Fabrication of Polymeric Optical Waveguides by B-Staged Bisbenzocyclobutene(BCB)*

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Abstract **This paper reports the fabrication of polymeric optical waveguides. Single mode planar slab waveguides and straight waveguides had been fabricated from the organic polymer B-staged bisbenzocyclobutene (BCB) from DOW® Chemical. A low cost fabrication method, chemical etching is used to form the waveguides on BK7 glass substrates. The processing conditions required for the fabrication of single mode optical waveguides are presented.**

I. Introduction

Optoelectronic technology and optical networking will become the key enablers of the future communications infrastructure through the elimination of the severe restrictions of bandwidth and bit-error rate inherent in traditional electromagnetic signal-based communications. The demand in optical networking for photonic components that meet performance criteria as well as economic requirements has opened the door for novel technologies capable for high yield low cost manufacturing while delivering high performance and enabling unique functions. The most promising new technologies are integrated optics. Integration permits the parallel production of complex multi-function photonic circuits on a planar substrate. Planar lightwave circuits (PLCs) based on layers of glass, polymers, or other materials deposited on a planar substrate are a low-cost manufacturing and high integration density by using well-established fabrication technologies from the silicon industry.

Several inorganic materials capable of multiple functions are under intensive investigation, including lithium niobate ($LiNbO_3$), silicon dioxide (SiO_2) on silicon, and III-V compound semiconductors. The fabrication costs associated with these materials are very high, which seriously jeopardizes the commercialization of the end products [1]. Polymeric materials are particularly attractive in integrated optics because of their ability to be processed rapidly, cost-effectively, and with high yields. Polymeric materials are allowed to form compact optical circuits by offering large refractive index contrasts. It has attracted a lot of attention with regard to applications in the all-optical network, basically, because they have the potential of added optical functionality and because they may be producible at low cost [2-5]. Optical polymers were engineered in many laboratories worldwide and some are available commercially. Classes of polymers used in integrated optics include acrylates, polyimides, polycarbonates and olefin (e.g., cyclobutene). Several researchers had fabricated optical devices based on polymeric materials and proved its feasibility [6-15].

In this paper, we report the fabrication process of optical waveguides by using PhotoBCB 4024-40 from The DOW Chemical Company and the processing conditions required for the fabrication of single mode optical waveguides.

II. B-Staged Bisbenzocyclobutene (BCB) from the Dow® Chemical

CYCLOTENE™ Advanced Electronics Resins from The Dow® Chemical Company are high-purity polymer solutions that have been developed for microelectronics applications [16]. The resins are derived from B-staged bisbenzocyclobutene (BCB) monomers and are formulated as high-solids, low-viscosity solutions. It has the properties such as low dielectric constant, low loss at high frequency, low moisture absorption, low cure temperature, high degree of planarization, low level of ionic, high optical clarity, good thermal stability, excellent chemical resistance, and good compatibility with various metallization systems and glasses. The resins are available in photosensitive and dry etch grades. BCB Polymer is being used in optical components such as cladding or core material for optical waveguides, lithium niobate optical modulators, microoptical and integrated optical fs/ps pulse shapers.

The CYCLOTENE™ 4000 Series Advanced Electronics Resins are I-line/G-line sensitive photopolymers that have been developed for use in microelectronics applications. CYCLOTENE™ PhotoBCB 4024-40 had been chosen as the raw material for waveguide fabrication because of its simplicity of the fabrication process. The CYCLOTENE™ PhotoBCB 4024-40 had been chosen as the raw material for waveguide fabrication because of its simplicity of the fabrication process. It inherently reduces the number of fabrication process steps and equipments required for patterning waveguides as photoresist avoided. It can be etched by chemical wet etching method without using high cost equipments such as reactive ion etching chamber (RIE).

The optical properties provided by the manufacturer shows that the PhotoBCB is suitable for optical waveguides fabrication which it has the refractive index around 1.543 at wavelength 1550nm [16]. It can be coated on glass substrates which having index of refraction around 1.5000.

III. Fabrication Procedures and Fabrication Conditions

The process scheme that is being developed for the fabrication of waveguides using PhotoBCB is similar to a thin film multi-chip module process. Single mode straight waveguides and planar slab waveguides as figure 2 had been fabricated. The cross section of the straight waveguide was modeled as trapezoidal shape (figure 1a) due to the limitation in the process of waveguide fabrication. It was difficult to obtain ideal structure (rectangular) due to the limitation of chemical etching technique.

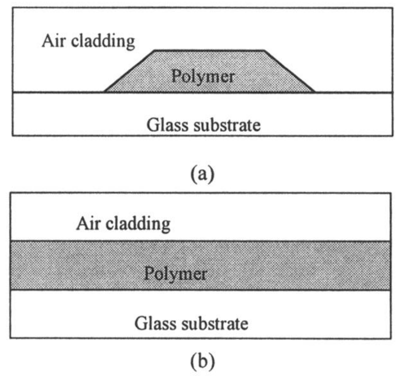

Fig. 1 Schematic diagram of (a) straight waveguide, (b) planar slab waveguide

The starting material is a yellow amber liquid that is kept refrigerated at temperature below -15 C and brought to room temperature before processing. The whole fabrication process was carried out in clean room environment, where the concentration and the size of particles, the temperature and the humidity of the environment were controlled according to a standard. Dust particles on the sample during fabrication can give problems with photolithography stages and masking of the waveguide. As devices become smaller, contamination must be more tightly controlled. Protecting wafers from particles will become increasingly important.

BK-7 glasses with good surface quality and refractive index of 1.500223 at 1550nm were used as the substrate material. The surface condition of the substrate is crucial to the coating properties, particularly to the adhesion of the coating. With glass substrates, typical contamination effects are dust and dirt from shipping or storage, and sample holder or finger prints from handling [17]. The substrates were prepared by washing them with de-ionized water in an ultrasonic cleaner, and blowing them dry with high pressure nitrogen.

Adhesion promoter was applied by spin coated on the substrates before the polymer coating. PhotoBCB resins were spun onto the substrates directly after the adhesion promoter application and spin dry. To get a well coated film, formation of bubbles need to be prevented when the dispensing of polymer by a syringe. The volume of solution dispensed kept constant for each sample to ensure the uniformity. The spin speed used to deposit the resins varied according to the final film thickness desired.

Table 1 shows the typical film thicknesses after soft bake, and final thicknesses (after full photo processing and hard cure) provided by The DOW® Chemical Company.

Table 1 Typical film thickness after soft bake, and final thicknesses (after full photo processing and hard cure) [16].

	4024 thickness (μm)	
Spin speed (rpm)	After soft bake	Final thickness
1500	10.2	7.2
2000	8.4	5.9
2500	7.4	5.2
3000	6.7	4.8
3500	6.2	4.4
4000	5.8	4.1
5000	5.2	3.7

After the spin coating, the films were heated on a hotplate for a specific time and temperature which depend on the composition of the substrates as well as the film thickness to remove the solvent and decrease tackiness (Table 2). High bake temperature will lead to wrinkling of the film. Since the coating was still in liquid form after spin application, adequate care had been taken to keep the substrate in a horizontal (level) position during soft bake process and while transferring the substrate from spin coater to hotplate.

After the soft bake, the substrates were allowed to cool to room temperature before photolithography. Photolithography is the process consists on the transference of two-dimensional patterns placed on the mask to the polymer. After being developed, it has an exact copy of the mask patterns. The PhotoBCB resins are negative acting, the exposed regions are crosslinked and will remain after development. Once the mask and the substrates were appropriately aligned, the exposure process can be carried out. In order to achieve a better resolution of the image, the mask was placed just a few micron above the film. The photoBCB films were exposed under UV light source to crosslink the polymer. Light source with higher power and higher exposure dose shortened the exposure time and gave a better resolution. The amount of incident radiation required for an optimum resolution depends on several parameters such as the coating thickness, underlying surface reflectivity, structure size, desired wall profile and also feature uniformity. In our works, we used a high power UV light source (1000W) for 3-5 seconds exposure.

Table 2 Hotplate soft bake temperatures for pre-exposure bake. All bakes are for 90 seconds [16].

CYCLOTENE pre-exposure thickness (μm)	Hotplate bake temperature (C)
<4.5	60
4.6-6.6	65
6.7-8.7	70
8.8-10.0	75
10.1-11.4	80
11.5-15.6	85
>15.7	90

After exposure and previous to the etching process, a thermal treatment, pre-develop bake was carried out to increase the etching resistance and films adhesion to the substrates. It stabilized the development endpoint time. Without this bake, the development endpoint time will increase as the films sit at room temperature and thus dependant on the time delay between process steps. The pre-develop bake temperatures were 10 C lower than the pre-exposure bakes and the pre-develop bake must be carried out immediately before developing (etching).

Etching processes was carried out to selectively remove the layer (unmasked area). In this work, the etching process had been carried out by the wet etching method which can be done without costly and bulky equipments such as RIE, ICP or plasma etching. By wet etching, it is understood the elimination of a material by its dissolution in an adequate etching solution It is also eliminating the application of other polymers as photo resists for these dry etching techniques. The drawback of wet chemical etching is the lower quality of side wall resolution of the waveguides. It can be improved by the shorter exposure time as mentioned. The substrate was placed on the spinning chuck of the spin coater and a puddle of developer (etching solution) was dispensed onto the surface. Sufficient developer was applied to allow the puddle to completely cover the substrate. The substrate was allowed to sit with developer on it for a pre-determined length of time to allow dissolution of the unexposed areas. When the puddle time is complete, the substrate was rinsed and spun dry. The substrate was put under a high power microscope for the developed pattern inspection. The etching process could be repeated if the waveguide was under etched.

To further dry the film and stabilize the via side wall, the substrate was baked on a hotplate immediately after developing. Finally, the substrate was cured in a box oven to remove residual solvents and harden the polymer. Two different cure profiles had been investigated. Soft cure was used for lower BCB layers when multiple BCB layers were used in a structure. It provides improved adhesion between polymer layers. A temperature of 210 C for 40 minutes in box oven was used for soft cure. Hard cure was used for single layer, or for the last layer in a multi layer build. It gives the film maximum chemical resistance and stable mechanical and electrical properties. In a box oven, a temperature of 250 C for 60 minutes was used for hard cure.

IV. PRILIMINARY CHARACTERIZATION

The fabricated planar waveguides and single mode straight waveguides had been characterized. Film thickness and refractive index had been measured using prism coupler and surface profiling using Wyko NT1100 Optical Profiler. Figure 2 shows the film thickness for different spinning speed. Thickness of fabricated waveguides are close to manufacturer's data. It shows the trend that higher spinning speed giving lower thickness. The refractive index of the fabricated waveguide is 1.56700 at wavelength 1550nm.

From the surface profiling, it shows the surface roughness of the slab waveguides are acceptable though some researchers reported the purity and uniformity of the film is rather poor by spin coating technique for film deposition [18]. The surface roughness is having a range between 3.99nm-6.42nm.

From our study, the heat applied during the fabrication processes did not much affect the refractive indices of fabricated waveguides. The refractive indices are higher than the data provided by DOW® Chemical and showed that the polymer is suitable for waveguides fabrication which required a higher core index than the substrate index.

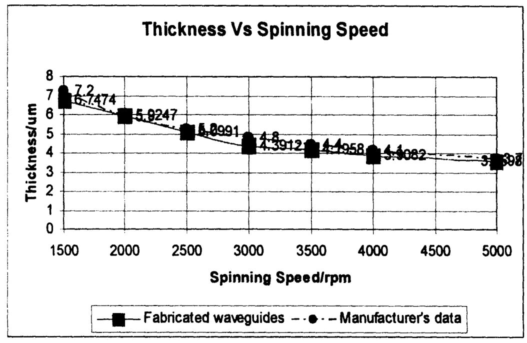

Fig 2: Film thickness(μm) vs spinning speed(rpm). (comparison between fabricated waveguides and manufacturer's data)

V. CONCLUSION

Single mode planar slab waveguides and straight waveguides had been fabricated from the organic polymer B-staged bisbenzocyclobutene (BCB) from DOW® Chemical by using a low cost wet chemical etching technique. The fabrication conditions are being studied and improved to achieve a better resolution of waveguides side wall in the further research.

V. ACKNOWLEDGEMENT

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