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Fabrication of Channel Waveguides by Photochemical Self-Developing in Doped Sol-Gel Hybrid Glass

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Abstract. Sol-gel derived inorganic-organic hybrid glass (HYBRIMER) films doped with benzildimethylketal (BDK) were prepared. Refractive index and film thickness increase by UV exposure due to photoinduced polymerization and photolocking of high refractive index BDK. This enables the channel waveguides in HYBRIMER film to be fabricated without using a developing process, which is called photochemical self-developing (PSD). The waveguides consist of three layers with under-cladding and over-cladding of undoped HYBRIMER films and core of BDK-doped HYBRIMER film. A 1 × 4 splitter of waveguides was fabricated and demonstrated.

Keywords: sol-gel hybrid glass, HYBRIMER, photolocking, photochemical self-developing, channel waveguide

1. Introduction

Sol-gel derived inorganic-organic hybrid materials (HYBRIMER) have begun to receive attention for integrated optical applications. Sol-gel process is versatile and flexible in composition and process, and low cost process. The channel waveguides using a photosensitive HYBRIMER or polymer can be fabricated by a photolithographic etching process, which offers easy and cheap processing. The photo-polymerizable HYBRIMER consisting of methacrylate and silicate/zirconia networks has been used for the fabrication of channel waveguides using the photolithographic etching process [1–3]. Also, a method to use photolocking of dopants inside the matrix without a wet etching process was proposed as a simpler technique to fabricate channel waveguides in polymers [4, 5]. This process, which has sufficient resolution to make single-mode waveguides, gave smooth interfaces and low optical losses of channel waveguides.

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Recently, we applied the photolocking of photoinitiators in the HYBRIMER films to fabricate channel waveguides [6, 7]. Thus, the photolockings of volatile higher refractive index species in HYBRIMER films can fabricate the channel waveguides. It was found that the volatile higher refractive index photoinitiators in the HYBRIMER were locked or fixed in the matrix resulting in increase in refractive index and thickness of the films upon UV exposure. Thus, the channel waveguide can be easily fabricated without using a developing process. This process to fabricate the channel waveguide has been called as a photochemical self-developing (PSD).

In this study, we used volatile BDK to be photolocked in the HYBRIMER films. Increase in refractive index and film thickness depending on UV exposure and BDK concentration was investigated. The processing conditions of photochemical self-developing to fabricate the single mode channel waveguide using a photomask in the HYBRIMER were determined. The waveguides consist of three layers. A core layer between cladding layers was fabricated. Finally, a

1 × 4 splitter device of waveguides was fabricated and demonstrated.

2. Experimental Procedure

HYBRIMER whose composition was already used in optical waveguide was prepared using methacryloxypropyltrimethoxysilane (MPTMS, $H_2C{=}C(CH_3)CO_2(CH_2)_3Si(OCH_3)_3$), zirconium n-propoxide (ZPO, $Zr(OC_3H_7)_4$), and methacrylic acid (MAA, $H_2C{=}C(CH_3)CO_2H$) as precursors [1–3, 6–8]. First, MPTMS was hydrolyzed with 0.75 equivalent of H_2O in the presence of 0.05 M HCl as a catalyst. ZPO was reacted with MAA in a molar ratio of 1:1 to avoid undesired precipitation of ZrO_2 particles by chelating complex formation. After that, the chelated ZPO solution was added to the prehydrolyzed MPTMS solution and stirred for 1 hour to advance hydrolysis and condensation. The mixed solution was reacted with additional water for 20 hours to complete the hydrolysis and condensation. Total amount of water was the 1.5 equivalent of total alkoxides in the solution. Benzyldimethylketal (BDK, $C_6H_5COC(OCH_3)_2C_6H_5$) was used as a photolocking agent as well as a photoinitiator.

The prepared solution was then deposited on Si and thermally oxidized Si wafers using spin coating method. Single coating yields approximately 4–5 μm thickness of the films. The films were illuminated by UV lamp (1 KW Hg-Xe lamp, 220–260 nm, Oriel 82521) for different UV doses to find out appropriate refractive index and thickness change. The UV illuminated films were dried at 50°C for 30 minutes. Finally, the films were baked 150°C for 5 hours. Refractive index and thickness of the films were determined by using a prism coupler (Metricon 2010) at wavelength of 632.8 nm.

3. Results and Discussion

3.1. *Photoinduced Change in Refractive Index and Film Thickness*

Figure 1 shows the refractive index increase and the film thickness increase by UV dose and BDK contents, respectively. For the BDK (30 mol%)-doped HYBRIMER film, the refractive index change is 3.0×10^{-2} from 1.52 to 1.55 at 633 nm and the film thickness increases up to 1.5 according to UV dose increase. That indicates the film thickness of the unexposed and the

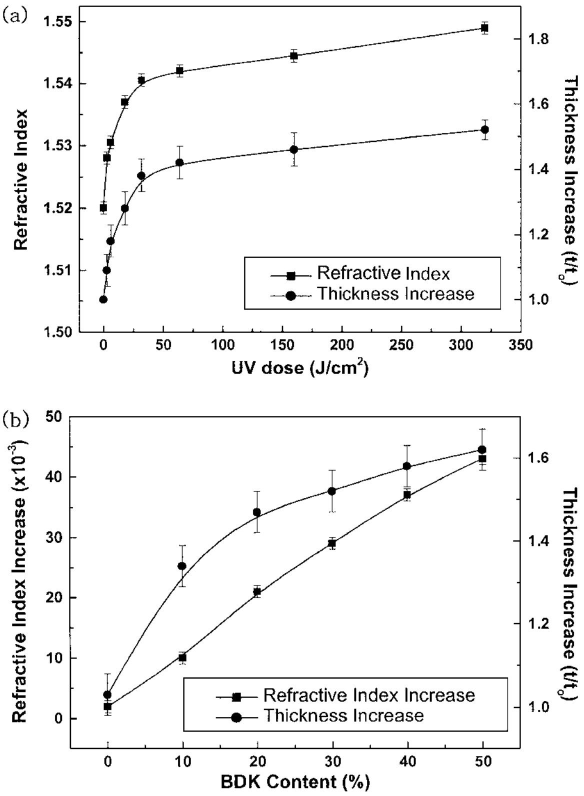

Figure 1. (a) Refractive index and normalized film thickness increase of BDK 30 mol% doped HYBRIMER films with UV exposure, and (b) refractive index increase and normalized film thickness increase of 320 J/cm^2 UV exposed HYBRIMER films with BDK contents (mol%).

UV exposed film is approximately 4 μm and 6 μm, respectively. The refractive index increases with increasing UV dose and BDK contents in the doped HYBRIMER films by photoinduced polymerization as well as photolocking of BDK in the films [8]. BDK was generally used as a photoinitiator to polymerize methacrylate monomers using decomposed radicals made by UV exposure. UV-unexposed BDK is mobile and volatile to be removed by heating. On the other hand, the photodecomposed radicals of UV-exposed BDK were fixed by photolocking in the HYBRIMER matrix during UV exposure. BDK was not photo-decomposed in the UV unexposed film, so it was evaporated during annealing and baking the film. In the UV exposed film, BDK of high refractive index remained during heating. Thus, refractive index and thickness of the films increase with UV dose and BDK content.

3.2. Fabrication of Channel Waveguide by Photochemical Self-Developing

Using the change in refractive index and film thickness through UV exposure and heating, the channel waveguides can be easily fabricated by photochemical self-developing without using a developing process in the HYBRIMER films. The coated film is so sticky that the film cannot be patterned by the contact of a photomask without drying the film. On the other hand, photolocking agent, BDK is very volatile and easily evaporated during heating. The drying method of the film without the evaporation of BDK is required to use the contact photomask. We dried HYBRIMER films using an IR lamp for a few seconds preventing the HYBRIMER films tagged with the photomask. In case of using the IR lamp, the film can be dried within a few seconds without evaporating of BDK under relatively low temperature. This was confirmed by measuring the refractive index and the film thickness of the BDK-doped HYBRIMER films after with and without IR lamp drying.

In order to fabricate channel waveguides, the BDK doped HYBRIMER film was dried by the IR lamp and then 320 J/cm^2 of UV was exposed with predefined photomask. Figures 2(a) and (b) show 3-dimensional and 2-dimensional (line profile) channel waveguide inflation observed by Atomic Force Microscopy (AFM), respectively. We made channel waveguides using the photomask with 5 μm opening and 4 cm long. Width of the waveguide channel is larger than the predefined photomask aperture due to the diffusiveness of the BDK. Shape of the photochemical self-developed

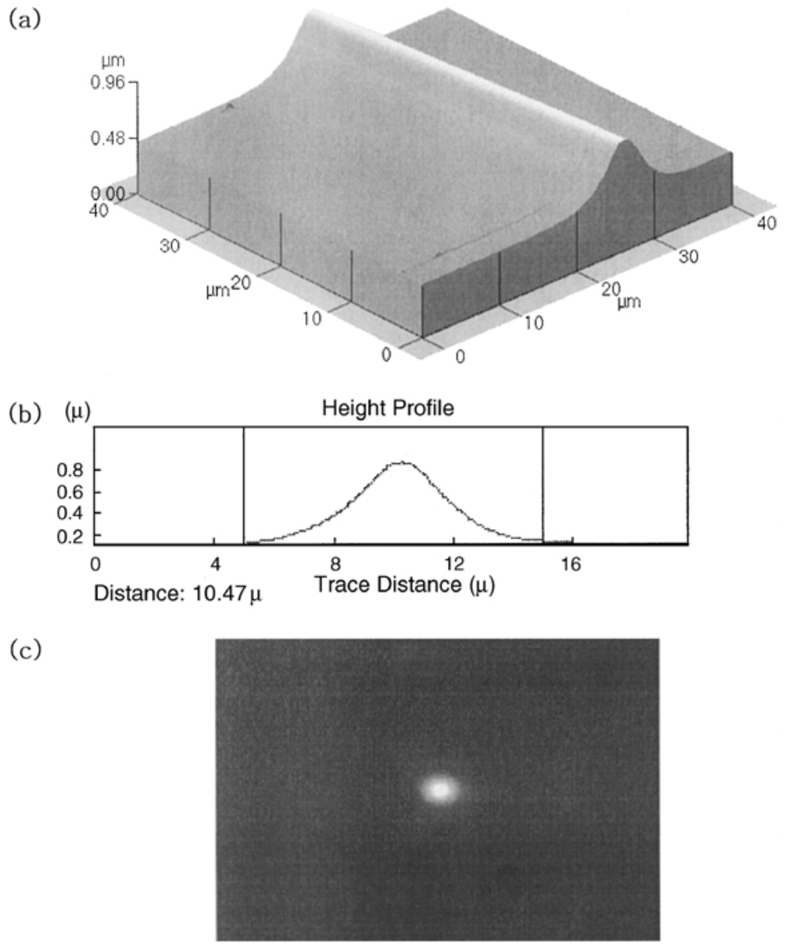

Figure 2. (a) 3-D AFM image, (b) 2-D patterned line profile AFM image, and (c) near field mode profile of the channel waveguide fabricated by using a photomask with 5 μm opening.

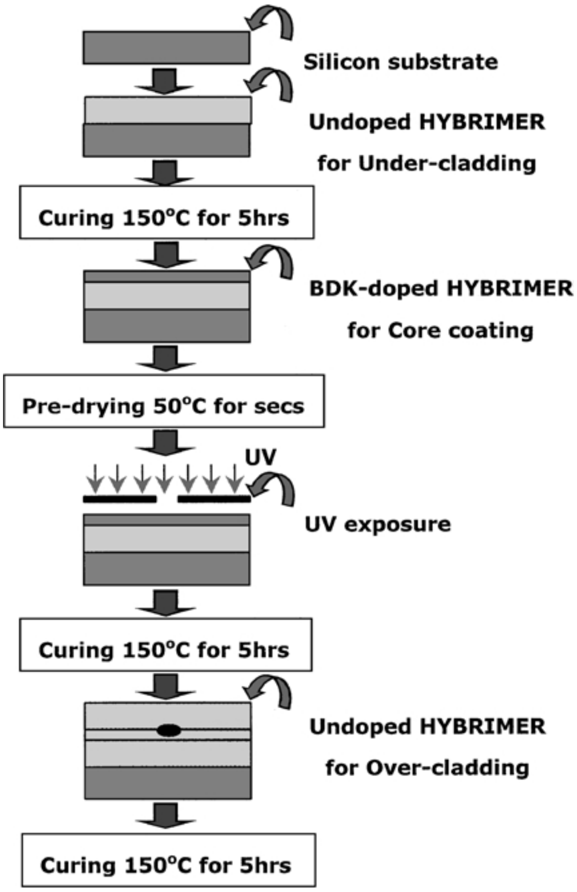

Figure 3. Schematic representation to fabricate three-layer waveguides using a photochemical self-developing process.

waveguide channel is gaussian shape, the same as that of a light beam. A symmetrical and intense single mode profile of the channel waveguide at 1550 nm can be found as shown in Fig. 2(c).

3.3. Fabrication of Waveguide Devices

In order to confine and guide the light effectively in the waveguide, under-cladding and over-cladding layers are needed. Thus, we fabricated the waveguides with three layers by using undoped HYBRIMER films as cladding layers and BDK-doped HYBRIMER films as a core layer. Figure 3 shows schematic representation how to fabricate the three-layer structure of waveguide using photochemical self-developing. First, undoped HYBRIMER was coated on silicon substrate for under-cladding layer and baked at 150°C for 5 hours. Then, BDK-doped HYBRIMER was coated on the undoped HYBRIMER under-cladding layer. After drying the film by the IR lamp for a few seconds, the channel waveguide was written by the photochemical self-developing process. The core layer was patterned without developing process. Finally, undoped HYBRIMER was coated for over-cladding layer and baked at 150°C for 5 hours. Thus, the three-layer waveguide devices could be easily fabricated without using any etching processes.

A 1 × 4 splitter with three-layer structure was also fabricated by photochemical self-developing. Low magnification optical microscope photograph of part of the 1 × 4 splitter is shown in Fig. 4(a). It can be seen that all the channels are well-defined. For waveguiding experiments, two ends of the sample were cleaved. Light of 1550 nm laser diode was coupled into the waveguides via an optical fiber and the transmitted light was focused on a camera. Figure 4(b) shows that near-field images of single mode are taken at the output of the splitters. The beam intensities of the output lights are nearly uniform. This might indicate the excitation of the same modes in the channels.

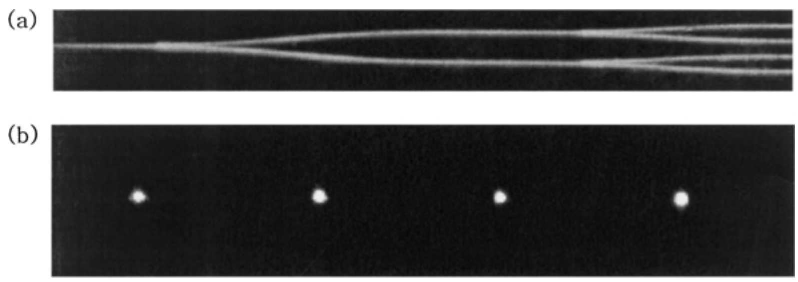

Figure 4. (a) Low magnification optical microscope photograph, and (b) near field mode profile of output in HYBRIMER waveguide 1 × 4 splitter.

4. Conclusions

The HYBRIMER film doped with BDK was prepared and photoinduced change in the refractive index and the film thickness was investigated. It demonstrated a single mode channel waveguide at 1550 nm and was fabricated by photochemical self-developing. The shape of the channel waveguide was gaussian shape. The channel waveguide was made of three layers with under-cladding and over-cladding layers of undoped HYBRIMER films and core layer of BDK-doped HYBRIMER film. Using the photolocking of BDK, a 1×4 splitter was also fabricated by photochemical self-developing (PSD).

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