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## THERMO-OPTICAL PROPERTIES OF POLYMER PLANAR WAVEGUIDES

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### ABSTRACT

The variation of refractive indices with temperature in polymer waveguides on silicon substrate is presented. The refractive index  $n$ , thickness and birefringence properties of the material has been studied in the temperature range of 40 °C to 80 °C. An apparent reduction of the refractive index with increase of temperature of the material was observed, while there was no significant thickness-variation with temperature in the film coating. This behavior may be attributed to the heat activate orientation mobility of the atoms of the polymer. The polarization anisotropy results are consistent with that would be expected of the transverse electric, TE and transverse magnetic, TM modes. The refractive index and thickness were examined as a function of spin coating parameter of the polymer. Temperature induced changes in  $n_{TE}$  and  $n_{TM}$  were studied for different planar waveguides parameters. The measured  $dn/dT$  coefficient of the polymer material matches with the standard value.

Keywords: Optical planar waveguides, polymers, refractive index, thin film

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### 1. INTRODUCTION

The demand for optical components that can meet the technical requirements and economic criteria has opened the way for the development of innovative technologies without sacrificing the high performance requirement<sup>1</sup>. Silica-

on-silicon is widely seen as a promising technology for mass production of low-cost integrated optical components<sup>2</sup>. Silicon is a suitable material for forming silica film due to its very high quality and low cost, excellent silica-silicon bond and process suitability with the current Complementary Metal Oxide

Semiconductor Integrated Circuit (CMOS IC) process technology.

The existing methods of depositing silica film on silicon substrate are<sup>3</sup> Flame Hydrolysis Deposition (FHD), Chemical Vapor Deposition (CVD), Plasma Enhanced CVD (PECVD), E-beam Deposition, and Thermal Oxidation. All these methods have high capital and operational costs, as the required equipments are very expensive. An alternative process and highly potential process that can eliminate the high cost factors in the fabrication of silica film on silicon substrate is the use of the spin-on polymer process technology.

Integration of all optical functions on a single chip makes polymer an ideal choice for optimizing the cost effectiveness of fiber optic communications. This material can be easily handled by methods such as embossing, stamping, sawing, wet etching and dry etching, plus it has a low cost at room temperature fabrication process. Polymer materials present several advantages that include design of the optical properties, ease in processing and device fabrication, high-density device integration, cost effectiveness, and high volume production<sup>4,5</sup>.

Polymers are currently being investigated for many optical applications as a result of their ruggedness, low cost, flexibility and optimal light propagation. The use of polymeric materials allows the mass

production of optical waveguides using minimal process equipment in addition to a variety of planar substrate materials<sup>6</sup>. These optical polymers are used to form planar single mode, multi mode and micro-optical waveguide structures ranging to hundreds of micrometers. Materials such as polymethyl methacrylate (PMMA), epoxy resin, polystyrene and poly organosiloxane, crosslinked benzocyclobutene (BCB), crosslinked acrylate polymer and polyimide are some of many optical polymers available<sup>6-9</sup>. Optical polymers are available commercially and some are engineered in many laboratories worldwide.

In this paper, a commercial polymer material had been utilized as the transmissive core layer of the waveguide. The objective of the experiment was to study the change of film thickness and refractive indices at different temperatures, which could be expressed as the thermo-optics,  $dn/dT$  coefficients of the material<sup>10</sup>.

## 2. MATERIALS AND METHODS

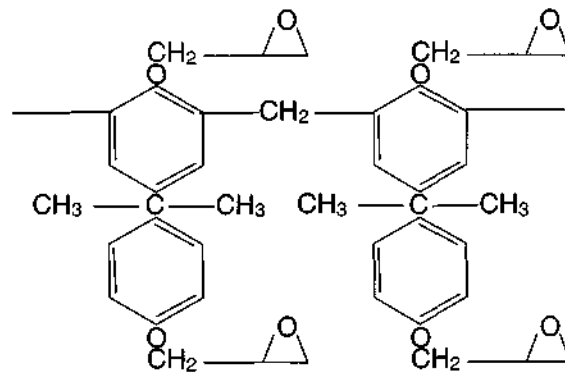
The polymer material used for the core layer of the waveguide is SU-8. It is a negative, solvent-developed, epoxy-type, ultra-violet (UV)-curable polymer with high contrast, epoxy based photoresist and it has other applications such as in microelectronics industry and other fields as photoresist or structure materials. It consists of a multifunctional, highly branched polymeric epoxy resin dissolved in an organic solvent, along with a photoacid generator. The epoxy

resin consists of a novolac glycidyl ether; an idealized structure is depicted in Figure 1.

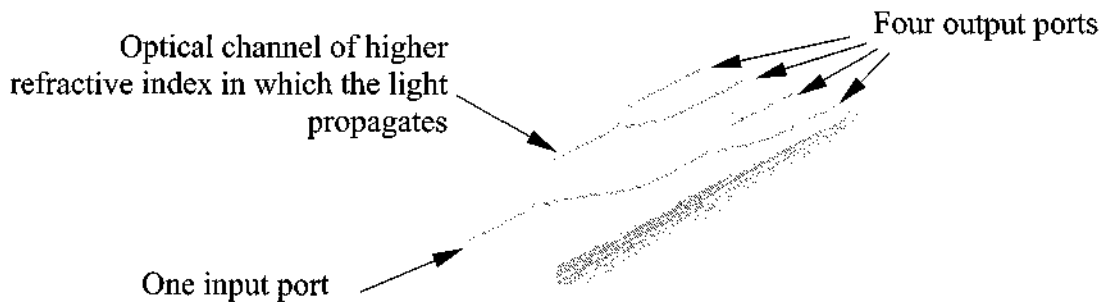
SU-8 has very high optical transparency above 360-nm wavelength and it is ideal for use in the C-band of the optical communication system. Upon exposure to UV, cross-linking proceeds in-two-steps; the formation of a strong acid during the exposure process, followed by acid-initiated, thermally driven epoxy cross-linking

during the post exposure bake (PEB) step.

Figure 2 shows a design of an optical channel waveguide, which consist of an input port and four output ports in the core layer of the polymer material. The optical polymer waveguides that were fabricated on silicon substrates have dimensions of 1.0 to 1.5 cm width, 1.5 to 2.0 cm in length and 2 to 3 mm overall thickness.



**Figure 1:** Main structure of SU-8.

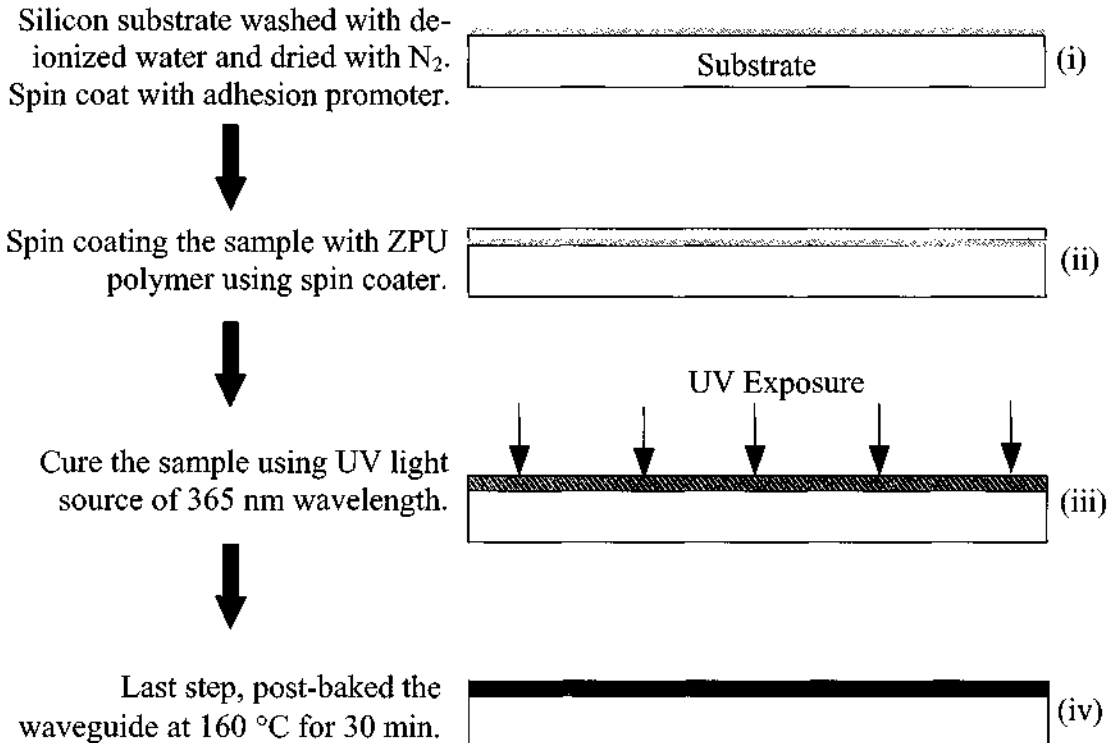


**Figure 2:** An optical channel waveguide designed for 1 x 4 channels.

## 2.1 Waveguide Fabrication Process

The fabrication process involved spin coating the polymer using a spin coater. An adhesion promoter was required in order to increase the silicon-polymer bond. The polymer was spin-coated onto the silicon surface using a standard tabletop spin coater. Three different spin speeds were used for three different silicon samples. The spin-speeds used were 1000 rpm, 2500 rpm and 3000 rpm.

After spin coating, the polymer was cured using a UV source of 365 nm wavelength, at  $16 \text{ mW.cm}^{-2}$  for 5 minutes. The curing step was done in nitrogen environment in order to avoid cracking of the polymer film. Finally, the sample was post-baked at  $160 \text{ }^\circ\text{C}$  for 30 minutes. Figure 3 shows the standard fabrication process for the UV curable polymer film on silicon substrate<sup>11</sup>.

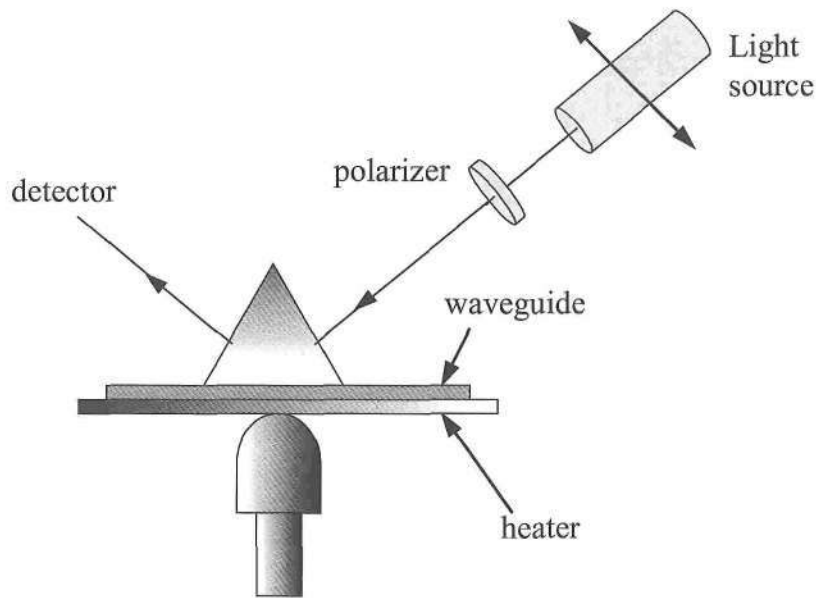


**Figure 3:** Standard fabrication process of a UV curable polymer film on silicon (i) sample pre-treatment / adhesion promoter (ii) spin coating of polymer film (iii) UV cure using UV light source (iv) post baking the waveguide.

## 2.2 Measurement Procedure

The optical measurements were done using a prism coupler system as shown in Figure 4. The waveguide sample was clamped between the heater and the prism using the pneumatic-controlled rod. The pneumatic pressure that controlled the air gap between the prism bottom base and the waveguide surface was fixed around 0.6 MPa. The laser source is at a 1-degree-angle step movement and this

will ensure that all the modes will be guided into the waveguide. A polarizer was used to switch between the transverse-electric TE and transverse-magnetic TM modes of measurements. The refractive index and thickness of the waveguide were measured simultaneously and the temperature was then increased gradually with a 5 °C-step increment. The  $dn/dT$  coefficient was obtained at 1550 nm wavelength.



**Figure 4:** The prism coupler system.

### 3. RESULTS AND DISCUSSION

The principle of optical confinement in the layer of polymer material is based on phenomenon of total internal reflection. Figures 5 and 6 show the excitation modes along the propagation path of the polymer waveguides. According to the modes guided in the waveguide and their angles, calculation of the refractive index and thickness of the materials can be done using phase condition as in Equation (1):

$$2kn_g d \cos\theta - 2\Phi_a - 2\Phi_s = 2m\pi \quad (1)$$

where  $k = \frac{2\pi}{\lambda}$ ;  $n_g$  is the refractive index of the guiding layer;  $d$  is the thickness of the layer;  $\theta$  is a acceptance angle, where

$$\theta > \sin^{-1}\left(\frac{n_g}{n_s}\right) \text{ and } m \text{ is an integer,}$$

which designates the mode number. At resonance condition,  $-2\Phi_a$  and  $-2\Phi_s$  are the phase changes caused by the light beam at the polymer-air

gap and polymer-substrate interfaces respectively.

A number of samples were measured using the advanced prism coupler system, which incorporates a temperature controller system. The coating layer was measured simultaneously for its refractive index and thickness. The silicon substrate, which is about 2 mm thick, has an index of refraction of 3.4. These selected samples were chosen from the list of samples and these are presented in Table 1 in the merit of its thickness with respect to the number of modes propagating in the core layer.

Figure 5 shows three optical modes propagating in the waveguide layer, which are represented by the sharp drops in the light intensities for certain acceptance angles. The drops in the intensity are due to certain portion of the light being guided into the waveguide layer whilst the rest of the light are reflected to the photo detector.

**Table 1.** Refractive indices and thickness of the samples at TE and TM modes.

Samples	1550 nm laser source			
	Refractive Index		Thickness of polymer layer ( $\mu\text{m}$ )	
	TE	TM	TE	TM
Sample S1	1.4500	1.4492	6.76	6.84
Sample S2	1.4495	1.4485	8.13	8.25
Sample S3	1.4506	1.4550	11.43	12.87



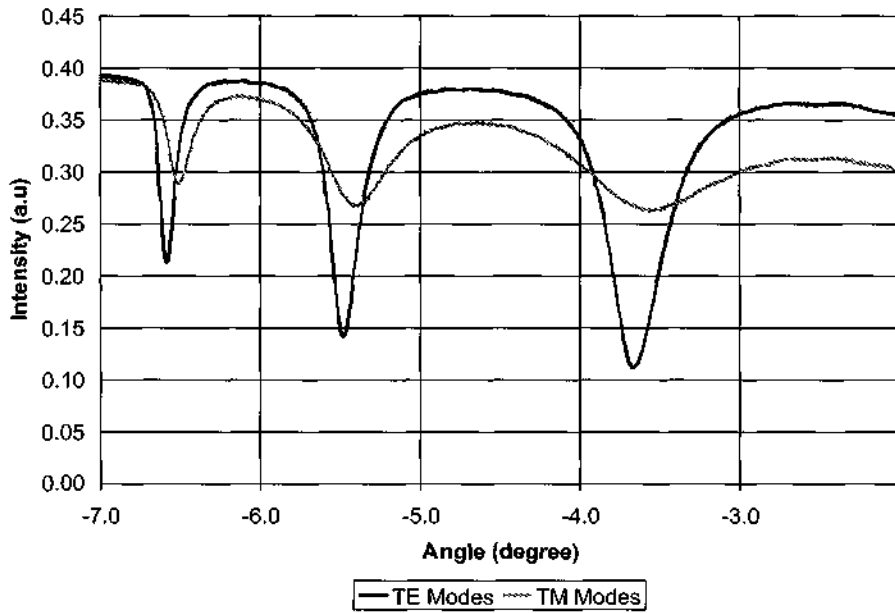


Figure 5: Number of modes guided in sample S1 for TE and TM polarization.

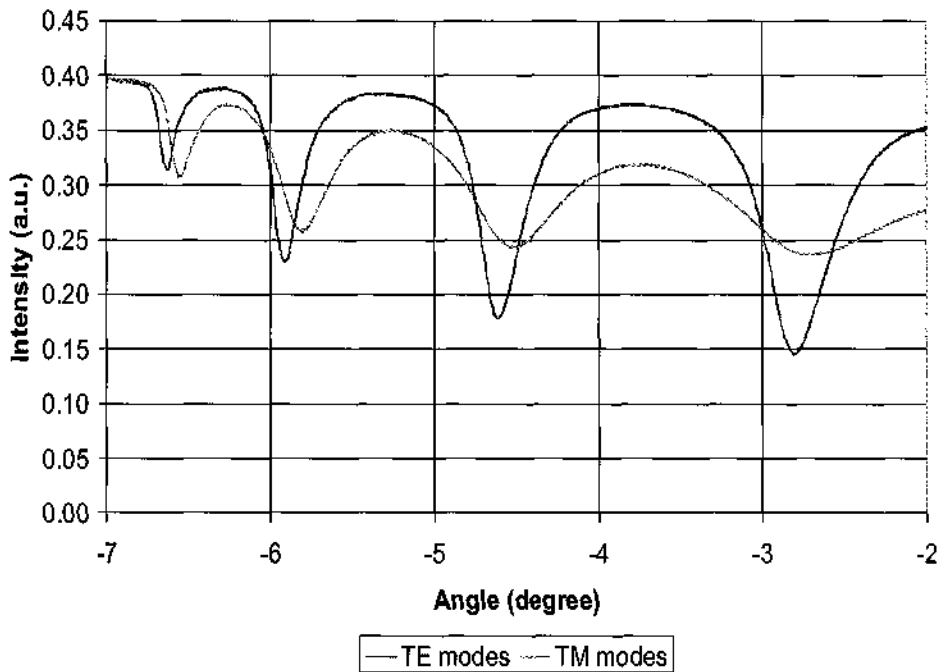


Figure 6: Number of modes guided in sample S2 for TE and TM polarization.

It is obvious that the number of modes propagating in the waveguide increases with the thickness of the core layer of the waveguide, as illustrated in Figure 6. It can be shown from the plots that an additional thickness of about 1.4  $\mu\text{m}$  layer of the film coating would induce additional modes to propagate into the waveguide. This is illustrated in Figure 5 and 6 for thickness of 6.76  $\mu\text{m}$  and 8.13  $\mu\text{m}$  where three and four modes were shown to propagate in the waveguide, respectively.

A relationship could be deduced from the spin-coater speed and the thickness of the core layer in which it would give an indication of a desired thickness of the layer to be coated. Sample S3 was coated at the spin speed of 1000 rpm while samples S2 and S1 were at the speeds of 2500 rpm and 3000 rpm, respectively.

The difference in the acceptance angles between the TE and TM modes are shown by the non-overlapping of the spectrum intensities in all the samples. These results are due to the changes in the refractive indices at different polarization modes. However, the refractive index differences between these two polarization states are at a margin of  $\pm 0.001$ -refractive-index accuracy of the prism coupler system. Hence, the optical anisotropic properties of the polymer material used in the measurement could not be clearly established.

The variation of the refractive index and thickness to the change of temperature was measured with anticipated results as shown in Figure 7 and 8. The temperature measurements were restricted to the control instrument range of 40°C to 80°C. Figure 7 illustrates a linear change of the refractive index with temperature from the three selected-samples. The increase of temperature caused the expansion of the film and hence reduced the optical density and varied the refractive index of the material. The high refractive index of the thicker layer in the waveguide, as shown in Figure 7 for sample 3, could be due to the high optical density of the polymer material, which could have been affected in the fabrication process, curing or baking processes. Heating of the material lowered the optical density, hence reduced the index of refraction. The  $dn/dT$  coefficient deduced from the fabricated samples is about  $-1.80 \times 10^{-4}$  per °C, which is comparable to the standard value of  $-2.00 \times 10^{-4}$  per °C.

Figure 8 illustrates the changes of the film thickness with temperature, which shows nanometer-increase of film thickness with temperature. The thickest polymer layer of the waveguide, sample S3, shows significant change of thickness as compared the other thinner layers, since the change of volume is proportional to the change in temperature of the polymer layer. The polymer material has the cubic coefficient of thermal expansion in the order of  $10^{-4}$  per °C<sup>12</sup>.

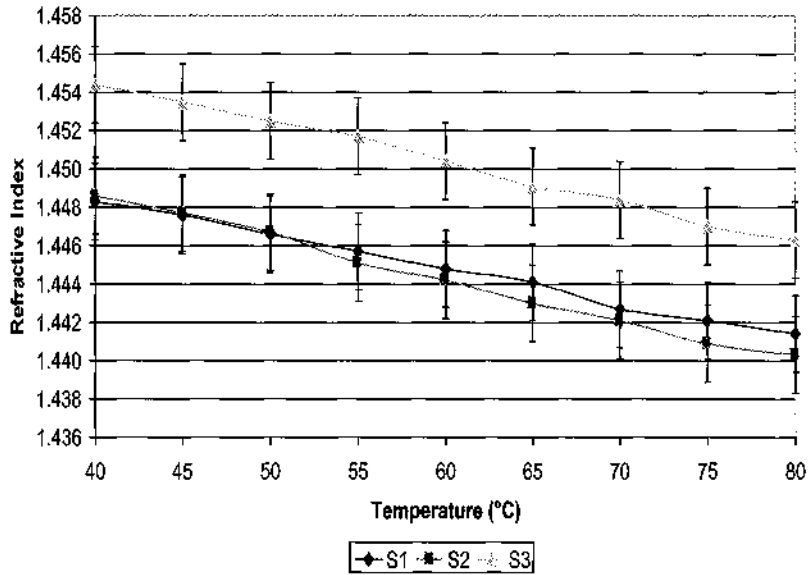


Figure 7: Effect of temperature on refractive index of the polymer material.

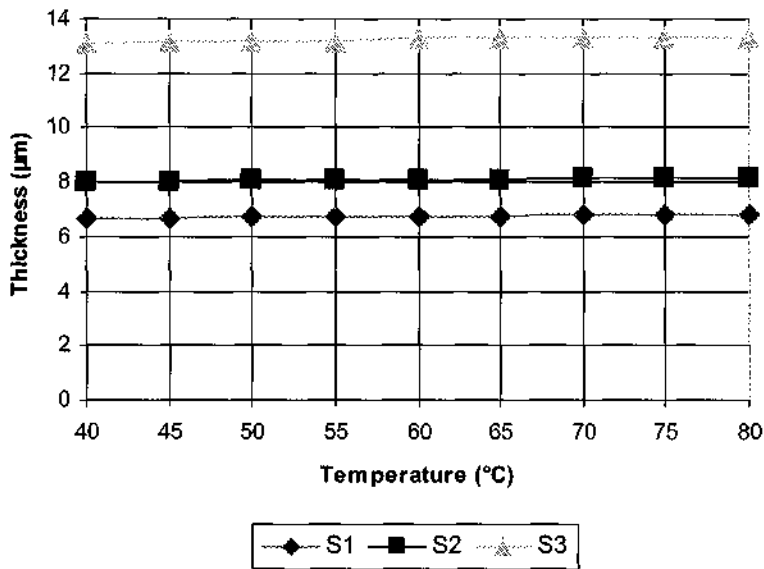


Figure 8: Effect of temperature on the film thickness of the waveguide.

#### 4. CONCLUSION

This paper presented the experimental work done in fabricating and

characterizing the polymer material coating on silicon substrate, which is to be used as an optical waveguide. Considerable measurements have been

done using the advance prism coupler system, which incorporate with temperature controller system. The birefringence of the optically transparent coating materials had been determined with the TE- and TM-polarization mode measurements. The changes of refractive index and thickness with temperature have been presented and thermo-optical coefficient,  $dn/dT$ , of the measured samples were comparable to standard value.

### ACKNOWLEDGMENT

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