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Curing Methods Yield Multiple Refractive Index of Benzocyclobutene Polymer Film

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***Abstract*—**Refractive index control of benzocyclobutene (BCB 4024-40) is achieved by facilitating different conditions during the thermal curing of BCB film. Refractive index (RI) change of 1.49% is obtained with curing of BCB film using an oven, while the RI change is 0.1% when the BCB is cured using a hotplate. The two different curing methods exhibit a temperature dependent refractive index change of the BCB photosensitive polymer. By carefully controlling the curing conditions, multiple layers of BCB with different RI can be fabricated, which can then be applied in the fabrication of optical waveguides.

***Keywords*—**BCB 4024-40, curing method, multiple refractive index, polymers.

I. Introduction

As optical communication networks expanding, the demands for low cost optical modules also increase. This is where the integrated optics or planar waveguide technology is playing an important role. Polymer materials are generally recognized to exhibit various favorable properties for use in terms of optical properties, cost effectiveness and simple fabrication process [1]. In addition, polymers can be deposited directly on any kind of substrates and this is advantageous over other optical waveguide materials such as SiO_2, $LiNbO_3$ and III-V materials [2].

Both refractive index and film thickness properties are important to fabricate optical waveguides. A slightly higher value in the refractive index of core layer is required for waveguiding by the principle of total internal reflection, while film thickness together with refractive index is defining the waveguiding mode profile. In this work, we focus our study to investigate the effects of cure temperature on the refractive index and its thicknesses using two different curing methods which are oven and hotplate. The outcome of this work shows that by using different curing method, the refractive index value of the BCB films could be tailored. This approach can be applied to fabricate optical waveguides using same polymer materials for core and undercladding layers.

II. Experimental

A. Characterization and preparation of BCB Films

The polymer used in this work is Benzocyclobutene (BCB 4024-40) which is in the I-line/G-line sensitive photo-polymers in the CYCLOTENE™ 4000 Series Advanced Electronics Resins. This polymer is derived from B-stage Divinylsiloxane bisbenzocyclobutene (DVS-BCB) formulated as high-solids, low viscosity liquid solutions. BCB has many desirable properties for microelectronic applications such as low dielectric constant and dissipation factor, low moisture absorption, rapid curing, low temperature cure and also minimum shrinkage in curing process [3].

The process starts with applying adhesion promoter (AP 3000) coated onto a silicon wafer follows by BCB 4024-40 solution at a spin speed of 5000 rpm. The spin coated wafers were soft baked under hotplate at 70 ^{0}C for 90 seconds to remove the residual solvent. For the curing process, two different methods were applied: oven and hotplate. According to [6], the recommended curing conditions using oven is in the region of 250^0 C for 60 minutes while for hotplate is about 300 ^{0}C for a few seconds. In this study, the cure temperature using oven was in the range of 210 ^{0}C to 280 ^{0}C with 60 minutes of curing time. On the other hand, for hotplate curing, the temperatures investigated were in the range of 260 ^{0}C to

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350 ^{0}C with 20 seconds of curing time. Note that both curing method were conducted in open environment. Measurements on refractive index and thickness were taken using Prism Coupler; model SPA-4000 with 1550 nm wavelength.

III. Results and Analysis

A. Curing using oven

Fig. 1 shows the refractive index obtained when the BCB films were cured using oven. Results obtained shows that, as the temperature increase, the value of refractive index decrease and at one point the value started to increase. For region below 240°C, higher curing temperature causes more free volume in the BCB film. The random crosslinking process occurs too rapidly at higher cure temperatures.

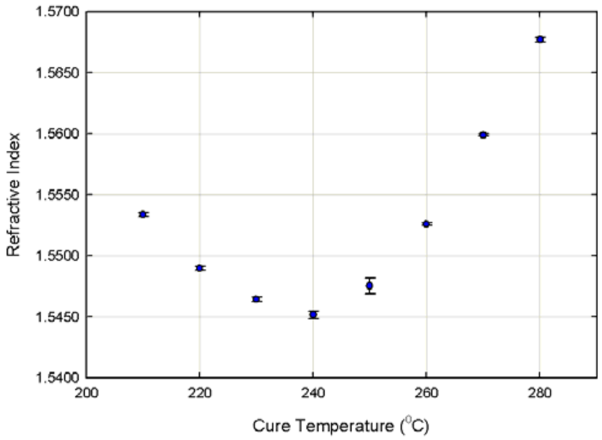

Fig. 1 Refractive index corresponding to cure temperature (°C) using *oven*

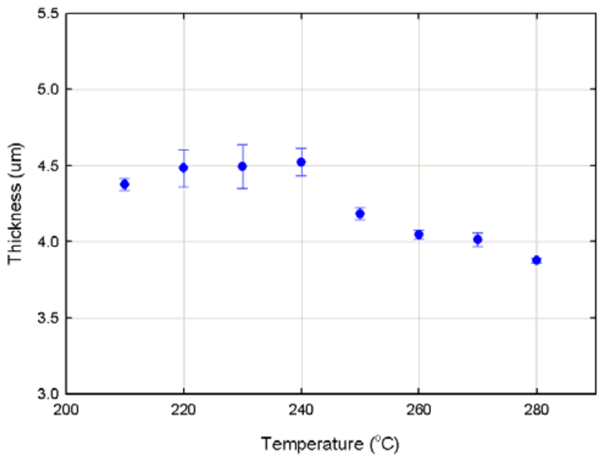

Fig. 2 Film thickness corresponding to cure temperature (°C) using oven

As the results, the short chains of polymer formed with dangling bonds left behind which later have to be aligned to react as the crosslinking process continue. The rotation of bonds within each chain causes free volume to increase [6-7]. However, for curing temperature above 240 °C the refractive index increases due to less free volume caused by the vitrification process. Vitrification is a physical changes process where the BCB material becomes glassy [5]. Less free volume leads to increase in refractive index value [7].

The effects of cure temperatures on thickness of the BCB films were illustrated in Fig. 2. The thickness is increased and at above 240 °C the values starting to decrease. The BCB films thickness changes are directly related to change in film volume and density. This phenomenon is agreed with the refractive index trend where vitrification process takes place for curing temperature above 240 °C.

B. Curing using hotplate

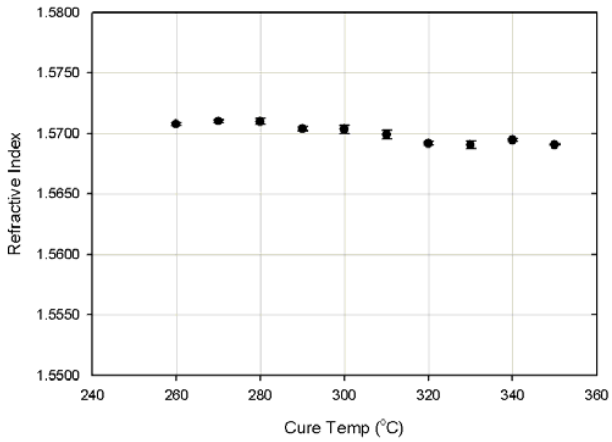

Fig. 3 Refractive index corresponding to cure temperature (°C) using *hotplate*

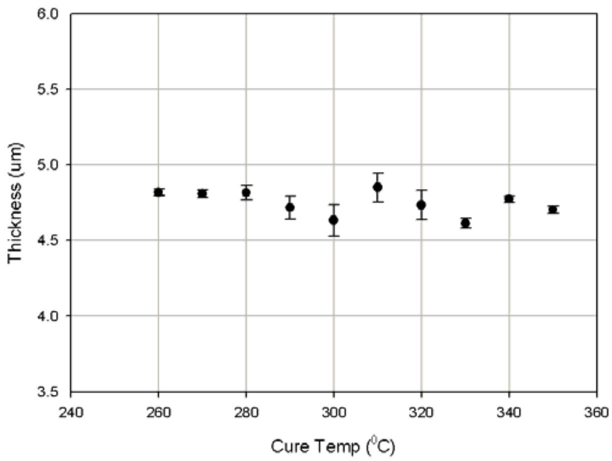

Fig. 4 Film thickness corresponding to cure temperature (°C) using *hotplate*

Similar to oven, high curing temperature resulted higher rate of random crosslinking process. However, opposite to oven curing where hotplate's curing time is too short, the short polymer chains are prevented to further crosslinked to form longer chain. This resulted, less free volume in the BCB film and the average refractive index is much higher than in oven curing. Besides, we suspect that due to the high curing temperature and short curing time, the rate of random crosslinking process are about the same throughout the tested temperature region. This resulted both the refractive index and film thickness is about the same or no significant trend was found.

C.Comparison between oven and hotplate

There are some significant differents between both methods. Firstly, their curing principle is different. Oven curing uses air circulation to heating up the BCB samples. The heating effects are from all directions and resulted a more uniform crosslinking process throughout the BCB film. We observe that the refractive index distribution across the BCB film for curing using oven (standard deviation average of 1.74 x 10^{-4}) is much more even than in hot plate (average of 2.00 x 10^{-4}). While in hotplate curing, direct heating is applied from the bottom of the samples. A temperature gradient exists between the bottom and the top of the BCB film. For a thick film, this temperature gradient may causes the film split into more regions due to the different in crosslinking rate. We do experience this effect before where dual layer characteristic was observed in prism coupled results for thick film.

Secondly, the curing temperature range and curing time are different for both methods. For oven curing, a long curing process with low curing temperature was applied while vice verse for hotplate curing. This different resulted the average refractive index obtained is lower for oven curing than hotplate curing as mention before in section II.

From the both curing methods discussed earlier, we summarize their properties in the Table I.

TABLE I
COMPARISON BETWEEN OVEN AND HOTPLATE CURING METHODS

Curing Methods	Refractive Index	Density	Free Volume
Oven	Lower	Lower	More
Hotplate	Higher	Higher	Less

D.Waveguides fabrication

Based on the results obtained earlier, dual layer BCB waveguides are able to fabricate. This is because of the refractive index different between the core and cladding layers are needed for a waveguides that govern by the total internal reflection principle. A straight channel ridge waveguide of dual layer has successfully fabricated. The undercladding layer was prepared by using oven and the core layer was prepared using hotplate as their curing process. This dimension of the channel is 4.6 µm in height x 4.0 µm in width and the propagation loss of the channel is 2.02 dB/cm at 1310nm wavelength measured by using cut-back method.

IV. CONCLUSION

It was discovered that curing using oven and hotplate could obtain multiple refractive index. In general, the results show that curing using oven can produce lower refractive index (in the range of 1.5450 to 1.5680) and curing via hotplate yields higher refractive index (in the range of 1.5700). Since the value of refractive index could be tailored, this could be applied to fabricate optical waveguides using same polymer materials of BCB 4024-40. The index contrast between the oven and hotplate curing methods, make it possible to create a dual layer ridge polymer waveguide.

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