

Thermally resistant UV-curable epoxy–siloxane hybrid materials for light emitting diode (LED) encapsulation†

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A UV-curable epoxy–siloxane hybrid material (epoxy hybrimer) was fabricated by photo-cationic polymerization of a sol–gel derived cyclo-aliphatic epoxy oligosiloxane (CAEO) blended with oxetane cross-linker in the presence of an onium salt. Antioxidants for fabrication of the UV-curable epoxy hybrimer with high thermal resistance against yellowing were incorporated in the UV-curable epoxy hybrimer. The UV-curable epoxy hybrimer with the antioxidants showed high thermal resistance without yellowing during 120 °C thermal aging. High thermal resistance of the UV-curable epoxy hybrimer was similar and higher compared to those of commercial thermally curable silicone and UV-curable epoxy LED encapsulants, respectively. The thermally resistant UV-curable epoxy hybrimer was successfully encapsulated on a LED without any cracking or delamination, and maintained a flat surface on the LED without distortion of the designed flat shape. Before/after thermal and blue light aging, the performance of the LED encapsulated by the UV-curable epoxy hybrimer was not changed. On the basis of its excellent properties as a LED encapsulant, the UV-curable epoxy hybrimer can be utilized as a UV-curable LED encapsulant for white LEDs.

Introduction

Since the development and commercialization of blue light emitting diodes (LEDs) in the 1990s, the application of white LEDs has rapidly expanded to traditional lighting fields, such as display backlighting, automotive lighting, and general lighting, as white LEDs offer extended lifespan, low voltage driving, and high luminescence efficiency. White LEDs are fabricated by incorporation of a blue LED chip as a light source and a yellow (or red + green) phosphor as a light converter in a LED encapsulant. Blue light emitted by the blue LED chip is converted into white light when it passes through phosphors dispersed in the LED encapsulant.^{1,2} Due to the high reliability of white LEDs with high junction temperature (~120 °C),^{3,4} thermal resistance against yellowing of the LED encapsulant has become a key issue in white LEDs. Accordingly, silicone-based materials with high thermal resistance have been recently developed and utilized as

LED encapsulants instead of conventional epoxy LED encapsulants.

Silicone-based LED encapsulants are generally fabricated by thermal curing: (1) silicone produced by a thermal hydrosilylation reaction between a vinyl group and hydrogen functionalized on silicon atoms, and (2) epoxy–siloxane hybrids produced by a thermal anionic polymerization reaction between cyclo-aliphatic epoxy groups functionalized on silicon atoms and an anhydride hardener.⁵ The thermally curable silicone-based LED encapsulants show higher thermal resistance against yellowing compared to conventional epoxy LED encapsulants. However, since thermal curing of the silicone-based LED encapsulants requires high temperature (>150 °C), as well as long curing time (>few hours), many problems arise, including degradation of the performance of the LEDs, distortion from the designed shape by thermal shrinkage, and low manufacturing productivity of LED encapsulants. One possible avenue to overcome the problems of thermally curable silicone-based LED encapsulants is to develop UV (ultraviolet)-curable LED encapsulants with high thermal resistance.

Photo-polymerization of acrylates or epoxides has been commercially used for various applications in industrial fields, such as optics and displays, due to the following advantages: rapid process, patternability, low cost, low process temperature, and low energy consumption.^{6,7} However, acryl or epoxy polymers fabricated by photo-polymerization have low thermal resistance due to the absence of siloxane bonds, which afford

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high thermal resistance against yellowing, and to the thermal oxidative degradation reaction of the hydrocarbon backbones initiated between free radicals generated from the catalyst and oxygen in air.^{5–8} Thus, acryl or epoxy polymers are not appropriate for use as UV-curable LED encapsulants.

In the present study, we report on novel UV-curable epoxy–siloxane hybrid materials (epoxy hybrimer) with high thermal resistance against yellowing that can be used as UV-curable LED encapsulants. For this work, we synthesized a sol–gel derived cyclo-aliphatic epoxy oligosiloxane (CAEO)/oxetane blend. The UV-curable epoxy hybrimer was fabricated by UV irradiation of the photo-cationic polymerizable CAEO/oxetane blend in the presence of an onium salt. Also, antioxidants, used to suppress the oxidative degradation reaction originating from free radicals produced by onium salts, were incorporated in the UV-curable epoxy hybrimer. The UV-curable epoxy hybrimer showed suitable properties to be applied as a UV-curable LED encapsulant, such as high optical transmittance, thermal resistance, refractive index, *etc.*, and successfully encapsulated a LED.

Experimental

Fabrication of thermally resistant UV-curable epoxy hybrimer

CAEO was synthesized *via* a sol–gel condensation reaction between 0.01 mol of 2-(3,4-epoxycyclohexyl)ethyltrimethoxysilane (ECTS, Gelest) and 0.01 mol of diphenylsilanediol (DPSD, Gelest) using barium hydroxide monohydrate (Aldrich) as a catalyst *via* a previously reported method.^{9,10} The CAEO and 3-ethyl-3[[[3-ethyloxetane-3-yl)methoxy]methyl]oxetane (DOX, Toagosei) were mixed at a weight ratio of 1.0 : 0.2. Triaryl-sulfonium hexafluoroantimonate salt (Aldrich) of 1.2 wt% was added as an onium salt to catalyze the photo-cationic polymerization. For minimization of discoloration of the UV-curable epoxy hybrimer originating from the onium salt, iso-octyl-3-(3,5-di-*tert*-butyl-4-hydroxyphenyl) propionate (SONGNOX® 1135 LQ, Songwon industrial Co., Ltd.), used as a primary antioxidant, and tris(nonylphenyl) phosphite (Aldrich), employed as a secondary antioxidant, were added according to various compositions to the CAEO/oxetane blends. The UV-curable epoxy hybrimers were fabricated by photo-cationic polymerization of the CAEO/oxetane blends with antioxidants. The CAEO/oxetane blends were irradiated with ultraviolet (UV) light for 2 minutes using a Hg lamp (80 mW cm⁻², 365 nm, Oriel 97453) under an air condition to obtain samples with a substantial thickness of 2 mm. Sequentially, the UV-cured samples were heat-treated at 120 °C for 30 hours under an air condition to promote cationic polymerization. The UV-curable epoxy hybrimer with the optimized antioxidant contents was prepared to evaluate various physical properties and used to encapsulate a blue LED under the same conditions. For comparison of the thermal resistance with the UV-curable epoxy hybrimer, a thermally curable silicone LED encapsulant (OE-6630) with a refractive index of 1.53 and a UV-curable cyclo-aliphatic epoxy resin (3,4-epoxycyclohexylmethyl 3,4-epoxycyclohexanecarboxylate, ECC) with a refractive index of 1.50 were purchased from Dow-Corning and Aldrich, respectively. After OE-6630, composed of two parts, was mixed, it was thermally cured in a mold with 2 mm thickness at 150 °C for 2 hours in air. ECC was

mixed with DOX, onium salt, and antioxidants of the same compositions as used for the UV-curable epoxy hybrimer. The 2 mm thick ECC was UV-cured using a Hg lamp for 2 minutes in air. The UV-cured ECC was heat-treated at 120 °C for 30 hours. Also, OE-6630 and ECC were respectively used to encapsulate a blue LED under the above-mentioned process conditions.

Characterization of thermally resistant UV-curable epoxy hybrimer

The photo-sensitivity of the CAEO/oxetane blend and CAEO was measured by a differential scanning calorimeter (TA Instruments Inc., DSC Q2000) equipped with a photocalorimeter accessory (TA Instruments Inc., high pressure mercury lamp). 3 to 4 mg of each sample was loaded to an aluminium pan and irradiated by UV light in air. The light intensity was adjusted to 20 mW cm⁻² and light wavelength of 250–650 nm was changed to a wavelength of 250–450 nm using a UV broadband filter. The optical transparency of each sample was obtained in a wavelength range between 350 nm and 800 nm using an ultraviolet-visible-near infrared (UV/VIS/NIR) spectrophotometer (Shimadzu, UV3101PC). The yellowness index of the UV-curable epoxy hybrimers was calculated using a color analysis program with the optical transmittance of a UV/VIS/NIR spectrophotometer (ASTM, D1925). The yellowness index is represented by the following equation.

$$YI = [100(1.28X_{CIE} - 1.06Z_{CIE})]/Y_{CIE}$$

X_{CIE} , Y_{CIE} , and Z_{CIE} are the CIE tristimulus values for red, green and blue, respectively. The yellowness index change of the UV-curable epoxy hybrimer was represented according to the change in the yellowness index *via* the following equation (ASTM, D1925).

$$\Delta YI = YI_{\text{final}} - YI_{\text{initial}}$$

ΔYI is the change in yellowness index, YI_{initial} is the yellowness index before thermal aging, and YI_{final} is the yellowness index after thermal aging.

The dynamic mechanical responses of the UV-curable epoxy hybrimer were measured using a dynamic mechanical analyzer (DMA 2980, TA Instrument, Inc.). The storage modulus (E') and $\tan \delta$ were obtained within a temperature range of –75 °C to 200 °C at a ramp rate of 5 °C min⁻¹. The vibratory offset force was fixed at 0.01 N at a frequency of 1 Hz. The thermo-dilatometric responses of the UV-curable epoxy hybrimer were evaluated using a thermomechanical analyzer (TMA, EXTAR series TMA/SS 6100, Seiko Instruments, Inc.). The displacement was measured from –75 °C to 200 °C at a heating rate of 5 °C min⁻¹ and the coefficients of thermal expansion (CTEs) were calculated from the displacement. The refractive index of the UV-curable epoxy hybrimer at the sodium D lines (589.0 nm) was measured by an Abbe refractometer (Bellingham and Stanley, UK). Shore D hardness measurement of the UV-curable epoxy hybrimer was performed with a shore D Durometer (HPSD, Schmidt). The oxygen and water vapor permeabilities of the UV-curable epoxy hybrimer were characterized by a permeability analysis (MOCON, OX-TRAN Model 2/21 and PERMATRAN-WMODEL 3/33,

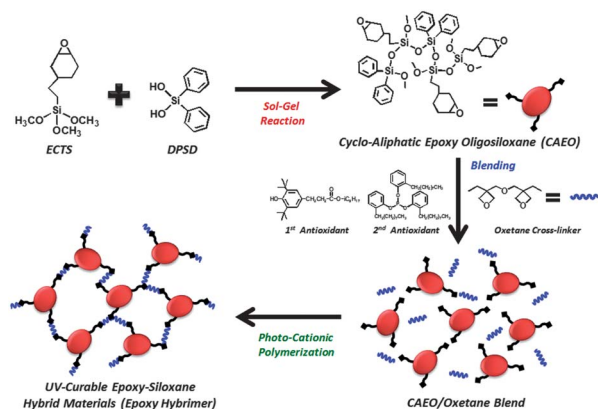
respectively). Electroluminescence (EL) spectra of the blue LEDs were measured on a DARSA PRO 5100 PL System (PSI Trading Co., Ltd., Korea) at room temperature using a xenon lamp (500 W) as an excitation source. A cross-sectional image of the blue LED chip encapsulated by the UV-curable epoxy hybrimer was obtained with an optical microscope (BX51M, OLYMPUS).

Results and discussion

Preparation and characterization of thermally resistant UV-curable epoxy hybrimer

A UV-curable epoxy hybrimer was fabricated as shown in Scheme 1. First, CAEO with siloxane bonds was synthesized by a non-hydrolytic sol-gel reaction between 2-(3,4-epoxycyclohexyl)ethyltrimethoxysilane (ECTS) and diphenylsilanediol (DPSD). The formation of siloxane bonds with high thermal resistance in CAEO was confirmed in a previous work.¹⁰ A difunctional oxetane cross-linker was blended with CAEO in the presence of an onium salt for fast photo-cationic polymerization (see Fig. S1 in the ESI†) and primary and secondary antioxidants were added to the CAEO/oxetane blend to inhibit oxidative degradation of the hydrocarbon part in the UV-curable epoxy hybrimer.⁸ Finally, the UV-curable epoxy hybrimer was fabricated by photo-cationic polymerization of the formulated CAEO/oxetane blend under UV irradiation.

Onium salts for photo-cationic polymerization of epoxide are photolyzed by UV, and produce free radicals as a by-product as well as cations for the polymerization reaction.¹¹ Through thermal oxidative degradation reactions between the free radicals and oxygen in air (Fig. 1), the hydrocarbon polymer (RH) becomes yellowish.⁸ To remove discoloration of the hydrocarbon part in the UV-curable epoxy hybrimer, it is necessary to suppress the oxidative degradation reaction arising from the onium salts. In general, primary antioxidants inhibit the chain propagation reaction between peroxy radicals (RO_2^*) and RH according to the following equation.⁸



Scheme 1 Fabrication of the thermally resistant UV-curable epoxy-siloxane hybrid materials (epoxy hybrimer).

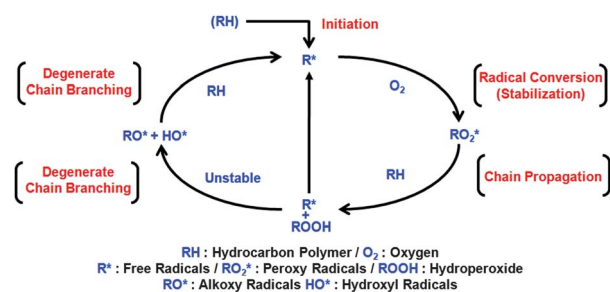
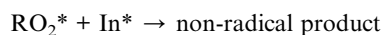


Fig. 1 General oxidative degradation reactions of the hydrocarbon polymer.



where InH is the primary antioxidant, and acts as a hydrogen donor to RO_2^* .

Also, secondary antioxidants suppress the spontaneous decomposition reaction of the hydroperoxide ($ROOH$) (degenerate chain branching) according to the following equation.



where HD is the secondary antioxidant, and decomposes unstable $ROOH$ to stable ROH .⁸

Thus, we applied primary and secondary antioxidants to the UV-curable epoxy hybrimer for inhibition of the oxidative degradation reactions of the hydrocarbon part in the UV-curable epoxy hybrimer originating from heat.

Fig. 2 shows the optimization results of the primary and secondary antioxidant content in the UV-curable epoxy hybrid materials using the yellowness index change (ΔYI). ΔYI of the UV-curable epoxy hybrid materials with the primary antioxidant before/after thermal aging at 180 °C for 144 hours in air was minimized at 1.2–1.5 wt% primary antioxidant content in the UV-curable epoxy hybrid materials. When the UV-curable epoxy hybrid materials incorporated a primary antioxidant of 1.35 wt%, ΔYI was minimized at 3.6 wt% secondary antioxidant content before/after thermal aging at 180 °C for 72 hours in air. The minimized ΔYI indicates that the antioxidants effectively suppress the oxidative degradation reaction of the hydrocarbon part in the UV-curable epoxy hybrimer. However, ΔYI of the UV-curable epoxy hybrid materials increases with the antioxidant content exceeding the optimized content. This is due to self-oxidative

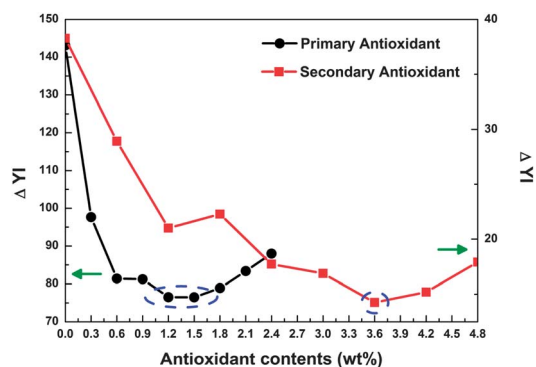


Fig. 2 Optimization of primary and secondary antioxidant contents in the UV-curable epoxy hybrid materials.

degradation of the antioxidants.⁸ Fig. 3(a) and (b) exhibit optical transmittances and photographs of the UV-curable epoxy hybridizers before/after thermal aging at 120 °C for 1008 hours in air. As shown in Fig. 3(a), the UV-curable epoxy hybridizer has an initial optical transmittance of 88.6% at a wavelength of 450 nm before thermal aging. The optical transmittance of the UV-curable epoxy hybridizer without antioxidants decreases by as much as 54.3% after thermal aging. However, in the case of the UV-curable epoxy hybridizer with the optimized primary antioxidant, the optical transmittance increases up to 77.6%. The UV-curable epoxy hybridizer with appropriate primary and secondary antioxidants has a high optical transparency of 87.8% after thermal aging. Also, discoloration improvement of the UV-curable epoxy hybridizers is clearly seen in the photographs of Fig. 3(b). The results in Fig. 3(a) and (b) indicate that the antioxidants are effective in terms of removing yellowing of the UV-curable epoxy hybridizer, which arises from oxidative degradation reactions of the hydrocarbon parts in the UV-curable epoxy hybridizer. Also, the suppression effect of oxidative degradation reactions by primary and secondary antioxidants could be monitored by carbonyl groups, in addition to yellowing of the UV-curable epoxy hybridizers (Fig. 4). Unstable ROOH spontaneously decomposed into two species: an alkoxy radical (RO*) and a hydroxyl radical (HO*). It is well known that alkyl radicals (R*) and carbonyl compounds can be formed by RO*.^{12,13} In the FT-IR results of Fig. 4, the intensity of the carbonyl groups of the UV-curable epoxy hybridizer is effectively reduced by the addition of the antioxidants after thermal aging. The low

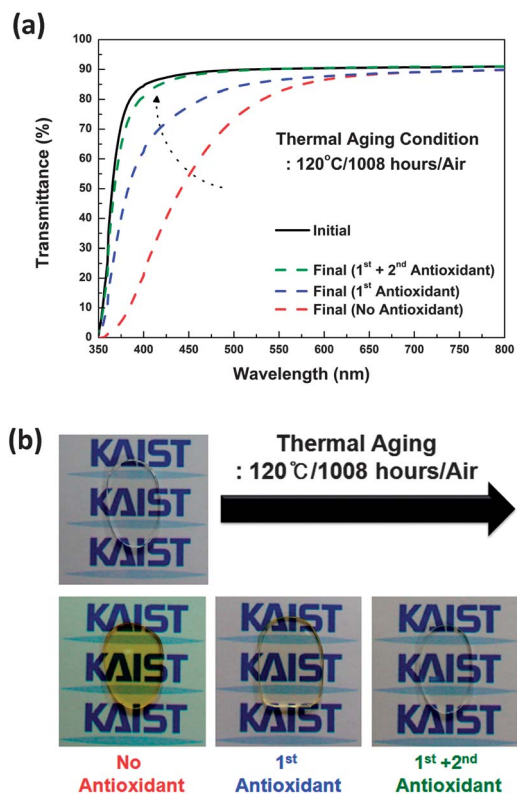


Fig. 3 (a) Optical transparency improvement of UV-curable epoxy hybridizers by antioxidants and (b) photographs of UV-curable epoxy hybridizers with/without antioxidants.

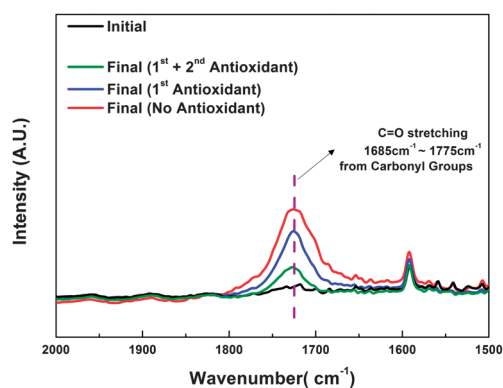


Fig. 4 FT-IR spectra of UV-curable epoxy hybridizers before/after thermal aging at 120 °C for 1008 hours in air according to the inclusion of the antioxidant.

intensity of the carbonyl groups in the UV-curable epoxy hybridizer with primary and secondary antioxidants indicates suppression of the oxidative degradation reaction generated from oxygen in the air and free radicals formed by onium salts.

We compared the thermal resistance of the UV-curable epoxy hybridizer with that of thermally curable silicone (OE-6630), which is used as a commercial LED encapsulant, and UV-curable cyclo-aliphatic epoxide (ECC), which has the same formulation as the UV-curable epoxy hybridizer (Fig. 5(a)). In Fig. 5(a), the UV-curable epoxy hybridizer has an initial optical transmittance of 88.6% at a wavelength of 450 nm. After thermal aging at 120 °C for 1008 hours in air, the optical transparency of the UV-curable epoxy hybridizer is maintained at 87.8% transmittance at 450 nm. The optical transmittance of OE-6630 shows nearly no change before/after thermal aging at 120 °C for 1008 hours in air (89.6% → 87.7% at 450 nm). On the other hand, ECC shows degraded optical transparency against thermal aging due to the absence of siloxane bonds, which leads to high thermal resistance (86.3% → 44.3% at 450 nm). Also, the discoloration degree of the UV-curable epoxy hybridizer, OE-6630, and ECC before/after thermal aging is clearly seen in the photographs of Fig. 5(b). Thus, the UV-curable epoxy hybridizer has similar and higher thermal resistance against yellowing compared to OE-6630 and ECC, respectively. The high thermal resistance of the UV-curable epoxy hybridizer indicates that it can be used as a UV-curable LED encapsulant.

Thermo-physical properties, such as glass transition behavior and coefficient of thermal expansion (CTE), are important physical properties for practical applications as a LED encapsulant. A LED encapsulant should have weak glass transition behavior and a low CTE to reduce cracking of the LED encapsulant and delamination between the LED encapsulant and the LED, which consists of various components, such as gold wire, reflector cup, LED chip, *etc.*, by thermal stress originating from heat generated by the LED. In Table 1 and Fig. 6, the storage modulus of the UV-curable epoxy hybridizer above/below the glass transition temperature ($T_g = 85$ °C) is changed by only one order of magnitude. The weak glass transition behavior of the UV-curable epoxy hybridizer is attributed to its high cross-linking density owing to the multi-functional organic groups and short siloxane chains of CAEO.¹⁴ On the other hand, general silicone

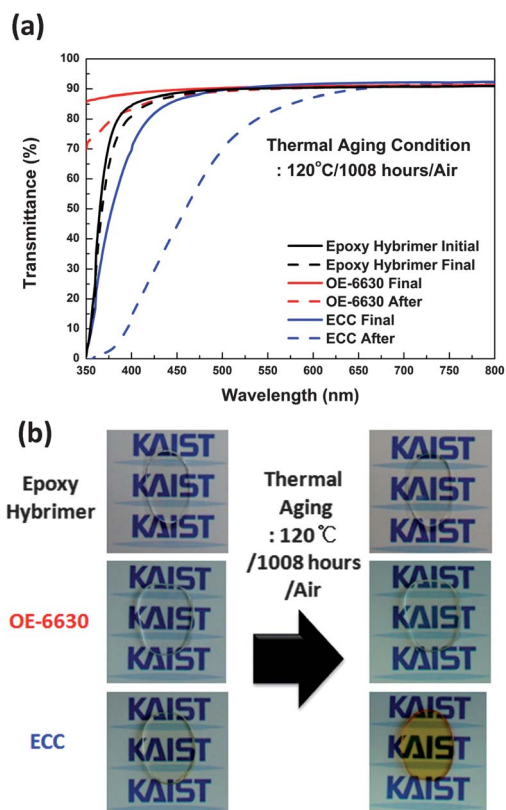


Fig. 5 Changes in optical transparency of UV-curable epoxy hybrimer, commercial thermally curable silicone LED encapsulant (OE-6630), and UV-curable cyclo-aliphatic epoxy LED encapsulant (ECC) before/after thermal aging at 120 °C for 1008 hours in air: (a) optical transmittance and (b) photographs.

Table 1 Characteristics of UV-curable epoxy hybrimers for LED encapsulation

Property	Unit	Value
E_g^a	MPa	3823.6
E_r^a	MPa	281.1
T_g^b	°C	85
CTE ^{αc}	ppm per °C	106.0
CTE ^{βc}	ppm per °C	196.1
Refractive index	—	1.540
Shore D hardness	—	80
O ₂ permeability	cm ³ mil m ⁻² day ^{-1 d}	2.95 × 10 ³
Water vapor permeability	g mil m ⁻² day ^{-1 d}	1.77 × 10 ²

^a E_g : storage modulus at glassy state (@ -50 °C), E_r : storage modulus at rubbery state (@ 200 °C). ^b T_g : glass transition temperature. ^c CTE^α: coefficient of thermal expansion between -50 °C and 0 °C, CTE^β: coefficient of thermal expansion between 150 °C and 200 °C. ^d 1 mil = 25.4 μm.

materials show a large storage modulus change of approximately two orders of magnitude, originating from the long siloxane chain.¹⁵ Also, the CTE^α and CTE^β of the UV-curable epoxy hybrimer are 106.0 ppm per °C and 196.1 ppm per °C, respectively. The small CTE change above/below T_g originates from the weak glass transition behavior by the highly cross-linked organic network. Also, the CTE^β of the UV-curable epoxy hybrimer is

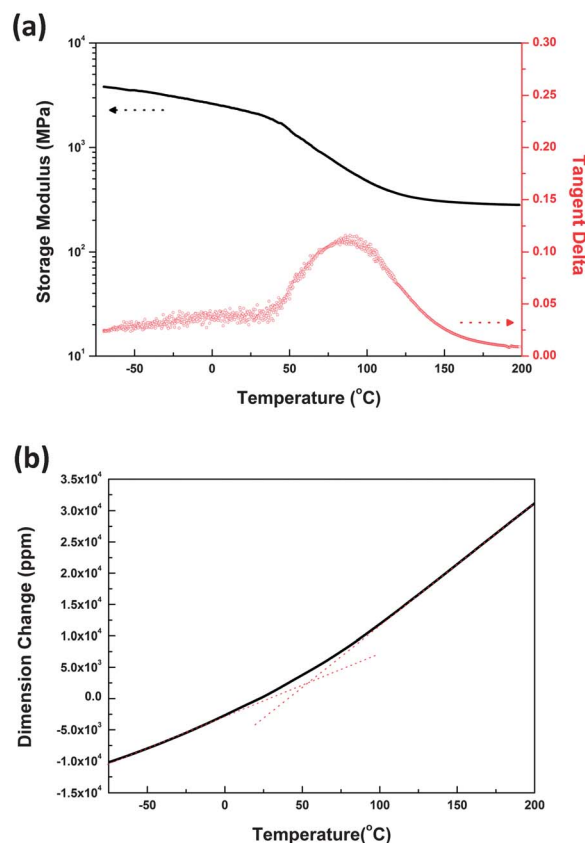


Fig. 6 Thermo-physical properties of UV-curable epoxy hybrimer: (a) DMA curve and (b) TMA curve.

lower than that of general silicone materials (>200 ppm per °C).¹⁶ The weaker glass transition behavior and lower CTE of the UV-curable epoxy hybrimer, compared to general silicone materials, are advantageous with respect to reduction of thermal stress between LED components and the LED encapsulant generated during operation of the LED with high junction temperature (~120 °C).^{3,4}

Besides high thermal resistance and excellent thermo-physical properties, the LED encapsulant must meet several requirements: a high refractive index for high luminescence efficiency, good gas barrier properties, and suitable hardness to protect the LED. As shown in Table 1, the UV-curable epoxy hybrimer has a similar refractive index of 1.54 compared to that of general

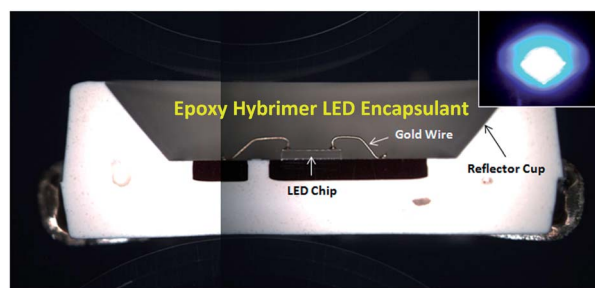


Fig. 7 Cross-section of the blue LED encapsulated by a UV-curable epoxy hybrimer. Inset shows blue light emission of the encapsulated LED.

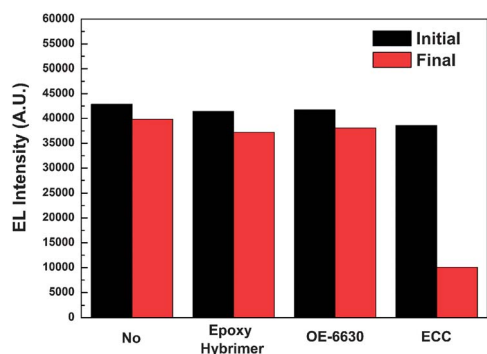


Fig. 8 Comparison of EL intensity change in the blue LED encapsulated by the UV-curable epoxy hybrimer, OE-6630, and ECC before/after thermal aging at 120 °C for 1008 hours in air.

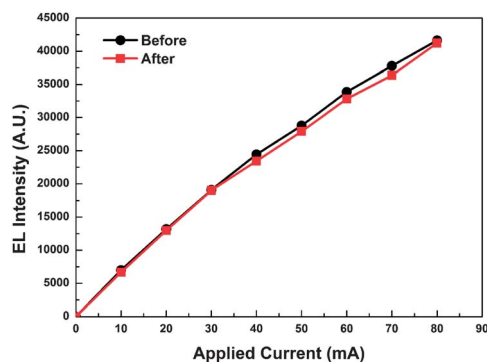


Fig. 9 EL intensity change of the blue LED encapsulated by the UV-curable epoxy hybrimer as a function of applied current before/after blue light aging for 24 hours.

silicone materials, which have a high refractive index of around 1.53–1.54.¹⁶ Also, the oxygen and water vapor permeabilities of the UV-curable epoxy hybrimer are $2.95 \times 10^3 \text{ cm}^3 \text{ mil m}^{-2} \text{ day}^{-1}$ and $1.77 \times 10^2 \text{ g mil m}^{-2} \text{ day}^{-1}$, respectively. These gas barrier properties are remarkably better than those of general silicone materials,¹⁷ and can facilitate protection of the LED from degradation by oxygen and water. In addition, the Shore D hardness of the UV-curable epoxy hybrimer is approximately 80, which indicates that the UV-curable epoxy hybrimer can sufficiently protect the LED devices from external shock.

The UV-curable epoxy hybrimer can be expected to be used as LED encapsulants, due to its suitable properties as LED encapsulants, such as high optical transparency, high thermal resistance, excellent thermo-physical properties, high refractive index, good gas barrier properties, and appropriate hardness. Nevertheless, a practical encapsulation test of the UV-curable epoxy hybrimer on a LED is required in order to confirm its applicability as a LED encapsulant. Accordingly, we encapsulated a blue LED with the UV-curable epoxy hybrimer.

LED encapsulation of thermally resistant UV-curable epoxy hybrimer

Fig. 7 presents a cross-sectional image of the blue LED encapsulated by the UV-curable epoxy hybrimer. Neither delamination between the UV-curable epoxy hybrimer and various

components of the blue LED nor cracking in the UV-curable epoxy hybrimer is observed. Therefore, the UV-curable epoxy hybrimer has a good adhesion property on various substrates of the LED, such as gold wire, reflector cup, LED chip, *etc.*, due to the hydroxyl groups generated by the epoxy ring opening after photo-cationic polymerization.⁷ The UV-curable epoxy hybrimer encapsulated blue LED has a flat surface without distortion from the designed flat shape, since UV-curing can minimize thermal shrinkage by heat treatment. Also, blue light after encapsulation is ordinarily emitted without damage of the LED by brønsted acid generated by the onium salt during photo-cationic polymerization of the CAEO/oxetane blend.¹¹

Comparison of the EL intensity change of a non-encapsulated blue LED and a blue LED encapsulated by UV-curable epoxy hybrimer, OE-6630, and ECC before/after thermal aging at 120 °C for 1008 hours in air is summarized in Fig. 8. Fig. S2 in the ESI† exhibits EL spectra before/after thermal aging.

First, the EL intensity of the non-encapsulated blue LED is slightly reduced after thermal aging. The decreased EL intensity indicates deterioration of the blue LED performance by heat. The EL intensity of the blue LED encapsulated by the UV-curable epoxy hybrimer does not change before/after thermal aging with the exception of a drop in EL intensity by degradation of the blue LED performance. A EL intensity change of the OE-6630 encapsulated blue LED is not shown, similar to the UV-curable epoxy hybrimer encapsulated LED, before/after thermal aging. However, the performance of the blue LED encapsulated by ECC is dramatically reduced, with decreased optical transparency before/after thermal aging.

Fig. 9 and S3 in the ESI† show the EL intensity change and practical EL spectra, respectively, of the blue LED encapsulated by the UV-curable epoxy hybrimer as a function of applied current before/after blue light aging for 24 hours in air. The EL intensity of the encapsulated LED linearly increases with an increment of applied current to the blue LED. The EL intensity of the encapsulated LED is maintained after blue light aging. The absence of degradation of EL intensity indicates that the UV-curable epoxy hybrimer offers resistance to yellowing without any change to the blue light, as well as to the heat generated during blue light emission from the blue LED.

Conclusions

A UV-curable epoxy hybrimer with high thermal resistance against yellowing was successfully fabricated by photo-cationic polymerization of a CAEO/oxetane blend with antioxidants. The UV-curable epoxy hybrimer showed similar and higher thermal resistance compared to commercial thermally curable silicone and UV-curable cyclo-aliphatic epoxy LED encapsulants, respectively. The UV-curable epoxy hybrimer successfully encapsulated a LED without any cracking, delamination, or performance degradation of LED, and maintained a flat surface on the LED without distortion of the designed flat shape by UV-curing. Before/after thermal and blue light aging, the performance of the LED encapsulated by the UV-curable epoxy hybrimer was maintained. On the basis of its excellent properties, the UV-curable epoxy hybrimer is expected to be utilized as a UV-curable LED encapsulant.

Acknowledgements

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