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Fabrication of Silicon Master Using Dry and Wet Etching for Optical Waveguide by Thermal Embossing Technique

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Masters for the fabrication of planar optical waveguides were fabricated from (100) silicon wafers. Deep reactive ion etching (DRIE) and wet chemical etching were used to form smooth rectangular patterns on the masters. The roughness of the etched patterns was small enough to fabricate planar optical waveguides. The treatment of a master surface with oxide and perfluoalkylsilane (PFAS) improved further the separation of the master and the substrate. The materials that were used as underclad and core layers were organic-inorganic hybrids called as-hybrid materials (HYBRIMERs). We successfully replicated the waveguides with the fabricated masters.

1. Introduction

The demand for optical waveguides for short-distance telecommunications will increase rapidly for optical signal transfer between chips in the near future. Optical fibers, which have been widely used for long-distance telecommunications are not suitable as waveguides for short-distance telecommunication, as their manufacturing cost is too high.(1)

Recently, an inexpensive embossing technique has been developed to fabricate low-cost waveguides for short- distance telecommunications.(2–6) The embossing technique requires a patterned plate called a master to fabricate planar optical waveguides. Several materials, such as nickel, silica, and silicon, have been used to fabricate masters with

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various advantages.

To fabricate a good planar optical waveguide, the master should be rectangular in shape with a smooth surface. A rough optical waveguide surface causes the chance of escape of the wave from the optical waveguide, resulting in increased propagation loss. We have used silicon as a master material, as a smooth surface can be obtained by anisotropic wet chemical etching.[7] In this case, however, it is impossible to form rectangular etched shapes, owing to the dependence of etching rate on crystal planes.

In this study, we employed dry and wet chemical etching to fabricate silicon masters. Deep reactive ion etching (DRIE) and wet etching were used to obtain rectangular shapes and smooth surfaces, respectively. Planar optical waveguides, which use organic-inorganic hybrid materials (HYBRIMERs) as core and clad materials, were formed by thermal embossing using the fabricated master.

2. Materials and Methods

(100) silicon wafers were used as substrates for the masters. Photolithography was carried out to form 1 × 2 and 1 × 4 split patterns that would be used to form optical waveguides. The patterns were etched anisotropically by DRIE to form rectangular shapes. The size of the etched pattern was about 50 × 50 μm.

A smooth etched master surface is very important for the fabrication of an optical waveguide. Ripple structures, however, were found on the etched surfaces, owing to the DRIE mechanism. After dipping the samples in a buffered HF solution for the elimination of the passivation material formed during the DRIE process, wet chemical etching was then carried out to reduce the roughness of the surface originating from the ripple structures. The chemical for the etching was TMAH of 25% concentration.[8]

The master and the fabricated waveguide should be easily separated after the embossing process. To increase the degree of hydrophobic character of the etched silicon surface, the surface was oxidized to form silicon oxide film and Perfluoalkylsilane (PFAS) film was coated on the oxide surface.

A schematic of the thermal embossing process is shown in Fig. 1. Methacrylic fluorinated HYBRIMER (MFD) as underclad and Methacrylic HYBRIMER (MD) as a core layer were spin coated on a silicon substrate. The refractive indexes of the MD and MFD at a wavelength of 850 nm were 1.54 and 1.51, respectively. The HYBRIMERs contain thermal initiator and harden when they are heated. The fabricated silicon master was placed on the spin-coated silicon substrate, and pressure and heat were applied to transfer the patterns on the master to the core layer on the substrate.

Scanning probe microscopy (SPM) and scanning electron microscopy (SEM) were used to observe the shape of the fabricated masters and planar waveguides. An optical transmission test through the planar waveguide splitter was performed to measure the optical mode by infrared-sensitive charge-coupled discharge (CCD) and the propagation loss using an 850 nm laser source.

3. Results

The shape of the patterns etched by DRIE is dependent on process conditions. We

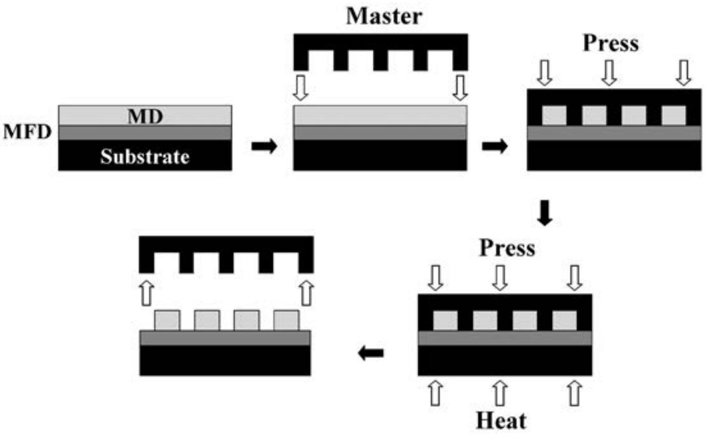


Fig. 1. Schematic of planar waveguide fabrication process.

investigated the shape according to etching step time with a fixed passivation time of 7 s. Figure 2 shows the ratio of the top and bottom widths of the shape after the DRIE process. The ratio decreased as the etching step time increased. A ratio less than 1, indicating that the bottom width is larger than the top width, would make the separation of the master and the fabricated waveguide hard after the embossing process. We, therefore, chose 9 s as an appropriate etching step time.

Figure 3 shows SEM images of (a) the fabricated silicon master and (b) cross-sectioned sidewall surface after the DRIE process. Ripple structures were formed on the sidewall surface of the pattern, owing to the characteristics of the DRIE mechanism.

Anisotropic wet etching was carried out to reduce the ripple structures. Figure 4 shows roughness of the sidewall surface as a function of the wet etching time.

Also, Fig. 5 shows SEM images of the sidewall (a) without wet etching and (b) with wet etching for 40 s. The roughness value was reduced to 5.5 nm from 14 nm. The roughness obtained by wet etching was small enough for the fabrication of planar optical waveguides. As the etching time increased, an inclined (111) plane began developing at each of the corners between the bottom and side walls owing to the anisotropic etching characteristics of the silicon crystal, as shown in Fig. 6.

The silicon master was completed using a DRIE step time of 9 s and by wet chemical etching for 40 s. Planar optical waveguides, which use organic-inorganic hybrid materials (HYBRIMERs) as core and clad materials, were formed by thermal embossing using the fabricated master. The embossed patterns were well duplicated from the fabricated master. Figure 7 shows an SEM image of an embossed planar waveguide. The easy separation of the master and the substrate is a result of the combined DRIE and anisotropic wet chemical etching to improve the sidewall surface of the master.

Figure 8 shows the optical characteristics of the fabricated planar waveguide. Most laser light is guided through the waveguide with a small amount of the light being leaked through the residual layer. The measured propagation loss through the optical waveguide was 0.4 dB/cm at 850 nm.

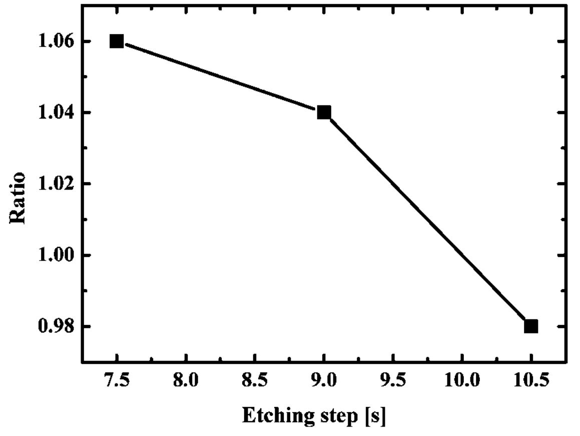
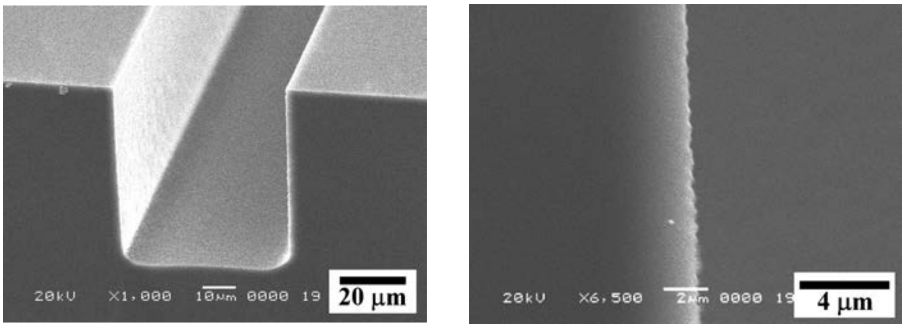


Fig. 2. Ratio of top and bottom widths of etched shape.



(a) (b)

Fig. 3. SEM images of (a) Si master and (b) cross-sectioned sidewall surface.

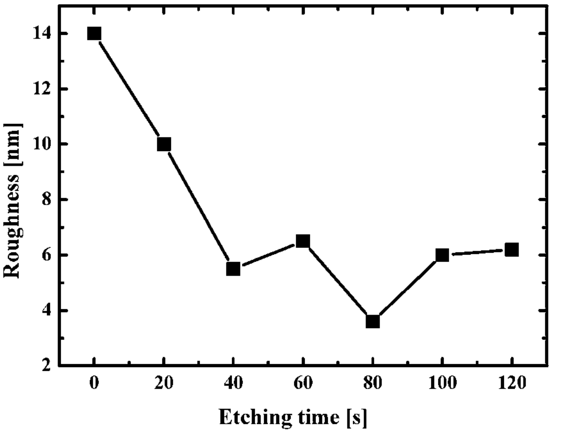
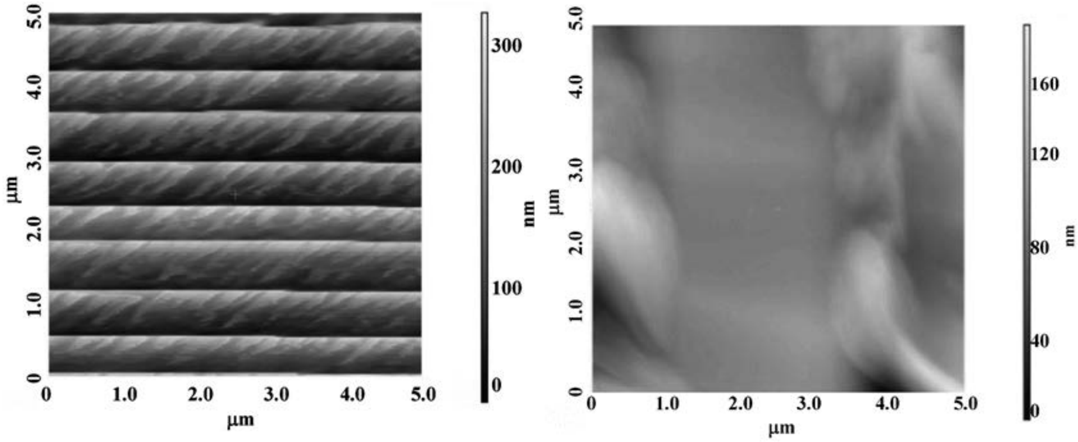


Fig. 4. Roughness variation of sidewall surface as function of wet etching time.



(a) (b)

Fig. 5. SEM images of sidewall (a) without wet etching and (b) with wet etching for 40 s.

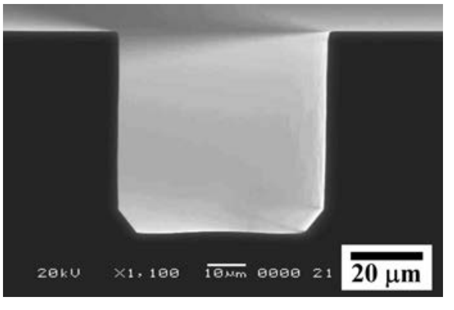


Fig. 6. SEM image of sidewall with wet etching for 2 min.

4. Discussion

Silicon hard masters were fabricated using (100) silicon wafers in order to form planar optical waveguides. By combining DRIE and anisotropic wet etching process, we obtained masters with etched patterns with rectangular shapes and smooth surfaces. The roughness value of the sidewalls was 5.5 nm, small enough for the fabrication of planar optical waveguides. The surface treatment of the master surface with oxide and PFAS improved further the separation of the master and the substrate. We successfully replicated planar optical waveguides with the fabricated master.

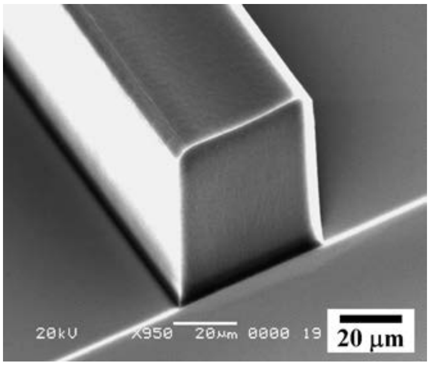


Fig. 7. SEM image of the embossed planar waveguide.

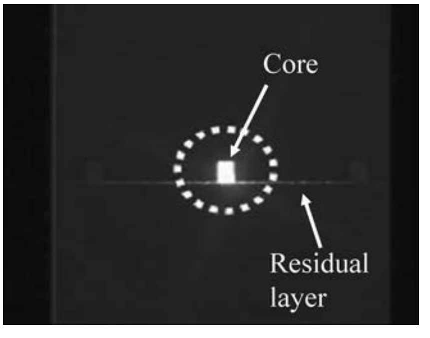


Fig. 8. Cross-sectioned optical microscope image taken by infrared-sensitive CCD showing transmitted laser beam of 850 nm wavelength.

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