Characterization of Poly(Phenylsilsesquioxane) Thin-Film Planar Optical Waveguides

K. S. Brown, *Member, IEEE,* B. J. Taylor, L. A. Hornak, *Member, IEEE,* and T. W. Weidman

Abstract— **Characterization results of thin-film poly-(phenylsilsesquioxane) (PPSQ) planar-optical waveguides are presented. Results of absorption spectrum, refractive index, thermal stress effect, and waveguide loss measurements performed on 1–2 μm PPSQ films indicate this silicon backbone polymer to be a strong potential candidate for optical waveguide integration within microelectronic systems. PPSQ films are shown to exhibit thermal stability with respect to volume, refractive index, and optical loss for temperatures up to 400 °C. The first TE mode of PPSQ planar optical waveguides between 1.32 and 1.72 μm in thickness fabricated on 5-μm HiPOX Si wafers exhibited optical loss of 0.16 dB/cm at 632.8 nm.**

Index Terms— **Optical interconnections, optical planar wave-guides, optical polymers, polymer waveguides, poly-(phenylsilsesquioxane), siloxane polymers.**

I. Introduction

Optical interconnections have been extensively explored as a means to relax increasing system-level interconnect performance barriers in present and emerging microelectronic systems [1]–[4]. However, for integrated optical waveguides to serve an interconnection role in these systems, they must be compatible with the advanced microelectronic packaging environment. Polymer materials show significant potential in this respect since they are already extensively used as interlayer electronic interconnection dielectrics, and their physical and optical properties can be engineered to provide the necessary processability, low-optical loss, and high-thermal stability [5]. While polyimides have been the focus of much effort, silicon backbone polymers offer the potential for improved processability, thin-film optical quality, and thermal stability over a wide-temperature range. Among this class of materials, polysilynes have been shown to exhibit unique index imaging properties for fabrication of optical waveguides but insufficient thermal and mechanical stability [6]. Siloxanes, however, are partially crosslinked silicon backbone polymers which have been extensively explored as a nonhermetic integrated circuit (IC) chip encapsulant and interlayer electronic interconnection dielectric due to their excellent transparency, electrical properties, and thermal stability to 500 °C [7], [8]. Poly(phenylsilsesquioxane) (PPSQ) is a siloxane polymer which is readily filterable, suitable for spin application, and patternable with a CF_4/O_2 reactive ion etch. This letter presents thin-film optical characterization results of PPSQ in order to determine its suitability as an optical waveguide material for microelectronic system co-integration.

II. Experimental Results

The PPSQ films characterized in this letter were fabricated on various substrate materials (silicon, oxide, and quartz) using standard spincasting techniques. After a conventional aqueous semiconductor clean, each substrate was primed with a spin application of toluene. This was immediately followed by the application of a PPSQ/toluene solution through a 0.45-μm filter, after which the substrate was then spun at a specific rate to form a given PPSQ film thickness. For the present studies, a 20% weight to volume (W/V) solution was used to fabricate PPSQ films of thicknesses between 1–2 μm using spin rates of 1–2 kr/min. Thinner films were obtained using lower percentage W/V solutions, but were not explored since they are generally not of interest in waveguide applications. Films thicker than 2 μm were obtained with higher W/V solutions, but experienced cracking during the final high-temperature phase of the thermal process adopted for thin films so were not explored as part of this study. All samples were thermally treated in a two step process beginning with one minute on a 100 °C hotplate following the spin application of the PPSQ films. Films were then transferred to a nitrogen purged furnace and thermally cycled starting at 80 °C for 25 min then ramping up 4 °C/min to 125 °C for 30 min. Samples were subsequently cooled to room temperature and prepared for characterization.

The experimentally measured absorption spectrum of a 1.77-μm PPSQ film is shown in Fig. 1 in terms of optical density over a spectral range of 250–1450 nm. Measurement of the PPSQ film, which was fabricated on a 1/8-in thick, 2-in diameter quartz wafer, was made in transmission mode using a dual arm spectrometer. A primary absorption band arising from the polymer's Si backbone appears prominently near 250 nm. The results indicate uniform, low-absorption loss over a spectral range of 300–1450 nm. An aperiodic variation with wavelength, as seen in the absorption data of Fig. 1, arises from thin-film interference of the probe beam in the PPSQ sample. Using this interference pattern, the index of refraction

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K. S. Brown, B. J. Taylor, and L. A. Hornak are with the Department of Electrical and Computer Engineering, West Virginia University, Morgantown, WV 26506 USA.

T. W. Weidman is with Bell Laboratories, Lucent Technologies, Murray Hill, NJ 07974 USA.

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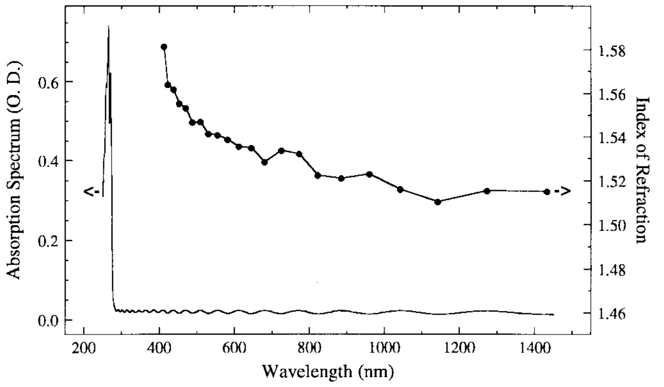

Fig. 1. PPSQ absorption spectrum (optical density) and inferred refractive index.

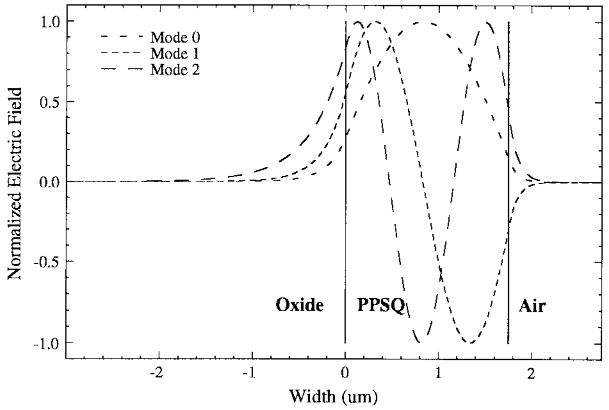

Fig. 2. Calculated TE mode normalized electric field profiles supported by a 1.75-μm-thick PPSQ film on SiO_2 at 632.8 nm.

of PPSQ as a function of wavelength was inferred, and is also shown in Fig. 1. At 632.8 nm, the inferred refractive index is 1.535 while at 850 and 1300 nm, the index is 1.522 and 1.515, respectively.

The transverse electric (TE) and transverse magnetic (TM) polarization refractive indexes of PPSQ films at 632.8 nm were obtained experimentally by a prism coupler. The measured TE refractive index is $n_{\mathrm{TE}} = 1.554$ while the TM refractive index is $n_{\mathrm{TM}} = 1.557$. This small, 0.19% birefringence is consistent with the amorphous nature of the crosslinked polymer structure. The 632.8-nm wavelength refractive index data obtained by the prism coupler was used to model the supported mode profiles for PPSQ films on SiO_2 using the effective index module of a commercial waveguide modeling package [9]. Fig. 2 shows the calculated plots of the normalized electric field for the TE modes of a 1.75-μm-thick PPSQ film on SiO_2. The effective indices of the three supported TE modes indicated by the modeling closely match (within 0.5%) the experimentally determined effective indices from the prism coupler.

Thermal stability is a critical issue for polymer integrated optics in microelectronic systems. In order to get an indication of the thermal stability of PPSQ thin films, five 1.83-μm-thick PPSQ films were individually thermally stressed for 30 min at different final nitrogen purged bake temperatures ranging between 125 °C–400 °C. Afterwards, the index of refraction of these samples was measured by a prism coupler. Fig. 3 shows the experimentally measured TE and TM refractive indices of these temperature stressed samples. The measured index of refraction is essentially constant for films that have been thermally stressed up to 400 °C. In addition, the measured film thicknesses remained constant, indicating no volume change as a result of the applied thermal stress.

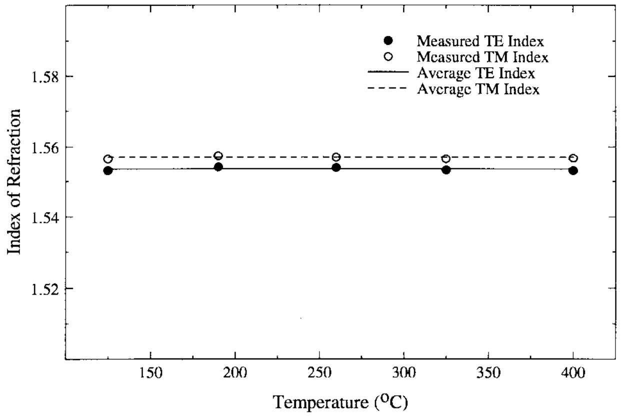

Fig. 3. Measured TE and TM refractive indices of PPSQ films at 632.8 nm as a function of thermal stress temperature.

An indication of the viability of PPSQ as an integrated optical waveguide material was determined through the measurement of the propagation loss at 632.8 nm exhibited by one dimensional PPSQ planar optical waveguides. While the experimental setup did not support longer wavelength measurements (e.g., 850 nm) an expectation of similar loss at longer wavelengths is consistent with the absorption spectrum of Fig. 1. Waveguides were formed from PPSQ thin films spun on 4″ Si wafers with a 5-μm layer of SiO_2 grown by high-pressure thermal oxidation (HiPOX). Using a prism coupler, light was launched into the PPSQ film at an incident angle corresponding to the first TE mode. While the optical path was visible in the film, the light radiated from the waveguide was insufficient to use the video scan technique (e.g., a CCD camera) to determine the waveguide loss. Instead, a quartz fiber bundle was brought close to the PPSQ film surface and scanned down its length with a computer controlled motorized stage to collect the radiated light. At its input end, the 100-μm diameter fibers in the bundle were formed into a linear array which was positioned near the PPSQ film with its length perpendicular to the streak. The output end of the fiber bundle was input to a Si photodetector. Optical loss results obtained from the measured scattered optical power versus propagation distance data indicate an average loss of 0.16 dB/cm for PPSQ planar waveguide thicknesses between 1.32–1.72 μm. Fig. 4 shows the optical loss for the first TE mode of a 1.37-μm-thick PPSQ planar optical waveguide on SiO_2. Each data point in Fig. 4 represents the average of nine separate optical loss coefficient measurements on a single waveguide at one coupling spot. Within experimental error, measurements of samples thermally stressed to 400 °C indicated no apparent change in optical loss.

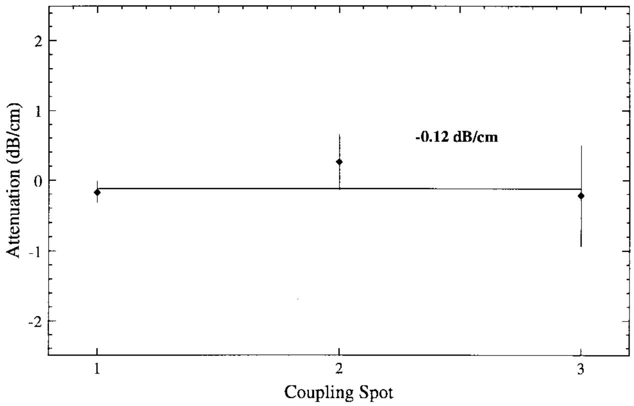

Fig. 4. Measured optical loss (at 632.8 nm) of the first TE mode of a 1.37-μm-thick PPSQ planar optical waveguide on SiO_2.

III. CONCLUSION

A characterization of PPSQ as an integrated optical waveguide material has been presented. Measurements of absorption spectrum, refractive index, thermal stress effects, and waveguide loss were completed on PPSQ thin films. Results indicate PPSQ is readily spuncast to form high-quality optical thin films from 1–2 μm in thickness with excellent thermal and optical loss properties. PPSQ thin films were experimentally shown to exhibit high-thermal stability with essentially no change in film volume, index of refraction, or optical loss up to the peak thermal stress temperature of 400 °C used in this study. PPSQ planar optical waveguides between 1.32–1.72 μm in thickness fabricated on 5-μm HiPOX Si wafers were also evaluated and shown experimentally to exhibit optical loss of 0.16 dB/cm at 632.8 nm (first TE mode). Characterization results indicate that PPSQ is a strong potential candidate for fabrication of optical waveguides in the advanced packaged microelectronic system environment.

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