Low-Cost and Low-Loss Multimode Waveguides of Photodefinable Epoxy

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***Abstract*—To satisfy the urgent need for low-cost multimode planar waveguides, we developed photodefined, multimode-fiber compatible waveguides with low-cost commercially available epoxies showing low losses from 550 to 1100 nm and around 1300 nm.**

***Index Terms*—Integrated optics, optical interconnections, optical polymers, waveguides.**

I. Introduction

In cost-sensitive areas of short distance optical communications, like datacom, CATV, optical interconnects in printed circuit boards (PCBs), and in optical sensing, a urgent need has emerged for low-cost multimode planar waveguide structures to be applied in components like splitters and couplers or integrated in PCBs. These waveguides have to be compatible with the standard 50-, 62.5-, or 100-μm core size multimode silica fibers combined with light-emitting diodes (LEDs) and low-cost vertical-cavity service-emitting lasers (VCSELs) with their emission wavelength at 850 nm. In addition, LEDs and upcoming VCSELs in the 600–1000-nm range and around 1300 nm are important application wavelengths. Some conventional (C-H containing) low-cost polymeric materials can meet these requirements because they can be deposited up to 100-μm film thickness by simple spin or dipcoating techniques; they can be formulated for direct photopattering; their refractive indexes can be tuned to yield waveguides with fiber-matched numerical apertures (NAs); and their transparency windows can coincide with the VCSEL wavelengths.

The commercially available photodefinable polymers, Truemode^{TM} (Exxelis) [1] and Ormocer^{TM} (Micro Resist Technology) [2], are based on acrylate crosslinking and form wet films after deposition. Photopatterning can only be done by using masks in the proximity mode, which degrades the resolution and which is not suited for large uneven substrates like PCBs where conformable (foil) masks have to be used. The alternative of direct writing is a slow serial process and, therefore, not cost-effective. Moreover, the acrylate (free radical) crosslinking process requires inerting to avoid cure inhibition by ambient oxygen, which adds to the production costs.

Photocurable epoxies do not possess these drawbacks. Their different (cationic) cure mechanism allows the processing of dry films with contact masks under normal ambient. In addition, epoxies are well known for their excellent adhesion, durability, dimensional stability, and chemical inertness. The negative photoresist SU-8 (MicroChem Corp.) is a well-known epoxy photopolymer which was also applied in planar optical waveguide applications [3]. However, a main drawback is its limited transparency at UV/visible wavelengths due to processing induced absorption (yellowing) from photoinitiator decomposition products and polymer impurities [3], [4]. In this letter, we present photodefined, multimode fiber compatible waveguides, based on commercially available low-cost epoxy materials, showing low losses from 550 up to 1100 nm and around 1300 nm.

II. Photodefinable Epoxy Formulation

We have formulated a photodefinable polymer system based on the most widespread used (in adhesives, coatings, encapsulants) and low-cost epoxy prepolymer, i.e., the diglycidylether of bisphenol A (DGEBA) [5]. This is available with low impurity content and different molecular weights (M_n). The higher molecular weight versions, starting from about $M_n = 1000$ g/mol are solid materials. The DGEBA molecular chains contain aromatic rings and have (two) epoxy endgroups which can be opened and crosslinked to yield an insoluble polymer network. The stiffness of the rings provide a high glass-transition temperature, while their aromatic character results in a high refractive index. Because a low M_n provides a high crosslink density and, consequently, a good photodefinition, the solid DGEBA with the lowest M_n (1000 g/mol) (e.g., Epon 1001F of Resolution or DER 661 of Dow) is used in the formulation.

The DGEBA is combined with the fluid epoxy monomer: 3, 4-epoxycyclohexylmethyl–3, 4-epoxycyclohexane carboxylate, UVR, (e.g., UVR 6110 of Union Carbide). Its molecules contain only aliphatic rings equipped with two highly reactive epoxy groups to yield a high glass transition temperature network with a low refractive index after crosslinking. It is also commercially available at low cost and with high purity and is used in UV curable coatings (PCBs, cans) and castings (LEDs) [5].

The combination of epoxies, thus, provides a low-cost formulation with high stability and wide refractive index tuning range. For the waveguide core formulation, the amount of the more reactive fluid UVR in the solid DGEBA is maximized to 17%. This results in a just dry, nontacky film suitable for contact masking. For the claddings, a larger amount of UVR is taken based on matching the NA of the waveguides with multimode fibers. These wet layers can be cured by unmasked flood exposure.

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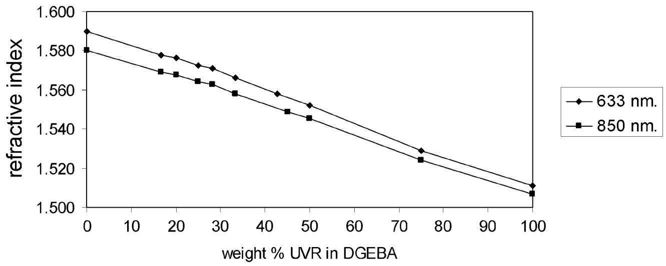

Fig. 1. Refractive index at 633 and 850 nm of photocured DGEBA-UVR formulations as a function of weight percent UVR.

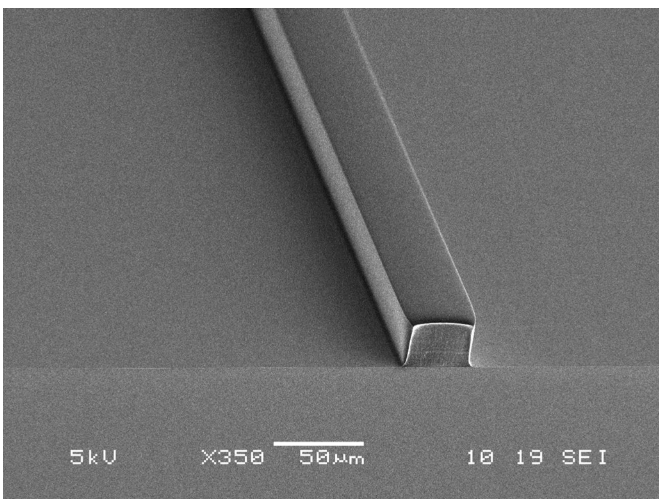

Fig. 2. SEM photograph of a photodefined bare multimode waveguide core on a silicon wafer.

The ringopening process of the epoxy groups is catalyzed by a strong acid generated by the decomposition of a photoinitiator. This photionitiator should be active for the operational wavelength of the exposure apparatus. Photoinitiators for the most common I-line maskaligners are readily available. Onium salts based on triarylsulfonium hexafluoroantimonate are widely used, including in SU-8, because of their effectiveness [6]. However, in our formulation, we used triarylsulfonium hexafluorophosphate (UVI 6992 of Union Carbide), because this yields less yellowing on postbaking. An amount of 4 wt% is used, which is twice as much as is typically used in SU-8. In the postexposure bake, the photoacid-catalyzed epoxy crosslinking takes place, resulting in insolubility of the latent photoacid image in the polymer which will not be washed away in the subsequent development step.

III. Results

Fig. 1 shows the refractive index of the photocured DGEBA-UVR formulation at 633 and 850 nm as a function of weight percentage UVR as measured in thin photocured films using an ellipsometer (Woolam M44).

Any index between 1.58 of the neat aromatic DGEBA and 1.51 of the neat cycloaliphatic UVR can be produced. With the formulation for the core containing 17% UVR, waveguides with

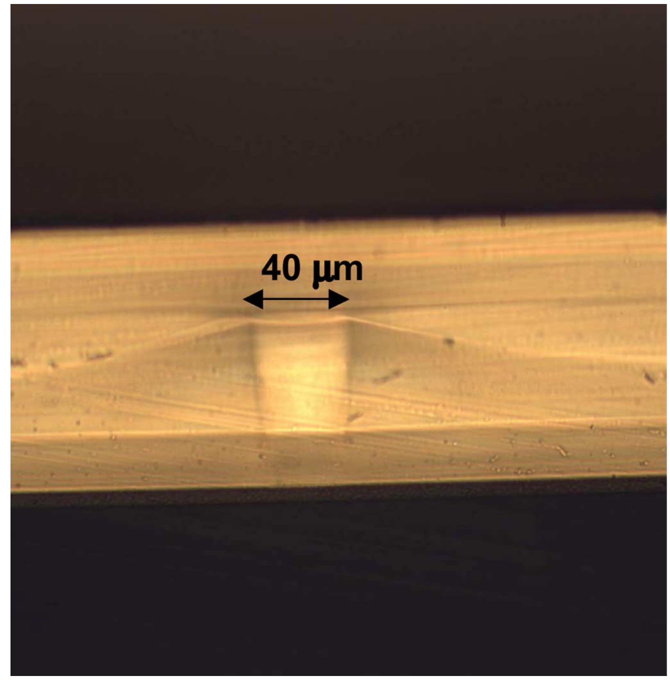

Fig. 3. Microscope photograph of a photodefined multimode waveguide cross section. (Color version available online at: http://ieeexplore.ieee.org.)

NAs up to 0.5 can be produced. This is well beyond the NAs of all standard multimode fibers $(\max\ \mathrm{NA} \sim 0.3)$.

We used a 45% UVR formulation as cladding material to obtain waveguides with $\mathrm{NA} = 0.25$. Cyclopentanone was used as a solvent in a 1/1 ratio with the epoxy mixtures to yield a layer thickness of about 25 μm for the spin coating speed of 500 r/min that was used. Layer thicknesses up to 100 μm can be produced by using a lower amount of solvent. A silicon wafer with 8-μm thermal oxide was coated with a single bottom cladding layer. After photocuring, the core layer was deposited in two coating steps. After exposure in a contact mask aligner, using a mask with 40-μm open lines, followed by curing and development, the top cladding was deposited in four spinning cycles followed by photocuring.

The processing parameters were identical to SU-8 50 processing parameters, according to the product data sheet of Microchem Corp. for the SU-8 50-μm formulation, with the exception for the exposure times in the 350 W, I-line, mask aligner (Karl Süss MA55). These were derived from the best lithography results and ten times longer than those for 50-μm SU-8 layers. A hard bake at 150 °C–200 °C was not applied.

Fig. 2 shows a scanning electron microscope (SEM) photograph of the bare multimode waveguide core on a silicon wafer. A smooth sidewall and topsurface can be observed.

Fig. 3 shows a microscope photograph of the cross section of a diced wafer. The waveguide structure and the excellent planarization of the polymer cladding can be observed.

Waveguide losses were determined from the optical output of samples with different lengths (cut-back by dicing) using butt-coupled 50-μm multimode fibers, a white light source at the input and an optical spectrum analyzer (Spectro 320, Instrument Systems) at the output. The results are shown in Fig. 4, together with the loss spectrum of a comparable SU-8 waveguide [3]. A

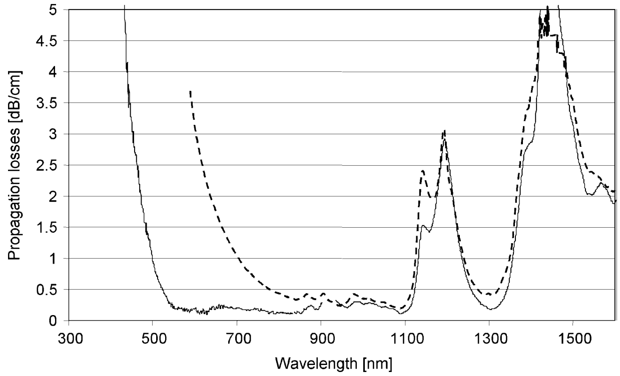

Fig. 4. Loss spectrum of photodefined DGEBA-UVR (solid) and SU-8 (dashed) multimode waveguides.

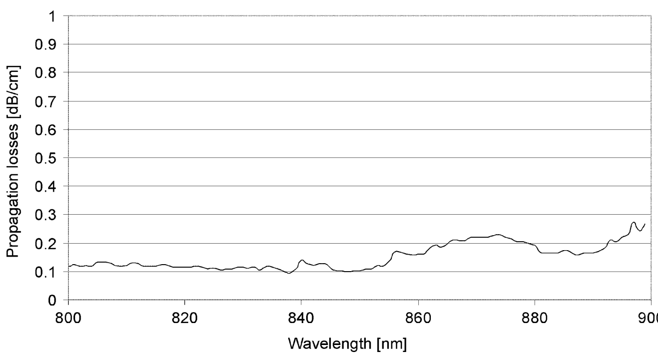

Fig. 5. Loss spectrum of photodefined DGEBA-UVR multimode waveguides around 850 nm.

zoom-in of Fig. 4 for the communication windows around 850 and 1300 nm are shown in Figs. 5 and 6, respectively.

The results show a much broader transparency window for the DGEBA-UVR waveguides than for the SU-8 waveguides. The SU-8 waveguides are brown colored due to strong absorption by yellowing. The transparency window of the DGEBA-UVR waveguides runs from 550 up to 1100 nm with losses <0.25 dB/cm and minima of 0.1 dB/cm around 850, 625, and 1090 nm. Around 1300 nm there is a low-loss window of 0.2 dB/cm.

IV. Conclusion

The low-loss properties of the novel photodefinable epoxy formulation, combined with its low-cost material and processing properties and its robustness makes this material attractive for planar waveguides compatible with multimode fibers and low-cost LED and VCSEL sources in particular with the important 850-nm wavelength used for short distance optical communication and sensor applications.

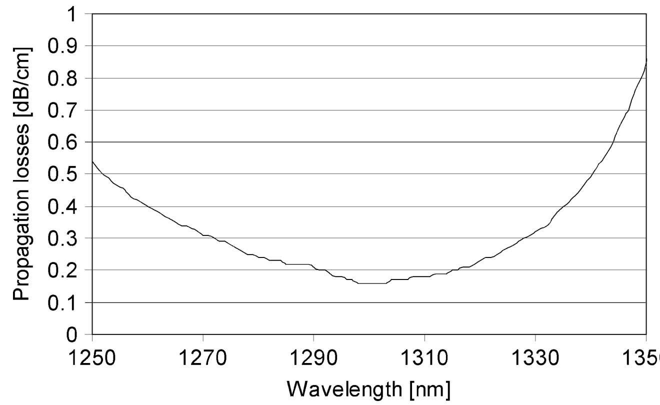

Fig. 6. Loss spectrum of photodefined DGEBA-UVR multimode waveguides around 1300 nm.

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