

Benzocyclobutene Optical Waveguides

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Abstract—Single-mode optical waveguides at 1300 nm have been fabricated from the organic polymer benzocyclobutene. This material system utilizes a 535

rmb

photodefinable resin for forming the core of the waveguide, allowing the waveguides to be processed in a fashion similar to a negative photoresist. The processing conditions required for the fabrication of single-mode benzocyclobutene optical waveguides are presented. With the measured losses in the waveguide equal to .81 dB/cm at 1300 nm, this material system is suitable for use in a variety of optical interconnect applications.

I. INTRODUCTION

AS electronic IC technology continues to evolve, it has become increasingly important to ensure corresponding advancements in the chip-to-chip interconnection technology associated with these IC's. While the capabilities of electrical interconnects have not yet been exhausted, it has become apparent that either new methods of interconnection or packaging techniques are required to support the needs of systems operating at very high frequencies. For this reason, the use of photonics for clock and data distribution in high-speed complex electronic systems has been the subject of intense study in the recent past [1], [2].

One form of optical interconnect that has met with great success is optical fiber. Optical fiber is a very low optical loss, low-dispersion medium that has become the dominant technology for long-haul data transmission in the telecommunications industry. However, its use in very short distance data communications has been mostly limited to interconnects that span distances on the order of a few meters. The difficulty of fabricating boards that incorporate optical fiber is the major reason that fiber is seldom used for chip-to-chip interconnects, where typical distances are a few centimeters long. The routing of fiber is a very time-consuming, serial process that is not easily integrated into the manufacturing process. Furthermore, due to its size (125 μm in diameter), the volume of space required for optical fiber interconnects would grow rapidly with more frequent use within the system. These issues have created an interest in using a material system that allows the fabrication of the waveguide structure by embedding them in or depositing them directly on the circuit board on which the integrated circuits are mounted. The challenge is to develop such a system that still produces sufficiently low optical loss and meets the needs of the electronic environment. In this letter, we consider the fabrication and optical loss of waveguides fabricated using the organic polymer benzocyclobutene (BCB).

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II. MATERIAL PROPERTIES OF BCB

Benzocyclobutenes are a relatively new class of thermally produced polymers possessing characteristics desirable for board-level optical interconnects. Designed originally for use as a thin film dielectric in applications such as multichip modules, GaAs IC's, magnetic media, and flat-panel displays, BCB possesses the necessary properties required for materials used in most electronic systems. Important properties include a low dielectric constant (2.7, 10 kHz–10 GHz), excellent planarization (>90%), low moisture uptake (<.23 wt.% after 24 h in boiling water), good adhesion to various substrates and itself, thermal stability in excess of 350 °C, and good mechanical properties [3], [4]. A recent work has reported the optical loss of this material to be low (0.04 dB/cm at a wavelength of 1300 nm) [5]. While these properties are required for any optical waveguide material, the emergence of a photodefinable version of BCB has made this material system very attractive for use as board-level optical interconnects. This negative working system allows the waveguides to be fabricated following steps similar to photoresist processing without the need for any plasma or reactive ion etching.

Two formulations of BCB are currently available based on the monomer, 1,3bis(2-bicyclo[4.2.0]octa-1,3,5-trien-3-ythenyl)-1,1,3,3-tetramethyl disiloxane. They are supplied as partially polymerized solids dissolved in mesitylene. The first version is a nonphotodefinable formulation and is currently marketed under the name CycloteneTM [6]. Upon completion of the polymerization, this material has an index of refraction of 1.559 at a wavelength of 589 nm and is used as the cladding layer in our waveguides. The second formulation of BCB is a proprietary material currently under development at Dow Chemical. This material is a photodefinable version of BCB based upon the above monomer and contains the photocrosslinking agent 2,6-bis(4 azidobenzylidene)-4-methylcyclohexanone, BAC-M. After this material is polymerized, it has an index of refraction of 1.562 at 589 nm and is used for the core material in the waveguides. The small index difference of .003 between the core and cladding materials results in this material system being capable of producing single-mode waveguides at 1300 nm with dimensions suitable for coupling to optical fiber, as will be shown below.

III. EXPERIMENT

The starting materials are pale yellow liquids with the cladding material containing 46% solids and the core material containing 38% solids that are kept refrigerated and brought to room temperature before processing. Silicon wafers were used as the substrate material. The substrates were prepared

by washing them with soap and DI water, and then soaking them in trichloroethylene for 15 min, rinsing them with acetone and then methanol, and finally blowing them dry with nitrogen.

The fabrication of the waveguides begins with forming the cladding layer. As mentioned above, the nonphotodefinable formulation is used for this purpose. To avoid coupling the light in the core into the silicon, a sufficiently thick cladding layer is required. To make a layer approximately 8- μm thick, the material was spun on a clean silicon wafer at 700 rpm for 25 s after an acceleration time of 15 s. The next step in the process is the polymerization of the film by a thermal cure. The goal of this step is to produce a film that is resistant to solvents, but will allow adhesion of the next layer of BCB. To achieve this, the film must only be partially polymerized. Curing the film so that all of the monomer units have been polymerized results in very poor adhesion between the core and the cladding layers. However, if the cladding has not been cured enough, the mesitylene in the core material, as well as the developing solvents, will penetrate into the cladding layer, also resulting in poor adhesion. The following schedule was found to produce the desired results: ramp up the temperature from 25 $^{\circ}\text{C}$ to 100 $^{\circ}\text{C}$ over 1 h, hold at 100 $^{\circ}\text{C}$ for 15 min, ramp up to 200 $^{\circ}\text{C}$ over 1.3 h, hold at 200 $^{\circ}\text{C}$ for 15 min, ramp up to 250 $^{\circ}\text{C}$ over 30 min, hold the temperature at 250 $^{\circ}\text{C}$ for 30 min, and then ramp the temperature down to 25 $^{\circ}\text{C}$ over 2 h. The cure was carried out in a nitrogen ambient (<100 ppm O_2) to avoid oxidation of the polymer. Oxidized films reveal a degradation in the electrical and physical properties, including a rise of approximately 0.025 in the index of refraction and a darkening of the film [3].

Immediately after the cladding layer is cured, the core layer is spun on the cladded wafers. In anticipation of coupling light from a single-mode fiber into the waveguide, it was desired to produce waveguides with a cross-sectional area approximately equal to that of the fiber's 8- μm -diameter core. To achieve this, the core material was spun onto the cladded wafers at 900 rpm for 25 s after an acceleration time of 20 s. The wafer was then pre-baked at 80 $^{\circ}\text{C}$ for 20 min in air to remove any residual solvents in the spun-on film. After pre-baking, the BCB is not tacky and is suitable for use in a contact printing system. However, an edge bead is formed along the wafer edge during spinning that was cleaved off in order to obtain the maximum resolution possible. The waveguides were patterned by placing the prepared substrates in contact with a chrome mask, and exposing the BCB using a 1000-W Hg-Xe lamp with 200–450-nm light. With a measured power density of 188 mW/cm^2 , typical exposure times are approximately 45 s for a 7.5- μm opening. After exposure, the waveguides are developed by immersion in Stoddard solvent [7] for 90 s. The unexposed regions are developed away leaving photopatterned waveguides. To complete the processing, the waveguides are then cured in a similar manner to the cladding layer, but with the time at 250 $^{\circ}\text{C}$ extended to one hour. Fig. 1(a) and (b) consists of scanning electron micrographs of BCB optical ridge waveguides. The photopatterned waveguides in Fig. 1 exhibit smooth surfaces and good resolution. Also note that the shape of the waveguides are not perfectly rectangular due to the

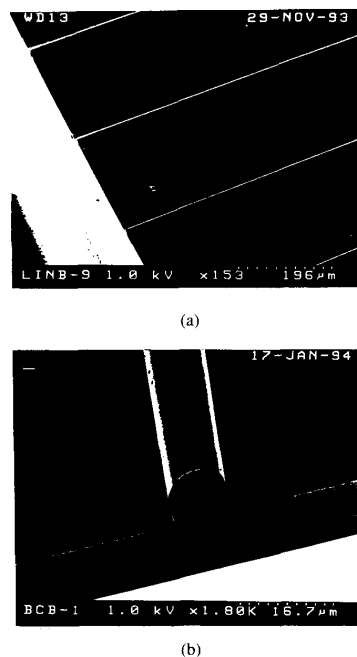


Fig. 1. Scanning electron micrographs of benzocyclobutene ridge waveguides. (a) Overview of several waveguides. (b) Cross section of a BCB waveguide illustrating the smooth surface and resolution of the waveguides.

diffraction effects associated with the mask opening and the spun-on film thickness.

IV. LOSS MEASUREMENT

The results of a cutback loss measurement performed on BCB optical waveguides are shown in Fig. 2. In this measurement, 1300-nm light was coupled from a single-mode fiber (8.3 μm core diameter; cleaved and polished) into the core of waveguides 8.7 μm wide and 6.8 μm tall. The slope of the line indicates that the optical losses in the waveguides are 0.81 dB/cm, while the coupling loss is equal to .95 dB. When examined through an infrared viewer, the waveguides appear to be of good quality due to the absence of defects and scattering centers. However, a loss of 0.81 dB/cm is large compared to the published absorption data for a slab of nonphotodefinable BCB of 0.04 dB/cm. The additional losses may be due to the addition of the photocrosslinking agent. Determining the source of the additional losses is one area for future research. However, with the losses equal to 0.81 dB/cm, these waveguides are suitable for use in relatively short (several centimeters) optical interconnect situations.

When fabricating these waveguides, it was desired to produce single-mode waveguides with core dimensions that closely match those of a single-mode optical fiber in order to allow efficient coupling of light from the fiber into the waveguides. The field shadow method [8] was used to theoretically determine the number of modes supported by these waveguides. Based upon that work, at 1300 nm the

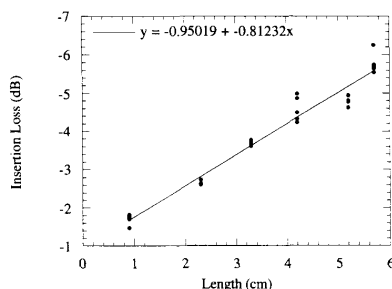


Fig. 2. Results of a cutback loss measurement performed on BCB waveguides at a wavelength of 1300 nm. The slope of the line indicates that the waveguide loss is equal to .81 dB/cm.

fundamental mode is weakly guided and all higher-order modes are far from cutoff.

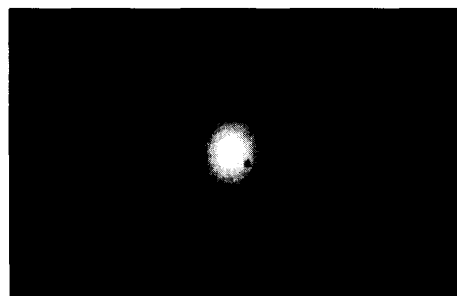
To determine the number of modes supported by these waveguides, an infrared imaging system was used to examine the mode structure at the output of the waveguides. Fig. 3(a) is an image of the waveguide output with 1.3- μm light coupled in at the input, while 3(b) is a surface plot of this image. The single lobe of light evident in these figures is a clear indication that these waveguides support only one mode at this wavelength. Inspection of Figures 3(a) and (b) reveals that the intensity distribution across the output of the waveguide is not perfectly symmetric. The asymmetry of the distribution can be attributed to the asymmetry of the waveguide structure. The waveguide has a BCB cladding only on one side, air on the others, and is not perfectly square. Therefore, it is reasonable to expect a certain degree of asymmetry in the intensity distribution.

V. CONCLUSION

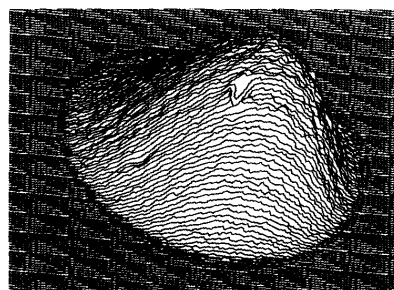
Optical ridge waveguides have been fabricated with the organic polymer benzocyclobutene using standard photolithographic techniques without the need for plasma etching. Since the BCB polymer was originally developed for use as a thin film dielectric, it is compatible with most processing steps and environments associated with electronic systems. The small refractive index difference of 0.003 between the two formulations described in this letter makes this system capable of producing single-mode waveguides with dimensions suitable for coupling to optical fiber. With the measured optical losses equal to .81 dB/cm at 1300 nm, these waveguides can be used for several optical interconnect applications in the electronics industry.

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(a)



(b)

Fig. 3. (a) Image of the waveguide output when 1300-nm light is coupled in at the input. (b) Surface plot of the output intensity shown in Fig. 3(a). The single lobe of light in each figure indicates the presence of a single mode in the waveguide.

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