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CASE STUDY

UV15: For Fabrication of Polymer Optical Waveguides

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Electro-optical (EO) polymers offer several advantages over inorganic materials in the fabrication of optical waveguide structures that form the basis of optical network components, optical links, and other photonic devices. Low optical loss, high bandwidth, large EO coefficient, ease of processing, and relatively low material costs have stimulated interest in the development of polymer optical waveguides.

Both single-mode and multimode waveguides can be fabricated using various combinations of polymeric materials for the core (guiding) layer and the upper and lower cladding (shield) layers. Through selection of appropriate materials and careful design of the fabrication process, engineers can develop polymer-based waveguides with different optical, physical, and mechanical properties that are suitable for a variety of applications, such as modulators, multiplexers, and power splitters.

Materials used in polymer waveguide design must have the appropriate physical, optical, and mechanical properties for the desired application. Minimal requirements include high optical transmission, low optical loss, a suitable index of refraction, and a smooth, crack-free surface that is of homogeneous thickness. Additional capabilities, such as compatibility with a substrate material or resistance to etching chemicals, may be required, depending on the application. Master Bond UV15 has been used in numerous polymer optical waveguide designs, due to its exceptional properties and superior ease of processing.

UV15 Meets Waveguide Design Criteria

Optically clear UV15 is an epoxy-based UV curable system that is commonly used for bonding, sealing, and coating applications in the optical, optoelectronic, aerospace and related industries. UV15 adheres well to surface-treated metals, glass, and plastics. Its low viscosity (115-350 cps) allows it to be applied through spin coating, which produces highly uniform surfaces. UV15 typically cures in thicknesses of a few microns to 0.015-0.020 inches when exposed to UV light with a wavelength of 320-365 nm for 15-30 seconds or less. When post-cured for 30 minutes at 125°C, its glass transition temperature (T_g) is 125-130°C. Because UV15 is 100% reactive, contains no solvents, and is free of oxygen inhibition, it exhibits very low shrinkage (1-2%) and exceptional thermal stability upon cure. UV15 is also highly resistant to a variety of chemicals, including acids, bases, fuels, and many solvents, as well as water.

UV15 is well suited for many polymer optical waveguide designs. It has a refractive index of 1.48 at a wavelength of 633 nm and adheres well to silicon, which is often used as a substrate for waveguide fabrication. One-component UV15 is easily spin-coated to create smooth, uniform films with thicknesses used in waveguides (roughly 5 to 100 μm). Because UV15 can withstand exposure to solvents used in photolithography, it can be patterned and etched to form ribbed waveguide channels.

Waveguide Research Studies Cite UV15

Master Bond UV15 has been selected for use in the fabrication of polymer optical waveguides for a variety of applications. In a research project conducted at RMIT University, UV15 was used for both the upper and lower cladding layers in an optical polymer slab waveguide.[1] UV15 formed the lower cladding layer in a waveguide designed for use as an optical modulator in a study at the University of Texas at Austin.[2] Researchers at the University of Twente (Netherlands) fabricated multimode polymeric waveguides using UV15 as the core layer.[3]

The waveguides in each of these three studies were fabricated using spin coating to deposit the cladding and core layers, photolithography to pattern the waveguide, and reactive ion etching (RIE) to transfer the waveguide pattern to the core layer. In each study, a different combination of materials (i.e., UV15 and one or two other polymeric materials) was selected for the core and two cladding layers and the fabrication process was adapted to meet specific design and performance goals.

Optimizing UV15 Properties to Achieve Design Goals

The characteristics of UV15 and other polymers used in waveguides can be modified in order to optimize performance for a particular design. By varying the parameters and conditions of the deposition, curing, and etching processes, differences in UV15 thickness, smoothness, thermal stability, and other properties can be achieved. Because there may be tradeoffs between different design goals, such as smoothness and sharpness of the waveguide channel, it is important to understand how each process variation affects the properties of UV15 film.

Spin coating

The success of a polymer optical waveguide design depends in part on proper preparation and deposition of thin polymer films. Design goals include controlling the thickness, ensuring surface uniformity, and minimizing the surface roughness of the films. Achieving these goals are critical to creating surfaces with the appropriate refractive indices while minimizing optical losses due to light scattering.

Spin coating a low viscosity polymer, such as UV15, onto a surface offers precise control over the thickness of the film. The thickness of a spin-coated film depends on the viscosity of the compound and on the spin coating speed and duration. Figure 1 shows the relationship between the thickness of a UV15 film and the spinning speed for a given viscosity and spin duration, as presented in the University of Twente study.[4] By varying the spinning speed from 400 to 6000 rpm, the thickness of the UV15 can be varied from roughly 34 µm to 3 µm, respectively. For many polymer waveguide designs, spinning speeds of 4000 rpm or higher are desired in order to produce a very thin UV15 film layer.

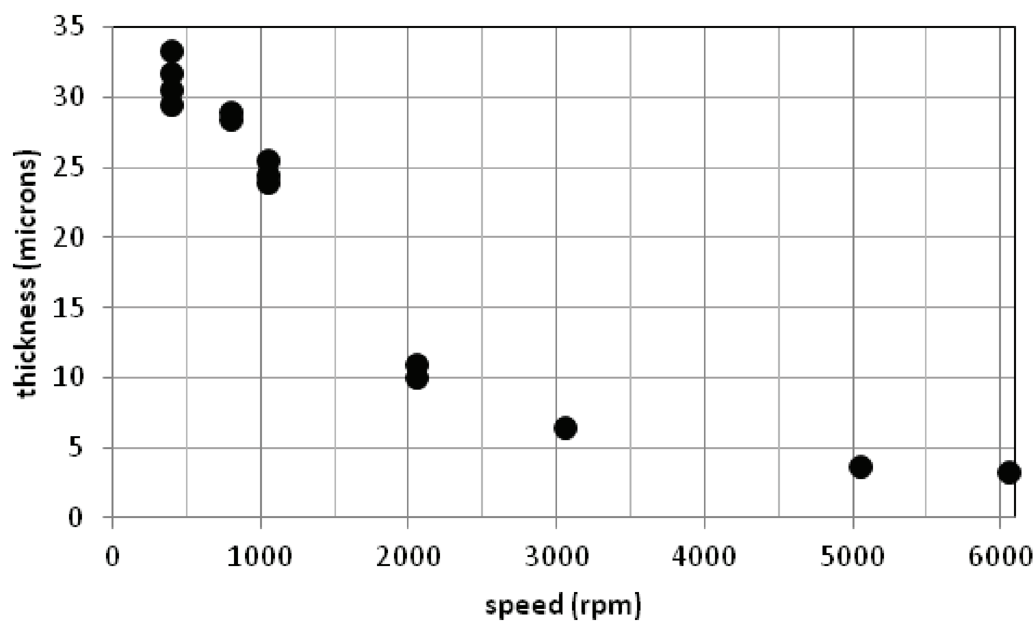

Figure 1: Film thickness of UV15 vs spinning speed.

Curing and the glass transition temperature

The glass transition temperature, T_g, is an important measure for polymeric compounds such as UV15. When exposed to temperatures below the T_g, such compounds exhibit higher thermal and chemical resistance, higher physical strength and stiffness, and greater electrical and dimensional stability than they do at temperatures above their T_g. In the fabrication of optical waveguides, the polymer cladding and/or core layers may be subjected to relatively high temperatures during the etching process. If the etching process heats a polymer film to a temperature higher than its T_g, the polymer may not be able to withstand etching.

For example, in the RMIT study, the UV15 lower cladding layer is etched to form a trench for the inverted rib of the core (guiding) layer. It is critical that the cured UV15 is sufficiently hard, has a high thermal resistance, and exhibits high chemical resistance in order to withstand the etching process. The RMIT researchers discovered that, if the T_g of the cured UV15 layer was too low, heat applied during the plasma etching process caused the cured UV15 film to soften and flow, creating wrinkles in the surface of the film. Similarly, in the University of Twente study, researchers found that when the etching power was increased from 75W to 100W, surface roughness of the etched channel sidewalls increased. Such surface irregularities lead to optical loss by scattering. To prevent surface wrinkles, the T_g may be increased by controlling the curing process.

The RMIT study examined the effect on the T_g of cured UV15 when the cure time and intensity are varied for both straight-cured and post-cured UV15. Differential scanning calorimetry (DSC) was used to measure the T_g. For UV15 cured solely with UV light at room temperature, increasing the curing time and intensity resulted in an increase in the T_g of up to 5.9°C (see Table 1).[5] A T_g of 53.4°C was achieved when UV15 was cured for 40 minutes at 7.2 J/cm².

Table 1: Glass transition temperature of straight-cured UV15

Curing time (min)	T_g (°C)	UV intensity (J/cm²)
10	47.5	1.8
20	48.4	3.6
30	49.5	5.4
40	53.4	7.2

For UV15 that was post-cured, the same upward trend in T_g was found (see Table 2), with T_g reaching 120°C when post-cured at 100°C for 40 minutes.[6] The researchers observed that while UV15 films with low T_g exhibited wrinkling due to surface flow, there was no surface wrinkling when UV15 was post-cured at 80°C for 30 minutes. This result was attributed to the high T_g (115°C).

Table 2: Glass transition temperature of post-cured UV15

Curing time (min)	UV intensity (J/cm²)	Heating temperature (°C)	Heating time (min)	T_g (°C)
10	1.8	80	30	112
30	3.6	80	30	115
40	7.2	100	40	120

Etching a smooth channel

For waveguide designs in which a UV15 film must be etched, the parameters of both the etching process and the UV15 curing process can affect the etch rate, channel depth, channel sharpness, and wall smoothness. The UV light intensity used to cure UV15 has a significant impact on the plasma etch rate. Experiments performed in the RMIT study showed that when higher UV energies were used to cure the UV15 film, shallower etch depths were achieved. An advantage for films cured with moderate UV energies was that the etched channels exhibited sharper steps, which is desirable for optimal channel definition. Additionally, as discussed in the previous section, if the etching process heats the UV15 above its cured T_g, surface wrinkling can result. Striking a balance between the curing and etching processes is necessary in order to prevent surface wrinkling while ensuring a smooth crack-free surface.

Fabricating Waveguides Using UV15

For each of the three studies that used UV15 in the design of optical waveguides, fabrication methodologies and processing parameters were customized to meet the specific goals of the waveguide design.

Upper and lower cladding layers of planar waveguide

In the research project conducted at RMIT University, UV15 was used for both the upper and lower cladding layers in inverted rib polymer slab waveguides that used polymethyl methacrylate (PMMA) as the core material. UV15 was selected because it has a lower refractive index than PMMA and does not dissolve in PMMA solution.

UV15 was spin-coated onto a silicon substrate at 4000 rpm for 60 seconds to create a 6-µm film. The UV15 film was cured for one minute at 10 mW/cm^2, post-baked at 110°C for 30 minutes, and then coated with photoresist and patterned using a standard photolithography process to create an etch mask. Reactive ion etching (RIE) at 100-200W and 400 cm^3/min intensity for 15 minutes was used to create relatively smooth trenches in the lower cladding layer. The resulting surface roughness was 0.002µm for a 0.15-µm deep trench and 0.007µm for a 0.500-µm deep trench. The PMMA core layer was spin-coated onto the etched lower cladding layer, forming an inverted rib, and a film of UV15 was then spin-coated onto the PMMA film to form the upper cladding layer.

Lower cladding layer of electro-optic modulator

The goal of the study at the University of Texas at Austin[2] was to design a single-mode waveguide to be used as the basis of an electro-optical modulator. The waveguide structure consisted of a ribbed core layer sandwiched between two cladding layers, with metal electrodes attached to the outer sides of both the upper and lower cladding layers. Each waveguide structure was fabricated on a silicon wafer topped with a 2-µm thick layer of silicon dioxide.

Three electro-optical polymers were designated as core materials for use in three different waveguide designs. After testing many different cladding materials, researchers selected Master Bond UV15 as the lower cladding material for two of the waveguides designs. Key properties of UV15 cited in the study are excellent thermal and photochemical stability, low optical loss, and good adhesion to metals, silicon, and silicon dioxide. Equally important in the selection process was the compatibility of UV15 with the core materials, PMMA and amorphous polycarbonate (APC), used in the two waveguide designs. Specifically, the refractive index of UV15 is lower than that of each core material, and UV15 is resistant to the solvents used to spin-coat each core material.

The thicknesses of each layer and the depth and width of the rib were calculated to optimize performance goals. Very thin layers of UV15 (3 µm and 4 µm) were required for the two waveguide designs. UV15 was diluted with cyclopentanone in a 2:1 (UV15:cyclopentanone) volume ratio and then spin-coated at 2000-3000 rpm onto the bottom metal electrode layer to form 3- and 4-µm thick films. The films were UV-cured for 30 minutes using a mercury lamp with an intensity of 10 mW/cm^2 and post-cured overnight at 90°C. The core material was then spin-coated onto the UV15 layer and, after curing, the core layer was patterned and RIE-etched to form the rib. Finally, the upper cladding layer and upper electrode were deposited, and the waveguide was edge polished to reduce the coupling loss.

In addition to its use as a cladding material, UV15 was used as a protective coating during two steps of the fabrication process. One of the core materials, APC, was coated with a 0.5-µm thick layer of UV15 prior to applying the photoresist to prevent it from dissolving during the photoresist application. This protective layer consisted of UV15 diluted with methanol in a 6:1 (methanol:UV15) volume ratio spin-coated at 6000 rpm and UV-cured with a large-intensity light. UV15 was also added to the edge of the fabricated waveguides prior to polishing, and a thin glass slide was placed against the uncured UV15. Once fully cured, the UV15 layer served to prevent the waveguides from stripping off during the edge polishing step.

Core layer of multimode waveguide

Researchers at the University of Twente (Netherlands) fabricated multimode polymeric waveguides using UV15 as the core layer and PMMA as the upper and lower cladding layers.[3] A 10-µm thick PMMA layer was first spin-coated onto a silicon substrate. Next, a 40-µm UV15 film was spun onto the PMMA layer. The UV15 film was then cured using UV light at 360 nm while exposed to a steady flow of N2 to inhibit oxidation during cure. The cured UV15 was spin-coated with a 3-µm PMMA protective film prior to depositing a 150-nm thick layer of aluminum, which was patterned using photolithography to form a resistant etch mask. Channels of varying widths (20-50 µm) were then etched 40 µm deep into the UV15 film using oxygen reactive ion etching at a power of 75W. Finally, a thick upper cladding layer of PMMA was deposited on the UV15 core layer. Scanning electron micrograph (SEM) images showed that the waveguide channels were free from cracks and had smooth sidewalls. These waveguides, which exhibited very low optical losses, served as the foundation for compact multimode power splitters and star couplers.

Conclusion

Master Bond UV15 has been successfully used in the fabrication of low-loss electro-optical polymer waveguides. Through careful control of the spin-coating, curing, photolithography, and etching processes, the properties of UV15 and other materials used in waveguide design can be optimized to achieve specific design goals. The resulting polymer waveguides are relatively inexpensive to fabricate and can be used to realize a variety of electro-optical devices.

References

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[6] Simon, 148.