Photosensitive Epoxy Materials and their Application to Multi-mode Optical Waveguides

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A photosensitive epoxy (PSEP) for multi-mode optical waveguide based on epoxy resins containing fluorene units and photo-acid generator (PAG) has been developed. PSEP is directly patterned by UV irradiation and wet chemical development, avoiding use of photoresist. Fabricated optical waveguides have 50μm width rectangle core pattern, which was smooth sidewalls and surfaces. PSEP optical waveguide exhibits high heat resistance and low optical loss 0.063 μ at 830nm. This simplification of the fabrication process is very attractive in manufacturing optical/electrical devices at low cost.

Keywords: photosensitive epoxy, fluorene derivative, multi-mode optical waveguide, core, cladding, optical loss

1. Introduction

Recently the demands for high-speed and high-density data transmission have increase in the short-distance data transmission area. However, current electrical interconnections are facing their limitation of data-transfer speed due to electromagnetic interference (EMI), cross talk and bandwidth limiting [1]. Accordingly optical interconnection is considered as one of promising solution to overcoming these technical issues.

Polymer optical waveguides have attracted considerable attention due to their high transparency [2,3], in which 600-1000 nm region LDs such as vertical-cavity surface-emitting laser diodes (VCSELs) are generally used as a light source for high-speed and short distance optical interconnection. In addition, polymer material can provide mass productivity and cost-effectiveness. Therefore, a number of research groups have reported several kinds of polymer waveguides fabricated by using various methods and materials [4-9].

We have previously reported single-mode optical waveguides for optical communication using fluorinated photosensitive polyimide (PSPI)-precursor and found that the PSPI exhibited high heat resistance and low optical loss at 1.55μm [10,11]. To take into consideration the use of VCSEL as a light source on optical/electrical (O/E) devices, however, their applications are considered to be limited because the PSPI has relatively low transparency around 850nm. Therefore multi-mode polymer waveguide materials should have low loss at about 850nm and high thermal stability. In this paper, we introduce PSEP containing fluorene units for optical waveguide and a simple process for the fabrication of low loss waveguide.

2. Experimental

2.1. Materials

All monomers and solvents were obtained commercially and used as received.

2.2. Lithographic evaluation

Typical procedure is as follows; the PSEP solution consisting of epoxy resins and PAG was spin-coated on glass substrate. It was prebaked at 100 °C for 15 min and then exposed to a 250W filtered super high-pressure mercury lamp using
mask aligner (Mikasa MA-60F). Imagewise exposure was carried out in a contact method. The film was baked at 150°C for 30 min. The film was developed with γ-butyrolactone.

2.3. Fabrication of PSEP optical waveguide
The PSEP optical waveguide was fabricated by following process as shown in Fig. 1. PSEP for cladding material was spin-coated on glass substrate and a 25μm-thickness under-cladding layer was formed by UV exposure and post exposure bake (PEB) at 100 °C for 30 minutes. PSEP for core material was spin-coated on the cladding material. After the core layer was exposed to UV light through a photo mask, PEB performed at 100 °C for 30 minutes. After development with γ-butyrolactone, the core pattern was post-baked at 150°C for 30 minutes. Finally an over-cladding layer was formed to bury to core patterns by UV exposure and PEB. Total thickness of PSEP optical waveguide was almost 100 μm.

2.4. Measurements
The film thickness was measured by surface texture measuring instrument with Dektak 3030 system (Veeco Instrument Inc.). The pattern was observed by scanning electron microscopy (SEM)(Hitachi S-570). The Thermogravimetric (TG) analysis was performed on a SEIKO TG-DTA 200 System at a heating rate of 10 °C·min⁻¹ under N₂. Differential scanning calorimetry (DSC) was performed by a SEIKO DSC 5200 at a heating rate 10 °C·min⁻¹ under N₂. Dynamic mechanical thermal analysis (DMA) was carried out using Seiko Instrument Inc. DMS 120 running tensile mode at an oscillation frequency of 10Hz at a heating rate of 5 °C·min⁻¹. Thermal mechanical analysis (TMA) was performed on Seiko Instruments Inc. TMA / SS 100 running tensile mode at a heating rate of 10 °C·min⁻¹. Refractive index was measured by prism coupling method. Waveguides were cut with a Disco No.522 dicing machine.

The optical loss measurement of 10cm-long waveguides was performed using multi-mode fiber (50μm φ) as the input and the output fiber, respectively as shown in Fig. 2. An 830 nm wavelength laser diode (LD) was used as a light source. The propagation loss of waveguide was measured by the conventional cut back method.

![Photo detector](Image)
![Waveguides](Image)
![Light source (830nm LD)](Image)

Fig.2 Experimental setup for loss measurement.

### 3. Results and Discussion

#### 3.1. Formulation of PSEP
Chemical structures of epoxy resins and photo-acid generator (PAG) used in this study show in scheme 1. The epoxy materials for the waveguide applications must have highly transparency at about 850 nm. We selected epoxy resins containing bisaryl fluorene units, which have high transparency in visible region due to card structure. In addition fluorene derivatives would be expected to thermally stable and show high refractive index. This system is utilized photo-induced curing of epoxy resins as an initiator of PAG.

![Scheme 1](Image)
Thus, the PSEP based on epoxy resins and PAG was formulated. Refractive indices of core and cladding materials can be easily controlled in the 1.50-1.62 at 830nm with a 0.001-order accuracy by blending fluorene derivatives with cycloaliphatic epoxy resin. Therefore, refractive index difference between core and cladding can be up to 0.12.

3.2. Properties of PSEP film
As fluorene containing epoxy resins have little absorption at 365nm, an i-line (365nm) used as an exposure light. The photosensitivity curve of a core film with 30μm thickness is shown in Fig. 3. This system shows photosensitivity (D_{0.5}) 3 J/cm\(^2\) with i-line exposure. It is presumed that the sensitivity was attributed to low reactivity of epoxy moieties in fluorene derivatives due to steric hindrance of bisaryl fluorene units.

Fundamental properties of UV curing PSEP film are listed in Table 1. The refractive indices of the core and cladding material were 1.615 and 1.593 at 830nm respectively. Glass transition temperature (T\(_g\)) and 5% weight loss temperature (T\(_d\)) of core material were 140 °C and 383 °C, respectively. These good thermal properties would be expected to use for O/E devices, which need soldering process.

3.3. Optical properties of PSEP optical waveguide
Fig.4 shows a scanning electron micrograph of PSEP core ridge. The core dimension is 50μm width and 50μm height. It was found that the ridge was almost vertical, and the sidewalls and surfaces of the core pattern were very smooth. The optical loss spectrum of PSEP optical waveguide is shown in Fig.5. The PSEP film has a high transparency at wavelengths ranging from 600-1100nm. Therefore, the PSEP is a suitable optical waveguide material for applications using 850nm.

In order to evaluate propagation properties of PSEP waveguide, we fabricated waveguide pattern using PSEP. The propagation loss of the straight waveguides at 830nm LD light source was measured by cutback method. The propagation loss at 850nm is found to be 0.063 dB/cm from slope of curve as a function of waveguide length as shown in Fig. 6. The low optical loss was attributed to low sidewalls roughness of core pattern. A near-field pattern of the output signal through the PSEP waveguide is also shown in Fig. 6.

![Fig.4 SEM photograph of PSEP optical waveguide.](image)

![Fig.5 Optical loss spectrum of 10cm-long optical waveguide.](image)
Fig.6 Loss dependence of the waveguide on waveguide length.

3.4. Reliability of PSEP waveguide

The reliability of the fabricated optical waveguide was evaluated as follow. To take account of the lead-free soldering process required during packaging, we carried out heating tests at 260 °C. In addition, a high temperature/humidity test at 85°C/85% R.H. were carried out. Fig. 7 (a) and (b) show the losses increment of 10cm-long waveguide samples. The changes of optical loss were less than 0.01dB after these reliability tests. These results indicate that developed material and fabricated waveguide are available for applications needing high reliability.

4. Conclusion

A photosensitive epoxy for multi-mode optical polymer waveguide based on epoxy resins containing fluorene units and PAG has been developed. The PSEP system shows 50 μm width pattern with smooth sidewalls and surfaces. The fabricated waveguide using the PSEP indicated low propagation loss of 0.063dB/cm at 830nm. There was little any loss increment in the waveguide after heating 260 °C. Therefore, we have confirmed that PSEP optical waveguides have potential for as optical devices components for optical interconnections.

References