Characterization of Poly(phenylsilsequioxane) for Planar Integrated Optical Waveguide Applications

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ABSTRACT

Our research characterized the fundamental optical properties of poly(phenylsilsequioxane) (PPSQ) planar waveguides in an effort to determine the material's suitability as a guided wave optical interconnect in polymer. Material characterization included determining the refractive index, mode structure, and optical losses of 1-2 μm PPSQ films. Optical loss measurements indicate that PPSQ planar waveguides have a propagation loss of 0.17 dB/cm at 632.8 nm for first order TE modes in thin films between 1.72 μm and 1.32 μm. The silicon backbone polymer is experimentally shown to be thermally stable for temperatures up to 400°C, with no apparent change in index of refraction, volume, or optical loss. Experimental results indicate that the material is compatible with standard microelectronic fabrication and a strong candidate for use in optical waveguide applications.

Keywords: poly(phenylsilsequioxane), polymer waveguides, optical interconnects, siloxane polymers, optical polymers

1 Introduction

The problems facing microelectronic system packaging and interconnects in the era of minimum sized, submicron CMOS pose significant challenges for system designers seeking continued dramatic performance improvements. To potentially enhance the performance of these increasingly complex microelectronic systems, non-traditional interconnect technologies and networks, like integrated optical waveguide interconnection networks, are being aggressively explored [1, 2, 3, 4]. The desire to develop integrated optical networks with CMOS electronics has fueled a search for optical materials that are compatible with silicon fabrication techniques.

Polymers, which can be engineered to have good thermal stability and are extensively used in electronic systems, have been synthesized with low optical losses and have emerged as good candidates for use in optical interconnection applications [5, 6, 7]. While much effort has been focused on polyimides, silicon backbone polymers offer a potential of improved processibility, higher thin film optical quality, and thermal stability over wide temperature ranges. Earlier studies of polysilynes, a class of silicon backbone polymers indicated that cross-linking of polymers can produce optically uniform films that are stable over a wide temperature range. Polycyclohexylsilyne (PCHS) was studied for its unique index imaging properties allowing waveguides to be fabricated by photooxidation bleaching. While PCHS waveguides were fabricated and used for exploration of experimental structures, the difficulties of the material's poor mechanical and thermal stability are detrimental to the use of PCHS in practical electronic environments [8]. The present research explores a partially cross-linked siloxane based polymer, poly(phenylsilsequioxane) (PPSQ), which can be readily spuncast into 1-2 μm thin films, and is patternable with a CF_4/O_2 reactive ion etch. Siloxane polymer materials have been extensively studied for electronic dielectric and encapsulant applications due to their high optical clarity, dielectric properties, and thermal stability [9, 10]. In this paper, PPSQ is characterized for its suitability as an optical interconnection medium in microelectronic systems by studying its absorption loss, index of refraction, thermal stability, and optical loss exhibited by one dimensional planar PPSQ waveguides on HiPOX Si wafers.

2 Experimental Results

PPSQ films were characterized to determine the suitability of the material in optical interconnect applications. Measurements focused on characterizing the absorption, index of refraction, thermal stability, and optical losses.

2.1 Fabrication of PPSQ Thin Films

The PPSQ films in this work were fabricated by standard spincasting techniques used in microelectronic fabrication. Characterization measurements required that the polymer be spun onto a variety of substrate materials like silicon, oxide, and quartz. Initially these substrates were prepared using a conventional aqueous cleaning process. Immediately before spincasting a polymer film, the substrate wafer was given a toluene primer spin. Afterwards a PPSQ/toluene solution was applied to the substrate through a 0.45 μm filter, and spun at a rate between 1-2 Krpm. These spin rates achieved film thicknesses between 1-2 μm for the 20% weight to volume (W/V) solution of PPSQ. Thinner PPSQ films were achieved by diluting the 20% W/V solution with toluene, but were not explored further since they are generally not of interest in waveguide applications. PPSQ films thicker than 2 μm were achieved by using a more concentrated solution, however the thicker films cracked during the hardening thermal cycle optimized for thinner films; therefore, the thicker films were not explored as part of this study. The freshly spun films were softbaked on a 100°C hotplate for one minute, and then hardened in a nitrogen purge furnace which was initially set at 80°C for 25 minutes and then ramped up at 4°C/minute to the final hardening temperature of 125°C for 30 minutes. After cooling to room temperature, the PPSQ film samples were prepared for characterization.

2.2 Absorption Spectrum Measurement

The experimentally measured absorption spectrum of a 1.77 μm PPSQ film in terms of optical density is shown in Figure 1. This absorption spectrum was measured in transmission mode on a PPSQ film fabricated on a 1/8"thick, 2" diameter quartz wafer and it was taken over a range of 250-1450 nm using a dual arm spectrometer. The data shows uniform, low absorption over a range of 300-1450 nm. An absorption peak occurs between 250 and 300 nm due to the silicon backbone of the polymer. The aperiodic variation with wavelength appearing in the absorption spectrum is the result of thin film interference of the probe beam within the PPSQ film. Using this interference pattern the index of refraction over a range of 400-1400 nm was inferred. The resulting refractive index as a function of wavelength is shown in Figure 2. These calculations yielded an index of 1.535 at a wavelength of 632.8 nm, 1.522 at a wavelength of 850 nm, and an index of 1.515 at a wavelength of 1300 nm.

2.3 Refractive Index Measurement

The refractive index of PPSQ films for the transverse electric (TE) and transverse magnetic (TM) polarizations were experimentally measured with a prism coupler, the setup of which is shown in Figure 3. Indices of $n_{TE} = 1.554$ and $n_{TM} = 1.557$ were found at a wavelength of 632.8 nm. The low, 0.19% birefringence is consistent with the amorphous structure of the cross-linked siloxane. Using index of refraction measurements collected by the

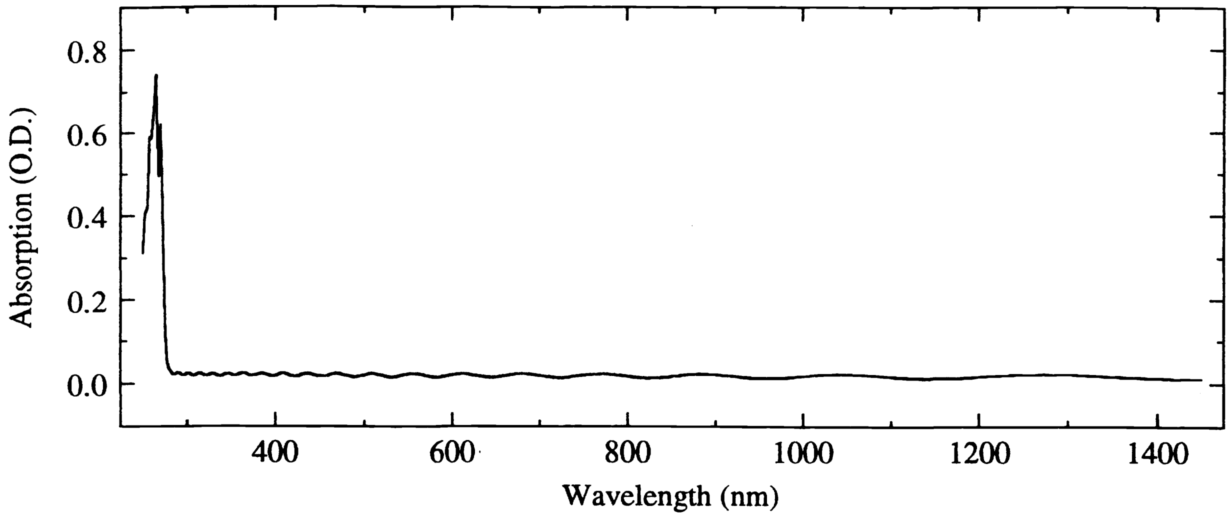

Figure 1: Absorption spectrum of PPSQ in terms of optical density (O.D.).

prism coupler, the mode structures in PPSQ slab waveguides was modeled with the effective index module of a commercial waveguide modeling package [11]. Mode profiles were determined by simulating PPSQ films on SiO_2 at a wavelength of 632.8 nm. An example of the calculated normalized electric field profiles of the TE modes in a 1.72 μm PPSQ film on SiO_2 is shown in Figure 4. The effective indices of the three TE modes calculated by the modeling tool closely matched the effective indices experimentally determined by the prism coupler (within 0.5%).

2.4 Thermal Stress Measurement

Thermal stability is an important characteristic for optical polymers which are to be cointegrated within advanced packaged microelectronic systems. Solder reflow can result in thermal stresses up to 300°C. A set of five 1.83 μm,

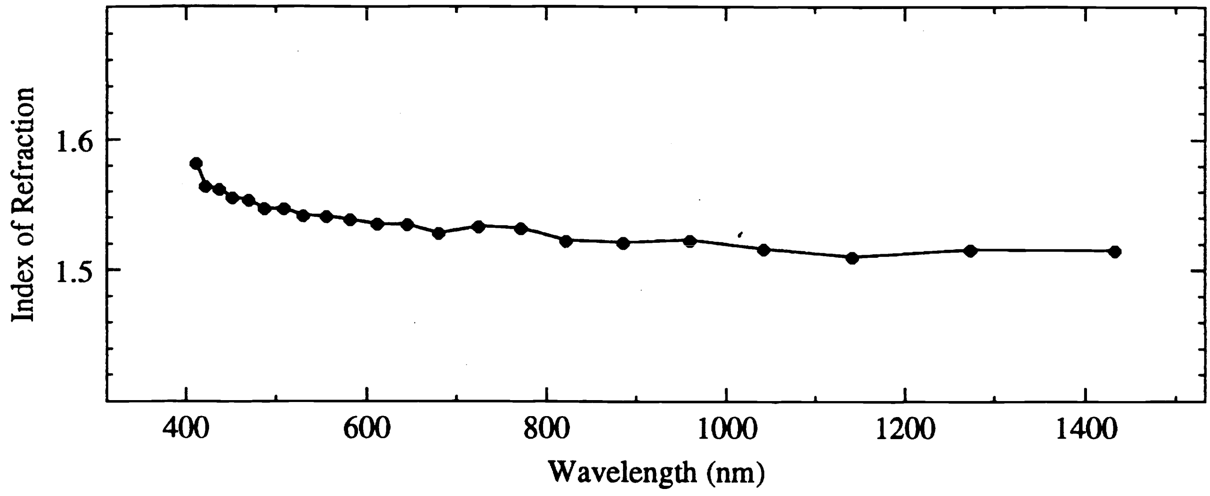

Figure 2: Refractive index of PPSQ as a function of wavelength.

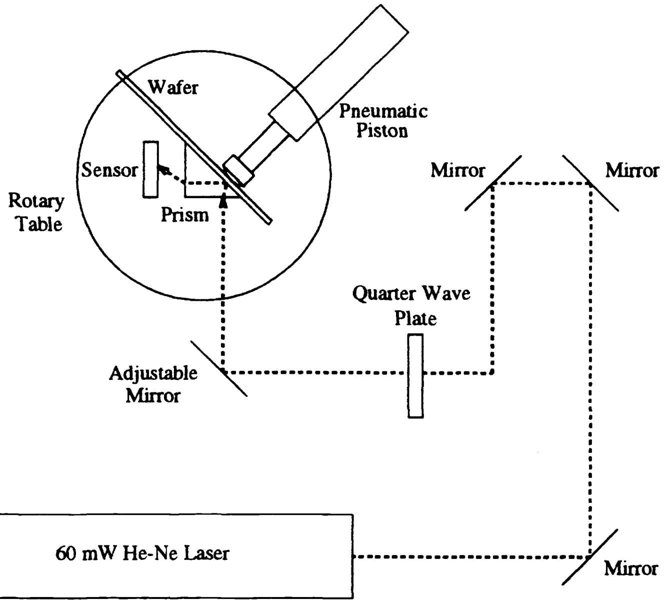

Figure 3: Setup of prism coupler for taking index of refraction measurements.

PPSQ films were thermally stressed by exposing each film to a different stressing temperature between 125°C and 400°C for 30 minutes. After the films cooled, their refractive index was measured using the prism coupler. The resulting TE and TM index measurements, which are shown in Figure 5, indicate that the indices are constant for temperatures up to 400°C. Thickness measurements of the films after thermal stress remained constant, indicated no change in PPSQ film volume due to temperature exposure.

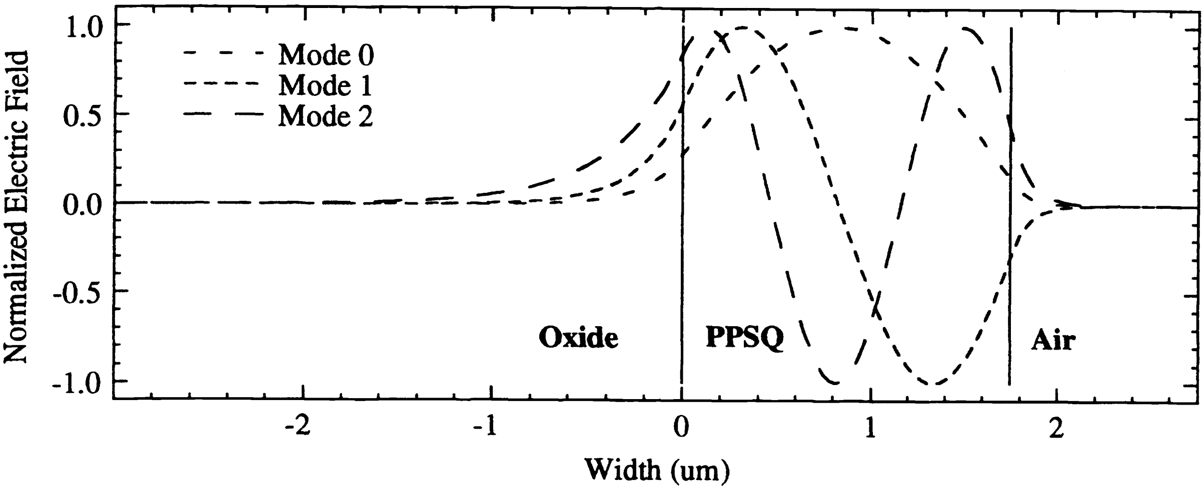

Figure 4: Calculated TE mode electric field profiles supported by a 1.75 μm thick PPSQ film on SiO_2 at 632.8 nm.

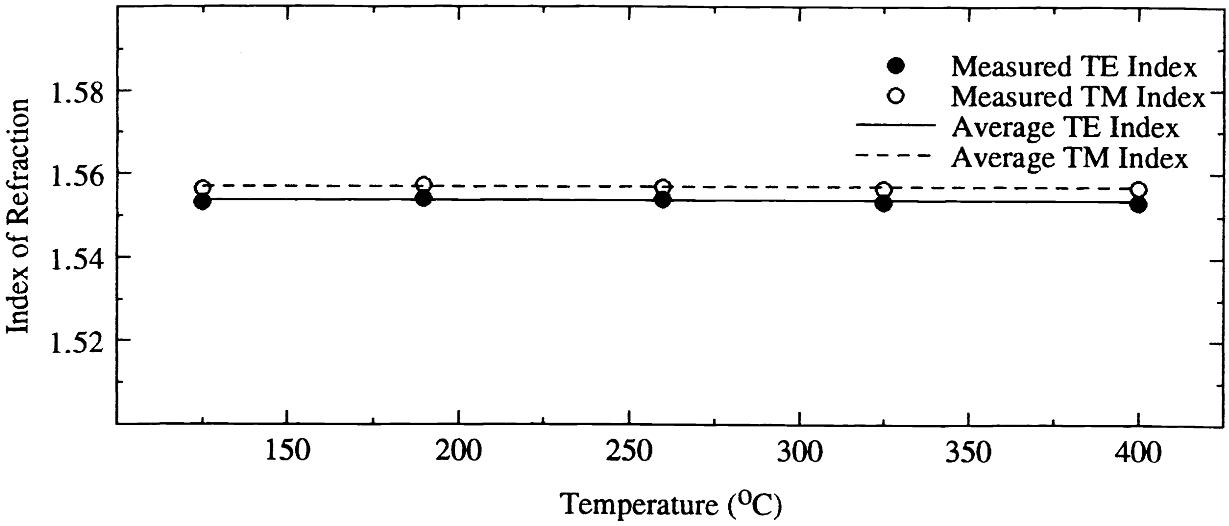

Figure 5: Measured TE and TM refractive indices of PPSQ films at 632.8 nm as a function of thermal stress temperature.

2.5 Optical Loss Measurement

The propagation loss of PPSQ thin film waveguides was measured to give an indication of the performance of the polymer in waveguide applications. One dimensional waveguides were fabricated by spinning PPSQ films on 4" Si wafers with a 5μm layer of SiO_2 grown by high pressure thermal oxidation (HiPOX). A prism coupler was used to launch the 632.8 nm wavelength laser light into the guide at a specific mode angle. By measuring the intensity of the light being scattered out along the optical path, the propagation loss of the waveguide was calculated from the scattered optical power versus propagation distance. Because the optical losses of thin film slab dielectric waveguides of PPSQ was very low, even though an optical path was present, the traditional video scan technique using a CCD camera could not be used. Therefore the loss of PPSQ thin film waveguides was measured using a fiber scanning technique. A bundle of 20, 100 μm quartz fibers was brought close to the film surface and scanned along the waveguide with a computer controlled stage. The input end of the fiber bundle, which was arranged in a linear array, was positioned perpendicular to the optical path so that it sampled a vertical cross section. The output end of the fiber was coupled to a silicon photodiode, where the photocurrent was read by a computer controlled ammeter vi GPIB interface.

Propagation loss results obtained from the measurements indicate a loss of 1.7 dB/cm for PPSQ waveguides of thicknesses between 1.32 μm and 1.72 μm. The loss for the first order TE mode of a 1.37 μm PPSQ planar waveguide on SiO_2 is shown in Figure 6. Each data point in the figure represents 27 separated optical loss coefficient measurements taken for a single guide produced at one coupling spot. Measurements of samples stressed at 400°C indicated no apparent change in optical loss within experimental error.

3 Conclusions

The characterization of the absorption, index of refraction, thermal stability, and optical loss of 1-2 μm poly (phenylsilsequioxane) (PPSQ) thin films has been presented. Characterization of the material for thin film waveguide applications show that PPSQ is thermally stable with no apparent changes in volume, refractive index, or propagation loss for temperatures up to 400°C. Planar PPSQ waveguides exhibited a measured propagation loss of 0.17 dB/cm for fabricated films between 1.72 μm and 1.32 μm on 5 μm HiPOX SiO_2 wafers at a wavelength of

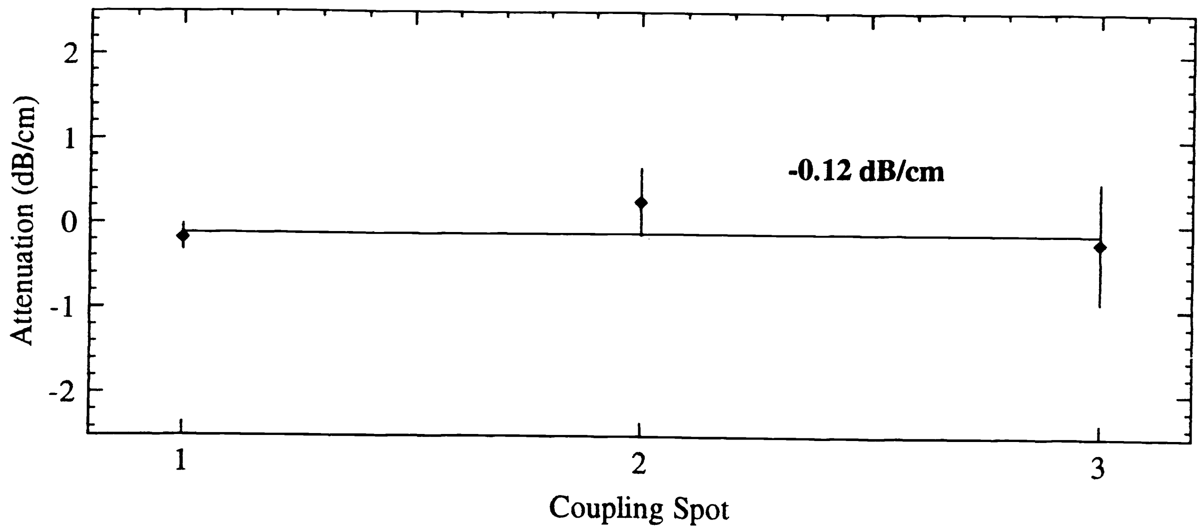

Figure 6: Measured optical loss (at 632.8 nm) of the first TE mode of a 1.37 μm thick PPSQ planar optical waveguide on SiO_2.

632.8 nm (first TE mode). Experimental results indicate that PPSQ is a good potential candidate for integrated optical waveguide cointegration within advanced packaged microelectronic systems.

Acknowledgments

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