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Multi-mode Planar Waveguide Fabricated by a (110) Silicon Hard Master

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Abstract

We fabricated (110) silicon hard master by using anisotropic wet etching for embossing. The etching chemical for the silicon wafer was a TMAH 25 % solution. The anisotropic wet etching produces a smooth sidewall surface and the surface roughness of the fabricated master is about 3 nm. After spin coating an organic-inorganic sol-gel hybrid material on a silicon substrate, we employed hot embossing technique operated at a low pressure and temperature to form patterns on the silicon substrate by using the fabricated master. We successfully fabricated the multi-mode planar optical waveguides showing low propagation loss of 0.4 dB/cm. The surface roughness of embossed patterns was uniform for more than 10 times of the embossing processes with a single hydrophobic surface treatment of the silicon hard master.

Key Words : Silicon hard master, Anisotropic wet etching, Multi-mode planar waveguide, Embossing

1. INTRODUCTION

The demand of optical waveguides in short-distance telecommunications will increase rapidly for opticalsignal transfer between computers and chips in near future[1]. The type of optical fiber that has been widely used for long-distance telecommunications is too costly to be used for the waveguides in short-distance telecommunications[2,3]. Recently, an inexpensive embossing technique was developed to fabricate low-cost waveguides for short-distance telecommunications[4-8].

In the embossing technique, a patterned plate called a master is used to fabricate the planar optical waveguide, and patterns are formed by pressing the patterned master on a substrate and curing it[9]. The embossed patterns on the substrate should be well duplicated from the patterns on the master. In order to produce the well duplicated patterns, the surface roughness of the master should be very smooth for easy separation between the pattern and the master. In particular, the sidewall roughness of the master is critical for the easy separation.

Several materials, such as nickel, silica, and silicon, have been used to fabricate masters with various advantages. A master fabricated with nickel has a long life-span but the fabrication procedure is expensive because it requires a process called *lithographie galvanoformung abformung*. In addition, when fabricated with this process, the nickel master has a high level of roughness. Masters can also be fabricated with silicon by means of deep reactive ion etching(RIE), and this method is popular because of the wide availability of the microelectro-mechanical system. Deep RIE, however, produces a scallop structure on the silicon sidewall, and an experienced operator is needed to control the structure.

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To fabricate a (110) silicon hard master, we used anisotropic wet etching. With this method, we obtained an atomically smooth etched surface because the anisotropic wet etching utilizes the varied bonding strengths of different crystal planes. We employed the hot embossing technique to fabricate multi-mode planar optical waveguides using organic-inorganic hybrid materials(HYBRIMERs) as core and clad materials. The HYBRIMERs show both advantages of organic and inorganic materials, and therefore their processes are easy and thermal stabilities are high.

2. EXPERIMENTAL

In the experiment conducted for this study, 3-(trimethoxysilyl)propylmethacrylate (MPTMS), perfluoro-alkylsilane (PFAS), and diphenyl-silanediol (DPSD) were used as precursor molecules, while barium hydroxide monohydrate ($Ba(OH)_2 \cdot H_2O$) was used as a catalyst to promote the poly-condensation reaction among these three precursors. The reaction between MPTMS and DPSD produces MD as the core HYBRIMER of the planar waveguide. Addition of PFAS (10 mol%) to MD to reduce the refractive index produces MFD as the cladding HYBRIMER. A detailed synthesis procedure for the HYBRIMERs is described elsewhere[10].

To fabricate the silicon masters, we used 4″ (100) p-type silicon wafers. The silicon wafers were oxidized in an electric furnace to form a 500 nm silicon oxide film on the wafers as a protection layer for silicon etching. Next, with the aid of a standard semiconductor photo-lithographic process, we used an photomask (Microimage) to transfer patterns onto the oxidized silicon wafers. Anisotropic wet etching with a TMAH 25 % (Nepes) solution was used to etch the silicon surface[11,12]. First, we heated the TMAH 25 % solution to 80 °C. We then put the silicon wafer with oxide patterns into the TMAS 25 % solution and shook the solution to detach any H_2 bubbles from the silicon surface. The surface of the fabricated silicon master should have a hydrophobic characteristic to ensure that the master can be separated smoothly from the formed patterns. To increase the hydro-phobicity of the etched silicon surface, we oxidized the surface again to form the silicon oxide film and we coated the oxide surface with a PFAS film.

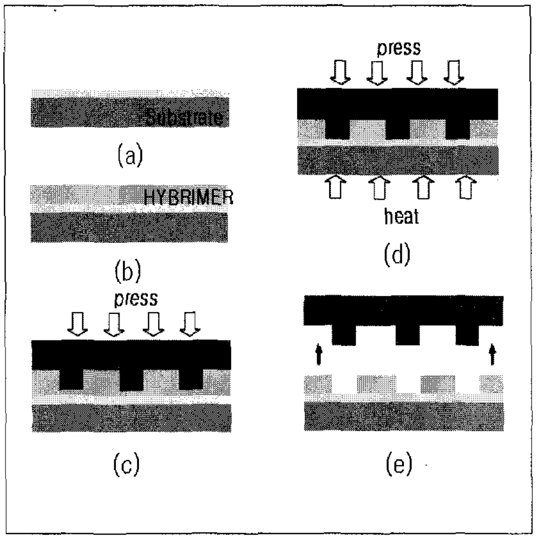
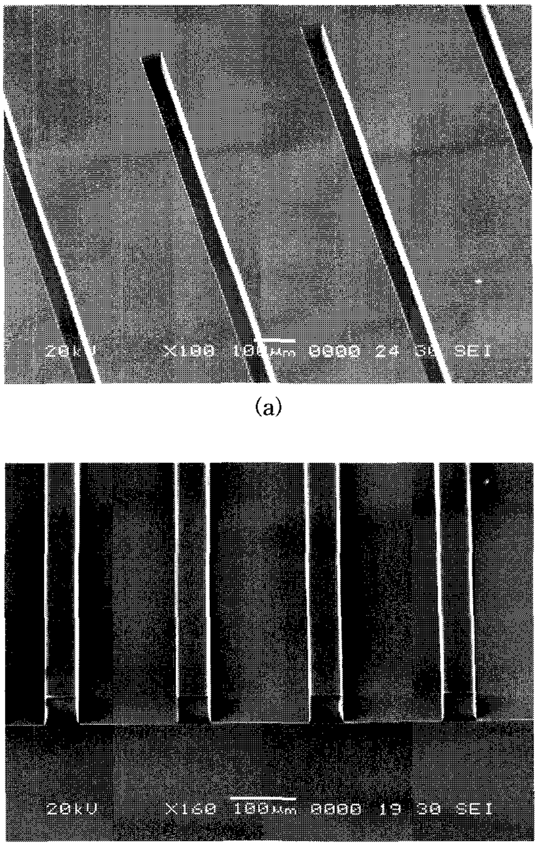


Fig. 1. Fabrication process of a planar wave-guide: (a) under-cladding layer formation, (b) core layer formation, (c) first master pressurization, (d) heat and second pressurization, and (e) master separation.

Figure 1 shows the fabrication process of optical waveguide made by hot embossing. First, we spin coated an under-cladding HYBRIMER layer onto a silicon substrate then cured by heat in N_2 atmosphere. The waveguide is formed by means of a hot embossing method. In the hot embossing method, the core HYBRIMER layer is spin-coated on the under-cladding HYBRIMER layer. After placing the silicon master, which we fabricated as described in the previous paragraph, on the spin-coated core HYBRIMER layer, we applied pressure in the range of 1 kg/cm^3 to 3 kg/cm^3 and heat at 100 °C for 10



(a)

(b)

Fig. 2. SEM images of (a) the (110) silicon master and (b) the embossed planar waveguide.

min in order to transfer the master patterns onto the core HYBRIMER layer on the substrate. We then separated the silicon master from the HYBRIMER spin-coated substrate. Finally, we analyzed the shape and surface roughness of the formed patterns by using an optical microscope, a scanning electron microscope (SEM), and a scanning probe microscope (SPM).

Optical transmission test through the planar waveguide was performed to measure the optical mode by infrared-sensitive charge coupled discharge (CCD) and propagation loss using an 850 nm laser source. The average propagation loss of the fabricated optical waveguides was measured by the cutback method.

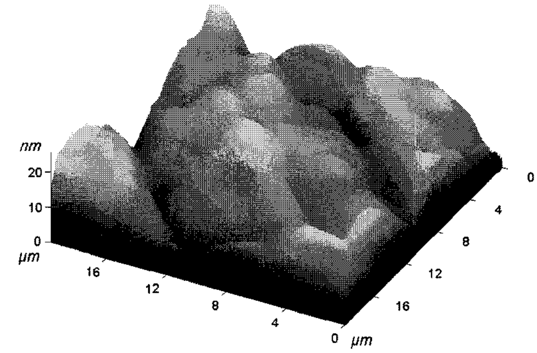


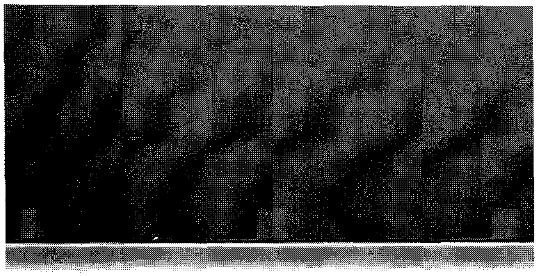
Fig. 3. An SPM image of embossed core surface on top region. The scan of the image is 20 µm x 20 µm.

3. RESULTS AND DISCUSSION

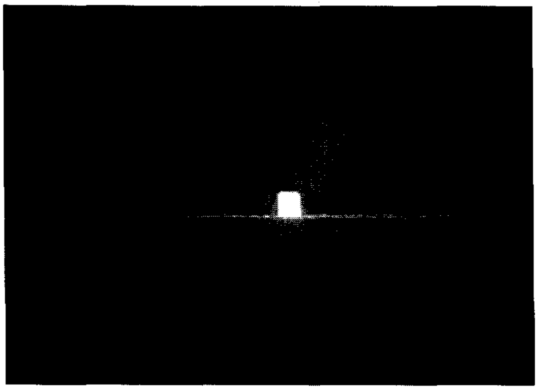
Figure 2 shows SEM images of (a) the patterns on the (110) silicon master (50 µm x 50 µm) and (b) the embossed waveguide patterns on a silicon substrate. The embossed patterns on the substrate shown in Fig. 2(b) are well duplicated from the patterns on the master shown in Fig. 2(a). The easy separation of the master from the substrate is the result of the oxidation and the PFAS treatment of the master, which increases the hydrophobicity of the master surface.

Figure 3 shows an SPM image of the embossed core surface on top region. The roughness value of the top surface and sidewall surface region is about 3 nm. This result is superior than that of deep reactive ion etched (RIE) silicon surfaces. The typical roughness of the DRIE sidewall region is about 20 nm[13]. Sidewall surfaces were usually a little rougher than top surfaces. The surface roughness, though the data was not shown in this paper, was uniform for more than ten embossment processes with a single surface treatment of the silicon master.

Figure 4 shows optical microscope images of (a) an embossed pattern showing 3 waveguides and (b) an embossed pattern with center wave-



(a)



(b)

Fig. 4. Cross-sectioned optical microscope images of (a) an embossed pattern showing 3 waveguides and (b) an embossed pattern with a center waveguide guiding laser light.

guide guiding laser light. We can observe that a small portion of laser light aligned to the center waveguide is leaking out through the residual layer of the core film as shown in Fig. 4(b). However, the portion of the leaked light is small enough that the adjacent waveguides are not affected.

Figure 5 shows the insertion loss as a function of waveguide length. From the graph, the average propagation loss of the fabricated optical waveguide was 0.4 dB/cm at 850 nm wavelength, which was measured by the cutback

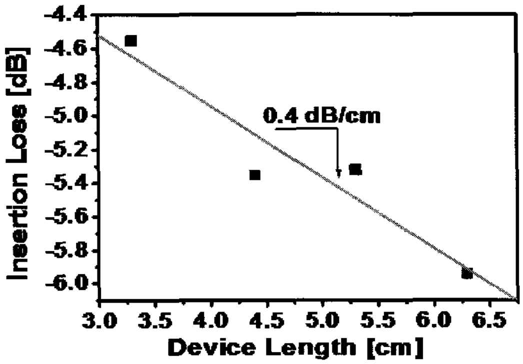


Fig. 5. Insertion loss as a function of waveguide length.

method. This result is quite good considering the loss of the laser light through the residual layer.

4. CONCLUSIONS

By using anisotropic wet etching and a TMAH 25 % solution, we fabricated a (110) silicon hard master, and we analyzed its surface property with the aid of an SEM and SPM. We then used PFAS to enhance the hydrophobicity of the master surface for easy separation. In addition, we used a hot embossing technique at a low pressure and temperature to form HYBRIMER patterns with the fabricated silicon master. As a result, the formed patterns were shaped almost the same as those of the silicon master, and the surface roughness of the embossed patterns was uniform, and about 3 nm. The waveguides fabricated by the hot embossing show good surface roughness (less than 3 nm) and optical properties (~0.4 dB/cm propagation loss).

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