fabricated waveguides are both less than 1 dB/cm for the TE and TM polarizations due to the gradient index stack. In addition, the couple efficiency between the fiber and the fabricated waveguide is significantly improved by the proposed structure.

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