Fabrication of Ridge Waveguides by UV Embossing and Stamping of Sol-Gel Hybrid Materials

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***Abstract*—Multimode large core ($45 \times 35\ \mu m^2$) optical ridge waveguides are fabricated in the room temperature by ultraviolet (UV) imprinting of soft rubber template with the organic–inorganic sol-gel hybrid materials. The fabrication processes may be either well-known UV embossing or stamping. A new sol-gel hybrid material that is thermally stable has been developed for the fabrication of low-loss optical waveguides. The UV curable methacrylic sol-gel hybrid material is used for the core layer and fluorinated methacrylic sol-gel hybrid material is used for the cladding layer. The optical propagation loss of fabricated waveguide measured by the cutback method is 0.36 dB/cm at 850 nm and the surface roughness of waveguide is about 5 Å root mean square.**

***Index Terms*—Large core multimode waveguide, organic–inorganic hybrid materials, photo and thermally curable, polydimethyl siloxane (PDMS) mold, ultraviolet (UV) stamping and embossing.**

I. Introduction

The OPTICAL waveguide devices have been actively studied and developed for low-cost mass production that uses simple fabrication processes [1]. Recently, ultraviolet (UV)-based soft lithography methods have been investigated for mass production of polymeric optical waveguides [2]. UV embossing and stamping have a special advantage compared with other fabrication methods (e.g., hot embossing), i.e., they consist of low-temperature and low-pressure processes [3], [4]. For the large core waveguides, the fabrication of high quality masters is not so easy. The pattern of the masters should be thick enough, but should be made fine for the low-loss waveguides and complex waveguide devices [5]. Although polymeric large core optical waveguides have been fabricated by using these methods [5], there has been little effort so far to apply them to the sol-gel hybrid materials. The glass submicron fabrication is done by micro-molding with the conventional sol-gel material [6]. Their micro-molding should be processed at high temperature (1100 °C) with the conventional sol-gel materials. The organic–inorganic hybrid materials prepared by the sol-gel process of organo–alkoxy silane, which will be called HYBRIMER, may be used in the room temperature for the fabrication of multimode large core optical waveguide, instead of polymers [7]. The HYBRIMER has the high-temperature resistance (over 300 °C) and very low birefringence (less than 10^{-4}). The HYBRIMER is curable by UV light and heat, since the polymerizable organic group can be incorporated in the HYBRIMER. Thus, the HYBRIMER may be used in UV embossing and stamping for the fabrication of optical waveguide.

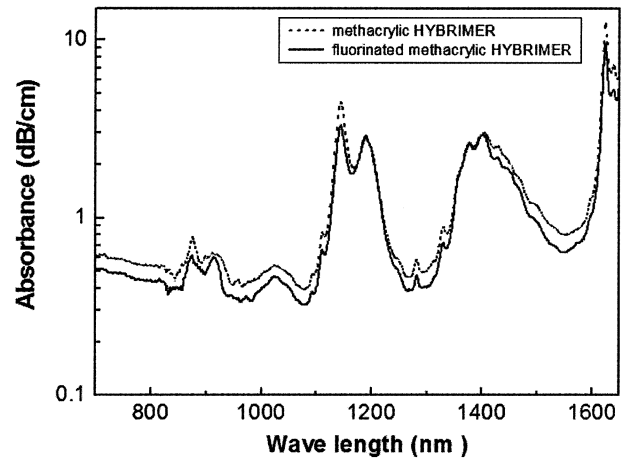

Fig. 1. Optical absorption of two HYBRIMERs (methacrylic HYBRIMER and fluorinated methacrylic HYBRIMER).

Usually, the stamp is fabricated by transparent quartz, metal, or polydimethyl siloxane (PDMS) rubber. PDMS rubber can cover large areas and has very low reactivity and interfacial energy toward the organic materials. In addition, it is so elastic that we may remove it from patterned organic materials without any deformation of replicated patterns [8]. Because the HYBRIMER material is compatible with silicon wafer substrate and PDMS replica mold, it is very simple to remove PDMS mold from the final patterned ridge waveguide without any other processes. In this letter, we report the fabrication of large core multimode optical ridge waveguide using UV embossing and stamping with the HYBRIMERs and PDMS mold.

II. Fabrication of Multimode Optical Waveguide

The HYBRIMER is synthesized by alkoxylation of diphenylsilanediol and 3–methacryloxy–propyltrimethoxysilane for the core layer [9]. The HYBRIMER for the cladding layer is synthesized by alkoxylation of diphenylsilanediol, 3–methacryloxypropyltrimethoxysilane, and perfluorodecyl–trimethoxysilane. The refractive index of the core HYBRIMER is 1.532 at 1550 nm and that of the cladding HYBRIMER is 1.50

Manuscript received March 24, 2004; revised April 19, 2004. This work was supported by the Sol-Gel Innovation Project (SOLIP) from the Ministry of Commerce, Industry, and Energy of Korea.

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Digital Object Identifier 10.1109/LPT.2004.831053

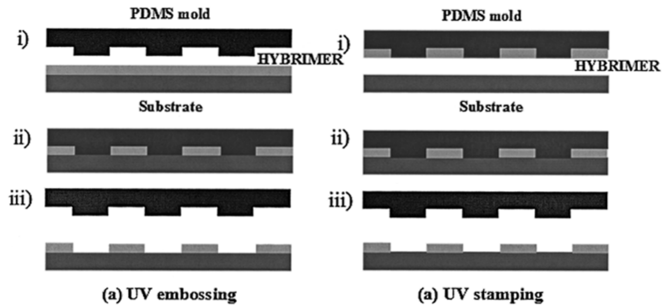

Fig. 2. (a) Schematic diagram of UV embossing method, and (b) UV stamping method. In process (a), the HYBRIMER is coated on the substrate first and the pattern is replicated by soft molding, and in process (b), the HYBRIMER is dispensed at PDMS stamp and the pattern is replicated by soft molding.

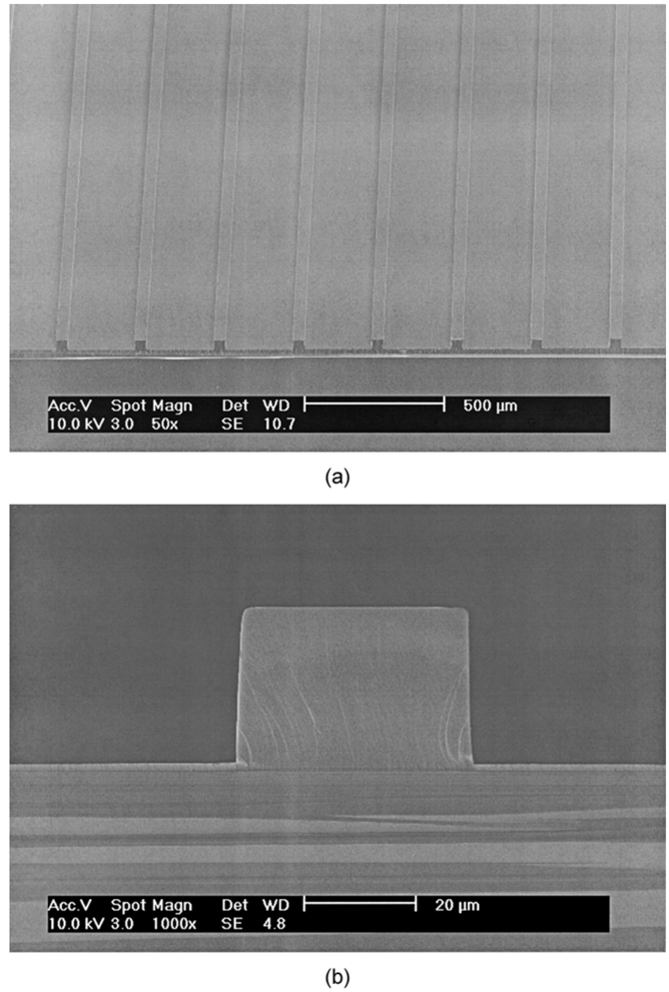

Fig. 3. (a) Scanning electron microscope image of the several ridge waveguide arrays, and (b) the end face of fabricated one ridge waveguide.

at 1550 nm. Fig. 1 shows the optical absorption of the HYBRIMERs. Optical absorption is measured by UV/Vis/Near IR sepctroscopy. Sample condition is resin contained in quartz sample holder (thickness is 1 cm). The optical absorption is the dominant factor to the propagation loss of optical waveguide. The methacrylic HYBRIMER, which is used for the core layer, shows low optical absorption because it contains low Si–OH content. The fluorinated methacrylic HYBRIMER is used for the cladding layer. In this HYBRIMER C-H is partially substituted by C-F, which results in a decrease of absorption over the whole detected spectral range. The absorption of fluorinated methacrylic HYBRIMER are 0.4 dB/cm at 850 nm, 0.4 dB/cm at 1310 nm, and 0.5 dB/cm at 1550 nm, respectively. The used photoinitiator, which may help for HYBRIMER to be cured by UV light dose during UV embossing step, is Irgacure369 (Ciba Geigy) and the used UV light is mainly 365-nm wavelength source.

The transparent and low-cost PDMS polymer mold is fabricated by the photolithography using the AZ9260 photoresist on silicon wafer [10]. In order to transfer the patterns of PDMS mold, we use UV embossing or stamping. In the UV embossing method, the HYBRIMER is spin-coated on the substrate. Then, PDMS mold is pressed on the HYBRIMER film. When the mold has a contact on the coated substrate, the air bubbles can be trapped between the substrate and the mold. Deforming the PDMS mold in a convex shape is necessary when placing the mold upon the substrate. Similarly, in the UV stamping method, the bare substrate is covered by PDMS mold containing the HYBRIMER and then pressed by the mold (Fig. 2).

Because we obtain the same result from the two methods, we will explain, representatively, about the UV-embossing method. First of all, we prepare the under-cladding layer of about 10 μm by spin coating of fluorinated HYBRIMER and curing by UV light. Then, the core HYBRIMER is spin-coated on the cladding HYBRIMER layer. And PDMS mold is covered and pressed on the coated sample. The waveguides are formed by filling the trenches of the mold by pressure and the core material is polymerized by UV light to maintain original replicated grooves. An appropriate pressure, not so high to deform the patterns of the mold, is necessary.

After detaching the PDMS mold, the replicated HYBRIMER waveguide pattern is obtained. Finally, the fabricated ridge waveguide is thermally cured. The curing process of the HYBRIMER is obtained in two steps, soft baking at 80 °C and hard curing at 150 °C to remove solvents in the HYBRIMER. Fig. 3 shows the end face of ridge waveguides fabricated by UV embossing. The waveguide width is about 45 μm and its height is about 35 μm and the residual layer thickness is about 1 μm.

III. Discussions

Multimode waveguide devices in the home network may be fabricated by UV stamping and embossing of sol-gel hybrid materials developed here. The thickness of HYBRIMER is variable from 5 to 150 μm by changing the speed of spincoater. Thus, HYBRIMER is suitable for the fabrication of multimode optical waveguide as well as single-mode waveguide. As shown in Fig. 3, we have a residual layer of about 1 μm between the core and the cladding layer, which raised little problem for our multimode waveguide. The condition that the core mode is not guided in the residual layer, is determined from the characteristic equation of TE_0 mode [11]. The thickness of the residual layer should be less than 1.03 μm. A further reduction of residual layer thickness is desirable. The average surface roughness of fabricated waveguide, measured by atomic force

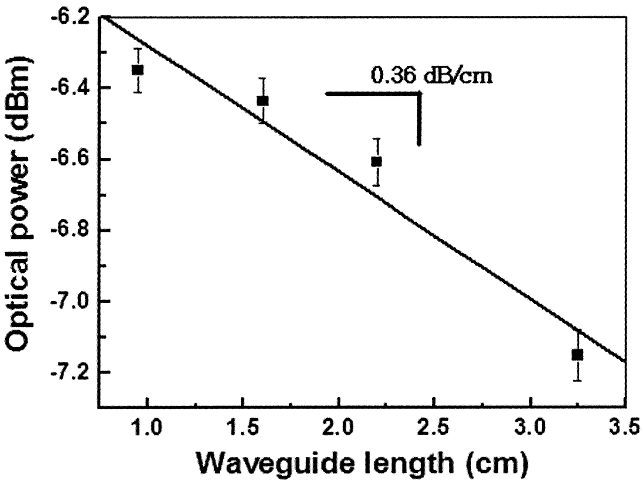

Fig. 4. Cutback optical loss result of fabricated waveguide at 850 nm.

microscopy, is about 5 Å root mean square. The average propagation loss of the fabricated optical waveguides was 0.36 dB/cm at 850-nm wavelength, which was measured by the cutback method (Fig. 4).

IV. Conclusion

We have demonstrated a multimode optical ridge waveguide of organic–inorganic hybrid materials fabricated by simple UV embossing and stamping methods. At a condition of low temperature and pressure, we can get thermally stable (over 300 °C) waveguide patterns with well-defined edges. The large core multimode waveguide can be used for the power splitter and the simple aligning optical interconnect.

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