

UV-curable, Transparent, and Low Volume-shrinkage Silicones for Efficient Mini-LED Encapsulation

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Electronic Supplementary Information

Abstract Mini light-emitting diodes (Mini-LEDs) show great application potential in high-end displays owing to their superior pixel density, brightness, responsiveness, and efficiency. However, current packaging materials for Mini-LEDs are predominantly thermally cured, which is energy- and time-consuming and can adversely affect electronic components. In this study, a novel UV-curable silicone resin containing phenyl, disulfide, and acryloyl groups (SPASR) is developed from commercially available siloxanes. The resin exhibits a refractive index (n_d) higher than 1.5, and it can be cured within 30 s under UV irradiation. After curing, it exhibits an optical transparency exceeding 92%, a lap adhesion strength of up to 1.84 MPa, and good thermostability ($T_{5\%}>265\text{ }^\circ\text{C}$). Notably, the volume shrinkage is less than 4.83%, attributed to the release of photopolymerization stress via UV-induced disulfide metathesis during UV curing. Mini-LEDs encapsulated with this resin show luminescence properties comparable to those of conventional thermally-cured sealants, and show excellent sealability without visible penetration after being immersed in red ink for 12 h. Consequently, these excellent properties make the SPASR resin an ideal candidate for microelectronic encapsulation, offering a more reliable and efficient solution for the electronics industry.

Keywords UV-curing technology; Silicone resin; Mini-LEDs encapsulants; Low volume shrinkage; Disulfide metathesis

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INTRODUCTION

Mini light-emitting diodes (Mini-LEDs), as a next-generation display technology, are expected to be widely adopted in high-end displays owing to their wide color gamut, high brightness, long lifetime, low energy consumption, and lightweight.^[1–5] To ensure reliable operation and longevity, LEDs must be encapsulated, with epoxy resins and silicones being the most popular materials, as they directly influence the luminous efficiency and brightness.^[6–9] Epoxy resins, known for their robust mechanical properties, strong adhesion, and chemical resistance, are widely used for LEDs encapsulation.^[10–12] However, they suffer from aging, yellowing, and long thermal curing times, typically requiring several hours at 100–150 °C.^[13] Silicones, with their unique organic-inorganic hybrid structures, possess superior thermostability, aging resistance, electrical insulation, optical transparency, and hydrophobicity, and have been extensively used in the electronics industry.^[14–16] Nevertheless, they are also challenged by their low refractive index and lengthy thermal curing process.^[17,18] The refractive index can be enhanced by introducing high-refractive-index components, such as phenyl

groups and sulfur atoms, to meet the LED encapsulation requirements.^[8,19–21] For instance, a Si—S polymer integrating aromatic groups and sulfur atoms achieves a refractive index of about 1.665 at 546 nm, whereas its thermal curing process is time- and energy-consuming.^[22]

Currently, UV-curing technology enables the rapid transformation of liquid photosensitive resins into solid products, offering distinct advantages such as high speed, environmental friendliness, energy efficiency, and high precision.^[23–28] It has been widely applied in inks, coatings, adhesives, dental materials, photoresists, and 3D printing. UV-curable silicones combine the merits of the UV-curing technology with the inherent properties of silicones. To date, free-radical photopolymerization of acrylates, thiol-ene photoaddition reactions, and cationic photopolymerization of epoxies have been integrated with silicones for applications in biomedicines, coatings, microelectronic encapsulation, and optical devices.^[14,29,30]

Several UV-curable silicones have been developed for LED encapsulation. For example, surface-functionalized zirconia nanoparticles (ZrO₂, about 14 nm) are composited with UV-curable methacrylate-end-capped polydiphenylsiloxane as LED encapsulants to optimize the light extraction efficiency (LEE).^[31] The nanocomposites exhibit a tunable refractive in-

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dex (1.55–1.61), and 11.2% enhancement in LEE over commercial silicone OE-7662, and robust environmental stability with 94.1% LEE retention after sulfur vapor exposure for 4 h. However, these nanocomposites require a long curing time (30–40 min). Thiol-functionalized polyhedral oligomeric silsesquioxane (SH-POSS) is mixed with a UV-curable silicone elastomer (UVSE) as an encapsulant (SH-POSS/UVSE).^[32] After immersion in boiling red ink for 2 h, the encapsulated LEDs exhibit no cracks or stains, indicating good adhesion and encapsulation. However, optical transmittance, refractive index, and aging resistance have not been reported. A thiol-functionalized silicone resin containing methyl or phenyl is also used in a UV-curable elastomer for LED arrays, achieving over 90% transmittance in the 400–800 nm wavelength range, but the UV-curing process remains slow (3 min).^[33] Obviously, UV-curable silicones show promise for Mini-LED encapsulation, but their curing time, volume shrinkage, refractive index, and aging resistance require further improvement to meet high-performance demands.

Therefore, this study aims to develop a novel UV-curable silicone resin with a high refractive index and low curing shrinkage for Mini-LED encapsulation. For this purpose, bis(triethoxysilylpropyl) disulfide (Si75), which contains a disulfide bond, was selected because UV-induced disulfide metathesis can release photopolymerization stress and reduce volume shrinkage during UV-curing.^[34] Due to the ability of the phenyl groups to improve the refractive index and compatibility with other components,^[35,36] methylphenyldimethoxysilane (MPDMS) containing phenyl groups was chosen. 3-(Dimethoxymethylsilyl) propyl methacrylate (KH-571), containing a UV-curable acrylate group, was used for UV curing. Thus, this UV-curable silicone resin (SPASR) contained phenyl, disulfide, and acryloyl groups. By varying their relative content, the molecular structure can be tailored to regulate the photopolymerization efficiency, refractive index ($n_d > 1.5$), and volume shrinkage ($< 5\%$). Mini-LEDs encapsulated with this SPASR silicone resin retained over 80% of their maximum luminance after 360 h of “double 85” (85 °C/85% RH) hygrothermal aging. This UV-curable silicone offers significant energy and time savings, demonstrating its feasibility as an encapsulant for electronics.

EXPERIMENTAL

Materials

Bis(triethoxysilylpropyl) disulfide (Si75), methylphenyldimethoxysilane (MPDMS), 3-[dimethoxy(methyl)silyl] propyl methacrylate (KH-571), and hexamethyldisiloxane (MM) were provided by Guangzhou Double Peach Fine Chemical Co., Ltd. Ethanol and HCl (36 wt%) were provided by Guangzhou Chemical Reagent Factory. The photoinitiator 2-hydroxy-2-methyl-phenyl-propane-1-one (photoinitiator Darocur 1173) was provided by Shanghai CUREASE CHEMICAL Co., Ltd. All chemicals were used as received without further purification. The AB adhesive was provided by Shenzhen Xinlun Co., Ltd.

Synthesis of UV-curable SPASR Silicone Resins

SPASR silicone resins were synthesized *via* hydrolysis–polycondensation of Si75, MPDMS, KH-571, and MM, as illustrated in Fig. 1(a). First, KH-571, MPDMS, MM, HCl, and H₂O were added to a four-necked flask equipped with a mechanical stirrer, ther-

mometer, condenser pipe, and dropping funnel, respectively. After reacting at 60 °C for 1 h, Si75 was gradually added, and the mixture was maintained at 45 °C for 3 h. The resin phase was separated, washed with 75 wt% ethanol to neutral pH, and dried under vacuum (−0.1 MPa) at 50 °C for 30 min to yield transparent liquid resins. The resulting resins with varying disulfide contents were named SPASR-Si75_x-Ph_y-KH571_z, where *x*, *y*, and *z* are the molar fractions of Si75, phenyl (Ph) and KH571, respectively (Table S1 in the electronic supplementary information, ESI).

Preparation and Curing of SPASR Silicone Resins

Silicone resins were prepared by mixing SPASR resins with the photoinitiator 1173. The distance between the UV light and the resin was set at 9 cm. Upon exposure to 365 nm UV light at an intensity of 40 mW·cm^{−2} for 15 s, the silicone resins transformed from liquid to solid (Fig. 1b).

Characterization

The nuclear magnetic resonance (¹H-NMR) spectra of the SPASR silicone resins were recorded on a Bruker AVANCE III HD 400 MHz NMR spectrometer using CDCl₃ as the solvent. The methacryloxy, phenyl, and disulfide group contents (mmol·g^{−1}) were determined by ¹H-NMR using 1,4-dioxane as the internal standard and calculated according to Eq. (1).

$$\text{Content} = \frac{\frac{A}{x} \times W_i}{\frac{B}{8} \times W_s \times 88} \times 1000 \quad (1)$$

where *A* is the peak area of the double bond, phenyl group, or methylene group (−CH₂−) adjacent to the disulfide bond, *x* is the number of protons in the corresponding functional group, *B* is the peak area of −CH₂− of 1,4-dioxane, *W_i* and *W_s* are the masses of 1,4-dioxane and the sample, respectively, 8 is the number of protons in 1,4-dioxane, and 88 is its molecular weight, g·mol^{−1}.

Raman spectra were recorded on a Micro Confocal Raman spectrometer (LabRAM HR Evolution, HORIBA Jobin Yvon) equipped with a 785 nm laser. Fourier transform infrared spectroscopy (FTIR) was performed using an IS-50 Nicolet FTIR spectrometer. The samples were coated on a KBr disc and scanned 32 times at a resolution of 4 cm^{−1} over 400–4000 cm^{−1}. Photopolymerization conversion was determined by real-time infrared spectroscopy (RT-IR). Each spectrum was an average of four scans with a resolution of 8 cm^{−1}, and the irradiation intensity at 365 nm was measured by UV-A Radiometer (Photoelectric Instrument Factory of Beijing Normal University). The conversion (*C*, %) was calculated from the peak area ratio of acrylates at 1640 cm^{−1} to Si−CH₃ at 1257 cm^{−1} according to Eq. (2).

$$C = 1 - \frac{(A_{1640}/A_{1257})_t}{(A_{1640}/A_{1257})_0} \times 100\% \quad (2)$$

where $(A_{1640}/A_{1257})_0$ and $(A_{1640}/A_{1257})_t$ are the peak area ratios before and after UV curing, respectively.

Photorheological analyses were performed by a HAAKE MARS 60 rheometer (Thermo Fisher) equipped with a specially designed quartz-contained parallel plate. UV irradiation was supplied by UVEC III-4 UV light and guided into the rheometer chamber *via* a flexible light guide. The liquid silicone resins were sandwiched between two plates at a fixed

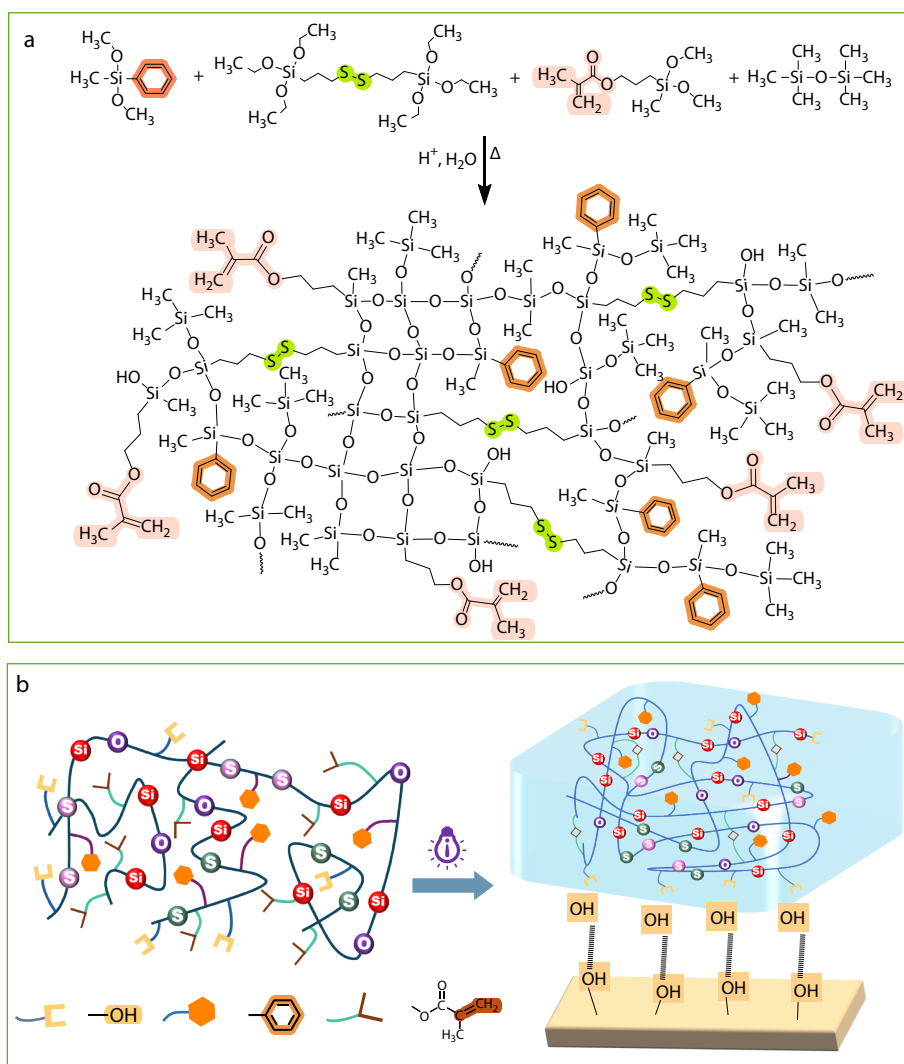


Fig. 1 (a) Synthesis route of SPASR silicone resins; (b) The crosslinking mechanism of UV-curable SPASR silicone resins.

gap of 0.2 mm, under a controlled stress mode with an oscillation frequency of 1 Hz. The normal force $|F_n|$ was set to 0 N. Samples were exposed to UV irradiation for 200 s. Volume shrinkage ratio (ξ , %) was calculated from the change in the plate distance during polymerization according to Eq. (3).

$$\xi = \frac{H_0 - H_t}{H_0} \times 100\% \quad (3)$$

where H_0 and H_t are the thicknesses of the silicone resin before and after UV curing, respectively.

The transmittance of the UV-curable SPASR silicone resins was recorded on a UV-visible spectrophotometer from 400 nm to 800 nm (UV2450, Shimadzu, Japan) with a sample thickness of 120 μm . Dynamic mechanical analysis (DMA) was performed on Metravib DMA-50N with a dynamic displacement of 10^{-6} m and a frequency of 5 Hz, from -80°C to 300°C at $10^\circ\text{C}\cdot\text{min}^{-1}$. Thermogravimetric analysis (TGA) was performed on a Perkin Elmer TGA 4000 spectrometer from 30°C to 800°C at $10^\circ\text{C}\cdot\text{min}^{-1}$ under a $20\text{ mL}\cdot\text{min}^{-1}$ nitrogen flow. Adhesion strength was estimated using lap-shear testing. Liquid samples were coated onto clean glass, aluminum, or iron plates ($75\text{ mm} \times 25\text{ mm} \times 10\text{ mm}$) with an overlap area of 25

$\text{mm} \times 12.5\text{ mm}$ and a thickness of approximately 0.20 mm. The specimens were UV-cured under 365 nm UV light at room temperature and tested on an STD5000 universal tester at a speed of $10\text{ mm}\cdot\text{min}^{-1}$ according to Chinese standard GB/T 7124-2008. The shear strength is expressed as the average of the five samples. The fractured surfaces were observed by scanning electron microscopy (SEM, Hitachi S-4800) after spraying with gold. The water contact angle was measured using a CA-100 contact-angle meter. The thermal aging test was performed at 100°C for 168 h in a hot-air oven. Moisture tolerance was tested by immersing adhesive specimens in water at room temperature for 168 h. "Double 85" test (85°C and 85% RH) was carried out for 360 h in a KTH215B temperature and humidity chamber (Kefuna, Shenzhen, China). The UV-curable SPASR silicone resin was used to encapsulate the Mini-LED panel equipped with F10C-EA chips from BOE HC Semiteck Corporation. The electroluminescence spectra and CIE coordinates of the encapsulated Mini-LEDs were measured with a PR-745 SpectraScan Spectroradiometer (Photo Research, America), powered by a WY-305 high-precision current source at 50 μA . The dielectric loss and dielectric constant were measured on a KEYSIGHT E4980A precision LCR

meter from 20 Hz to 2 MHz.

RESULTS AND DISCUSSION

Characterization of SPASR Silicone Resins

The chemical structures of the SPASR silicone resins are analyzed by FTIR, Raman, and ^1H -NMR. The IR spectra (Fig. 2A) show broad absorption bands at 1723 and 1634 cm^{-1} , corresponding

to the stretching vibrations of $-\text{C}=\text{O}$ and $-\text{C}=\text{C}$ in methacryloxy groups, respectively. The band at 1592 cm^{-1} is the stretching vibration of the phenyl groups. The absorption band at 1000–1150 cm^{-1} is the stretching vibration of the $\text{Si}-\text{O}-\text{Si}$ skeleton. The bands at 736 and 700 cm^{-1} correspond to the bending vibrations of the phenyl groups.^[37] In Fig. 2(B), the band at 506 cm^{-1} corresponds to the $\text{S}-\text{S}$ bond, and the band at 620 cm^{-1} represents the $\text{C}-\text{S}$ bond.^[38,39] The band at 695

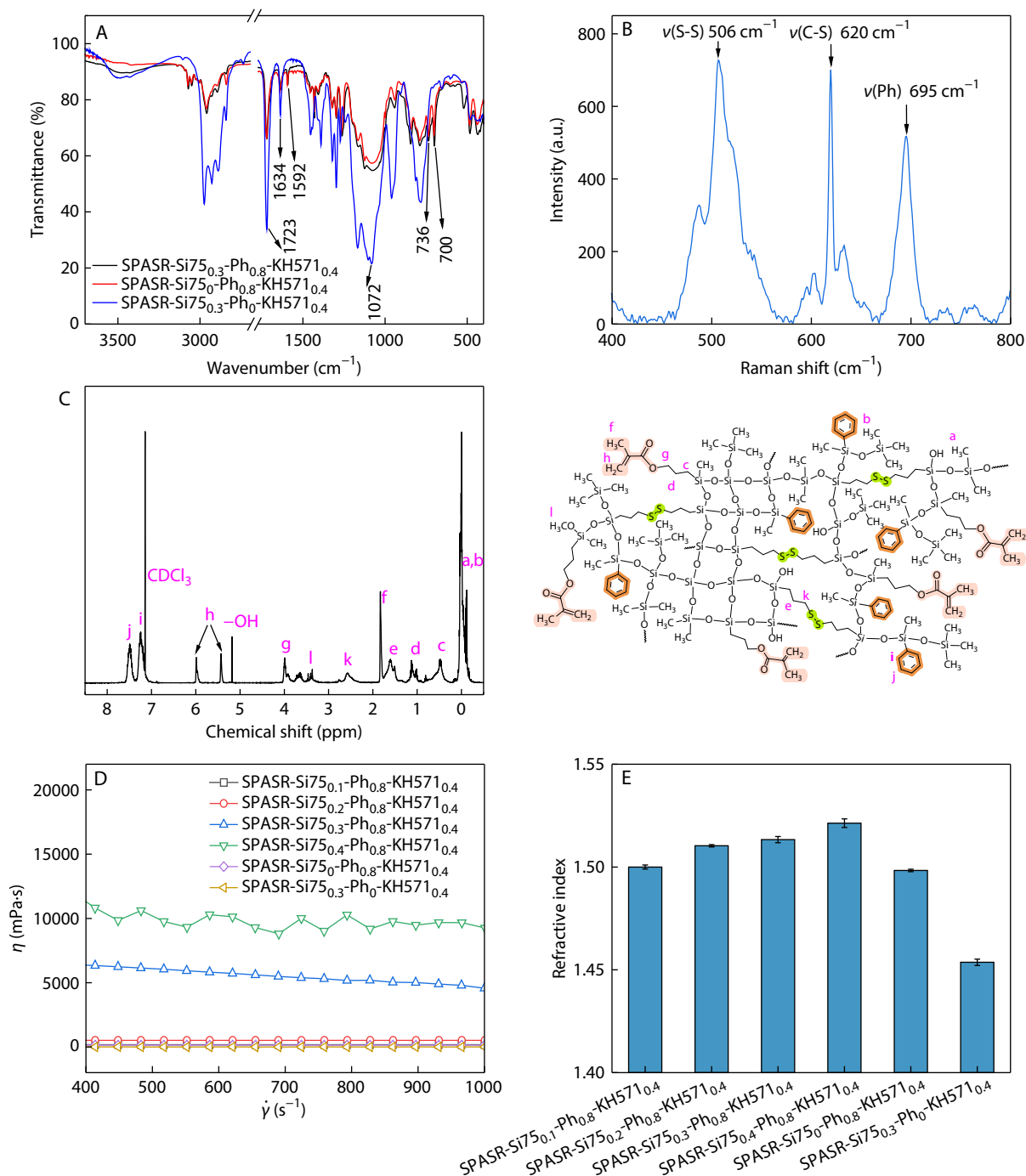


Fig. 2 (A) FTIR spectra of SPASR-Si75_{0.3}-Ph_{0.8}-KH571_{0.4}, SPASR-Si75₀-Ph_{0.8}-KH571_{0.4} and SPASR-Si75_{0.3}-Ph₀-KH571_{0.4}; (B) Raman spectrum of SPASR-Si75_{0.3}-Ph_{0.8}-KH571_{0.4}; (C) ^1H -NMR spectrum and chemical structure of SPASR-Si75_{0.3}-Ph_{0.8}-KH571_{0.4}; (D) Viscosity-shear rate curves of SPASR silicone resins; (E) The n_d of SPASR silicone resins.

cm^{-1} is associated with the benzene ring vibration.^[40] The ^1H -NMR spectrum (Fig. 2C) displays the following signals: 5.98 ppm (2H, s, $\delta\text{H}^{\text{h}}$, $-\text{C}=\text{CH}_2-$), 3.95 ppm (2H, s, $\delta\text{H}^{\text{g}}$, $-\text{CH}_2-$), 1.11 ppm (2H, s, $\delta\text{H}^{\text{d}}$, $-\text{CH}_2-$), 0.49 ppm (2H, s, $\delta\text{H}^{\text{c}}$, $-\text{CH}_2-$), 2.56 ppm (2H, s, $\delta\text{H}^{\text{k}}$, $-\text{CH}_2-$), 1.80 ppm (2H, s, $\delta\text{H}^{\text{e}}$, $-\text{CH}_2-$), 5.17 ppm (2H, s, $-\text{Si}-\text{OH}$), 0.03 ppm (3H, s, $-\text{CH}_3$), 7.24 ppm (2H, s, $\delta\text{H}^{\text{i}}$, $\text{Ar}-\text{H}$), 7.49 ppm (2H, s, $\delta\text{H}^{\text{j}}$, $\text{Ar}-\text{H}$). Fig. 2(D) shows that SPASR-Si75_{0.4}-Ph_{0.8}-KH571_{0.4} has the highest viscosity, which is attributed to the six hydrolyzable $\text{Si}-\text{O}-\text{R}$ groups in Si75 that can increase crosslinking. Thus, varying the Si75 content allows control over viscosity. Although a high phenyl content generally reduces the polymerization degree and thus the viscosity, SPASR-Si75_{0.3}-Ph₀-KH571_{0.4}, which lacks phenyl groups, exhibits a lower viscosity than SPASR-Si75₀-Ph_{0.8}-KH571_{0.4}. This result is attributed to the reduced steric hindrance and intermolecular friction in the absence of phenyl

groups because phenyl groups enhance intermolecular interactions.^[41] Fig. S1 (in ESI) indicates that higher methacryloxy and phenyl contents reduce the viscosity due to steric hindrance reducing the polymerization degree. Additionally, Fig. 2(E) shows that n_{d} of SPASR silicone resins exceeds 1.5, reaching up to 1.522, owing to the high content of phenyl groups and disulfide bonds.^[17,42]

UV-curing Kinetics of SPASR Silicone Resins

Fig. 3(a) shows that the acryloxy absorption band at 1640 cm^{-1} gradually decreases during photopolymerization, whereas the $\text{Si}-\text{CH}_3$ band at 1257 cm^{-1} remains unchanged. Thus, the conversion can be assessed based on the relative changes in the peak areas. The acryloxy band area decreases only slightly within the first 20 s, but drops markedly after 50 s, as disulfide bonds in SPASR silicone resins can scavenge partial free radicals and delay photopolymerization.^[43,44] Fig. 3(b) indicates that moder-

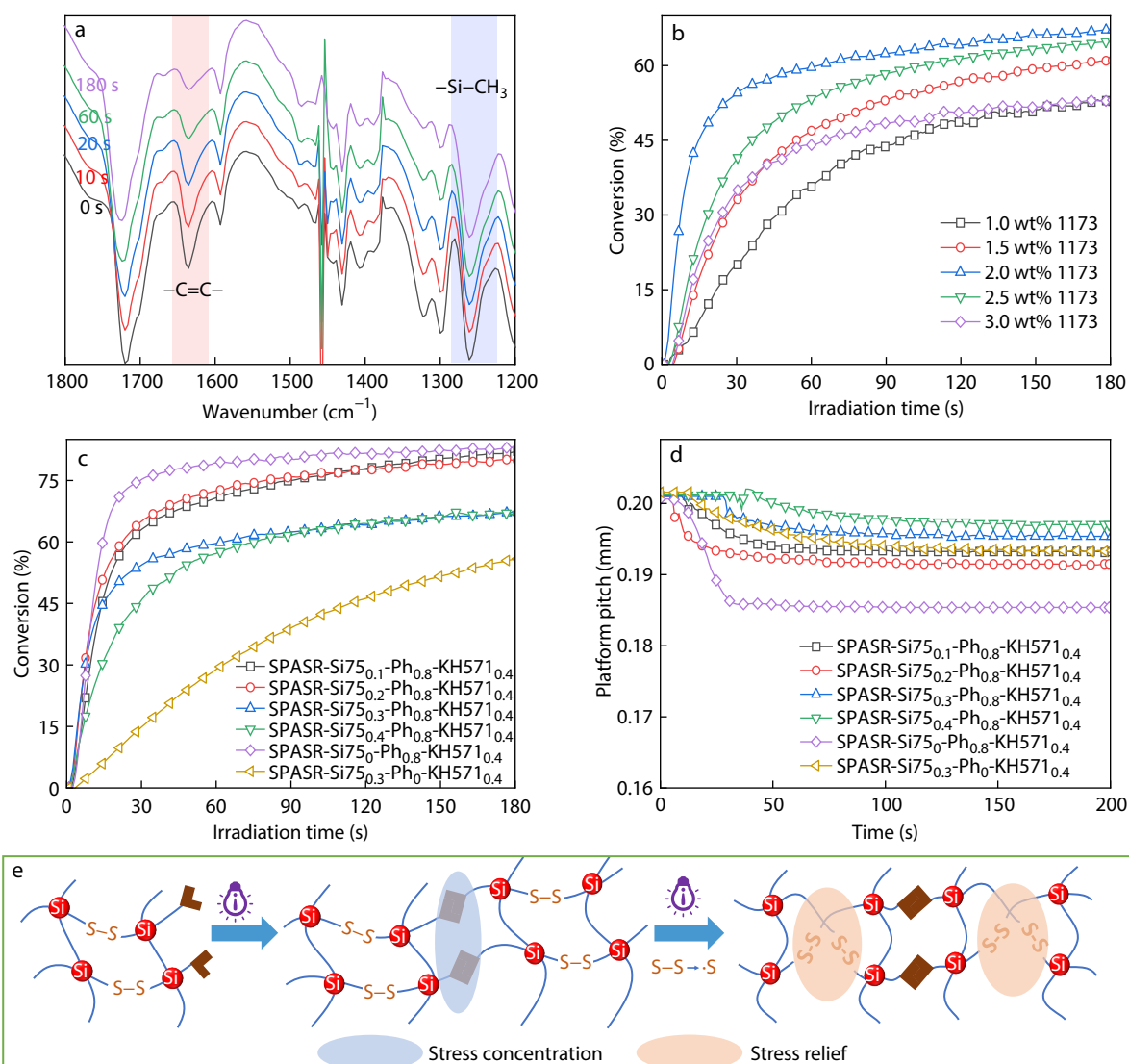


Fig. 3 (a) Infrared spectra of SPASR-Si75_{0.3}-Ph_{0.8}-KH571_{0.4} at different irradiation time. Methacryloxy conversions of (b) SPASR-Si75_{0.3}-Ph_{0.8}-KH571_{0.4} with different doses of Darocur 1173 under $30\text{ mW}\cdot\text{cm}^{-2}$ UV irradiation, and (c) different SPASR silicone resins with 2 wt% Darocur 1173 under $30\text{ mW}\cdot\text{cm}^{-2}$ UV irradiation; (d) Platform pitch of different SPASR silicone resins as a function of irradiation time in photo-rheological test; (e) Stress concentration and relief under UV irradiation.

ate photoinitiator concentrations improve conversion, since more initiators generate more active radicals and promote polymerization. However, excess initiator can lead to the cage effect, reducing the efficiency.^[21,45] The maximum conversion is approximately 68% with 2 wt% photoinitiator 1173. Fig. 3(c) shows significant differences among SPASR resins: SPASR-Si75_{0.1}-Ph_{0.8}-KH571_{0.4}, reaching 82% conversion, which is higher than the 67% conversion for SPASR-Si75_{0.4}-Ph_{0.8}-KH571_{0.4}, because high viscosity restricts the molecular mobility of the reactive groups.^[46] Fig. S2(a) (in ESI) indicates that the SPASR resins with similar viscosities exhibit similar conversions. However, Fig. S2(b) (in ESI) reveals that a higher KH571 content leads to lower conversion even at similar viscosities, likely because overly rapid polymerization restricts radical mobility.^[47] Furthermore, a higher Si75 content increases the chain entanglement and reduces the conversion. The control sample without disulfide bonds (SPASR-Si75₀-Ph_{0.8}-KH571_{0.4}) cures quickly, while SPASR-Si75_{0.3}-Ph₀-KH571_{0.4} remains incompletely cured after 180 s. Figs. 3(d) and 3(e) reveal that Si75 reduces volume shrinkage. The SPASR resins shrink by only 2.06%–4.83% (Fig. S3, in ESI), compared to 7.98% for SPASR-Si75₀-Ph_{0.8}-KH571_{0.4}, because under UV irradiation, dynamic disulfide metathesis that can simultaneously break and recombine is activated, which can rearrange the crosslinked network and thus release polymerization stress.^[38,48,49]

Physical Properties and Adhesive Performance of UV-curable SPASR Silicone Resins

Fig. 4(a) indicates that all UV-curable SPASR resins show transmittance over 92% in the visible region (400–800 nm), indicating excellent optical transparency for potential applications in optical devices. Fig. 4(b) demonstrates their high thermal stability owing to the high bond energy of Si–O bonds and the inherent heat resistance of the phenyl groups.^[50] The 5 wt% weight-loss temperature ($T_{5\%}$) exceeds 250 °C, with major weight loss occurring at 300–500 °C due to the decomposition of organic components.^[51] In contrast, SPASR-Si75₀-Ph_{0.8}-KH571_{0.4} and SPASR-Si75_{0.3}-Ph₀-KH571_{0.4} show inferior thermal stability owing to the lack of crosslinked network structure formed from Si75 and the absence of phenyl groups, respectively. The storage modulus (E' , Fig. 4c) and glass transition temperature (T_g , Fig. 4d) also increase with higher conversion. SPASR-Si75_{0.2}-Ph_{0.8}-KH571_{0.4} achieves the highest E' (about 634 MPa) and T_g (about 69 °C), reflecting an optimized crosslinking density.

Furthermore, the adhesion performance of UV-curable SPASR silicone resins is evaluated by lap-shear tests on different substrates, including glass/glass, glass/Al, glass/Fe, and transparent plastics (PVC, PMMA, and PS). Fig. 5(a) demonstrates that a higher Si75 content generally reduces shear strength, as lower viscosity promotes radical migration and improves polymerization efficiency (Fig. 3c), thereby enhanc-

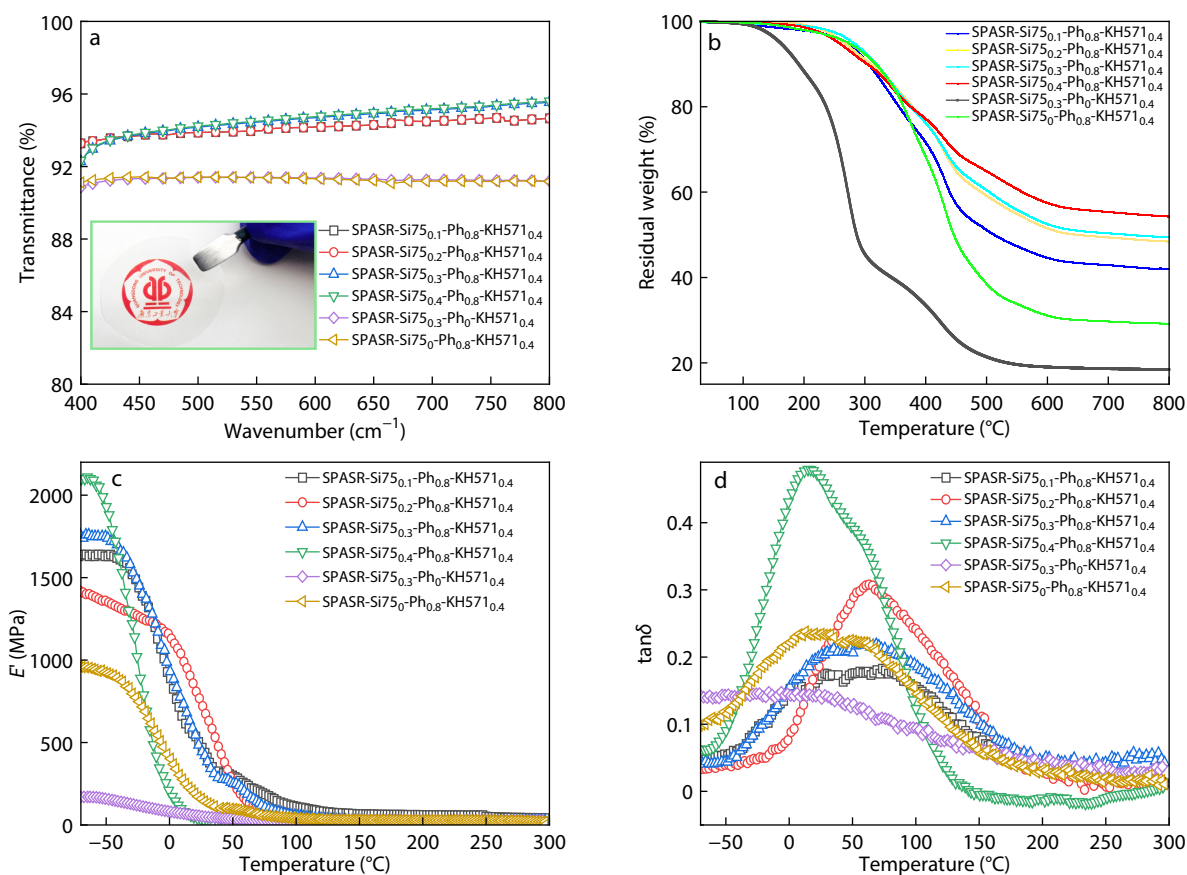
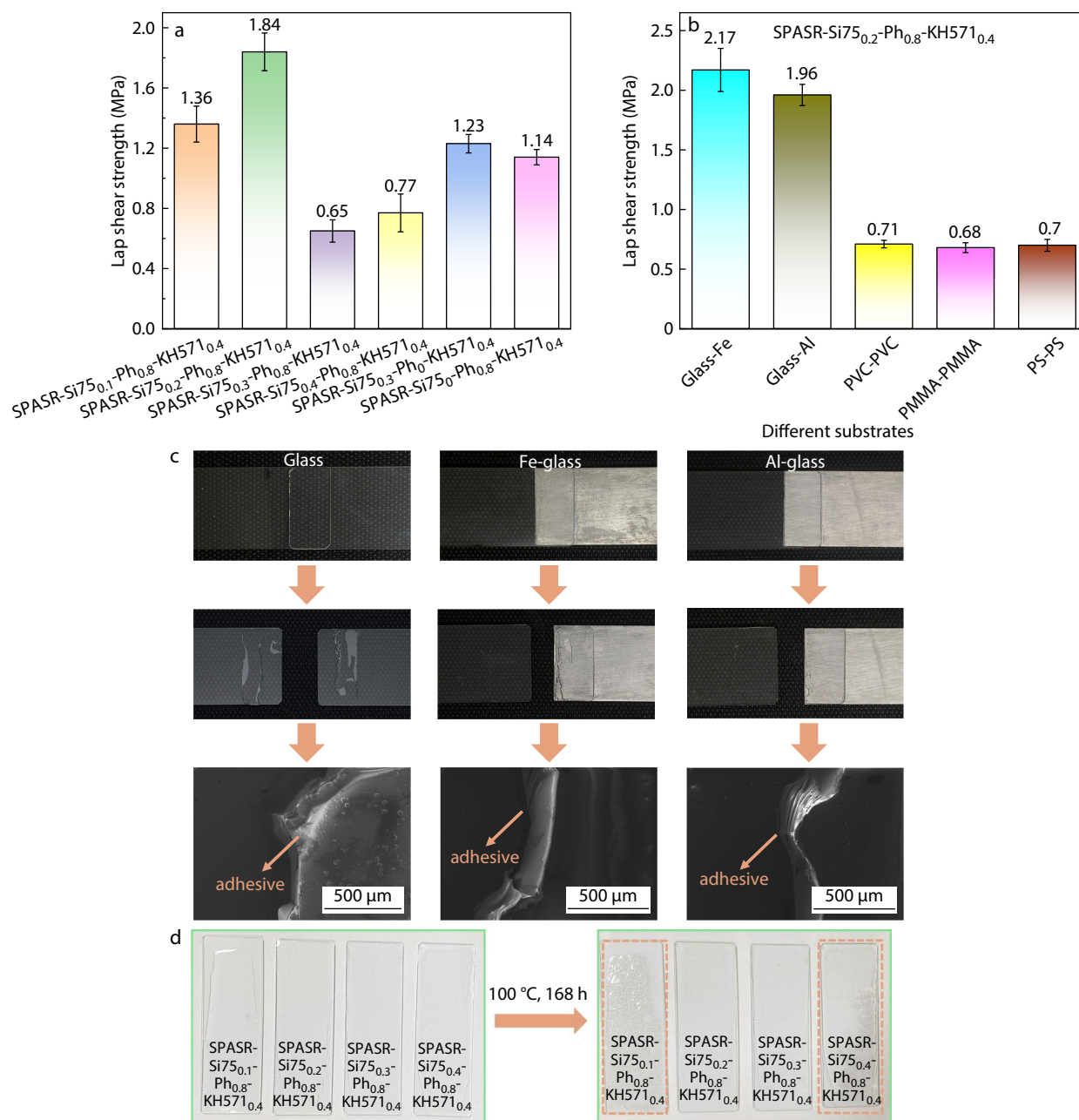


Fig. 4 (a) UV-visible curves between 400–800 nm; (b) Thermogravimetric curves; (c) Storage modulus and (d) $\tan\delta$ curves of UV-curable SPASR silicone resins.

ing the cohesive strength. By controlling the Si75 content, viscosity can be optimized to achieve good wetting and cohesive strength.^[52] Owing to its favorable mechanical strength (Fig. S4, in ESI), SPASR-Si75_{0.2}-Ph_{0.8}-KH571_{0.4} exhibits the best adhesion performance, with a maximum shear strength of 1.84 MPa on glass. Fig. 5(b) also reveals that this resin also bonds well to other substrates, achieving 2.17 MPa for glass-Fe and 1.96 MPa for glass-Al. Macroscopic analysis indicates that the failure is primarily caused by interfacial disruption (Fig. 5c). The resin also adheres to transparent plastics (PVC, PMMA, and PS) with an adhesion strength of approximately 0.7 MPa. The fractured surface morphology suggests a brittle fracture under shear stress.

Aging can severely degrade adhesive properties, mechanical strength, and transparency.^[53,54] The anti-aging effect

of SPASR silicone resins with different Si75 contents is conducted at 100 °C for 168 h. Fig. 5(d) clearly reveals that SPASR-Si75_{0.1}-Ph_{0.8}-KH571_{0.4} and SPASR-Si75_{0.4}-Ph_{0.8}-KH571_{0.4} debond and fragment owing to insufficient disulfide content or low T_g , whereas SPASR-Si75_{0.2}-Ph_{0.8}-KH571_{0.4} and SPASR-Si75_{0.3}-Ph_{0.8}-KH571_{0.4} remain intact. To further assess the resistance to UV irradiation and high temperature, thermal aging at 100 °C and UV aging at 25 °C are conducted. Fig. 5(e) shows that after 168 h of UV aging, SPASR-Si75_{0.2}-Ph_{0.8}-KH571_{0.4} still retains a shear strength of 1.49 MPa with a color difference value of 1.74. In contrast, the lap shear strength drops to 1.05 MPa after 168 h at 100 °C with a color difference value of 1.05. The greater decline under thermal aging is attributed to the degradation of the methacryloxy group, thereby reducing the cohesive strength of SPASR.^[55]



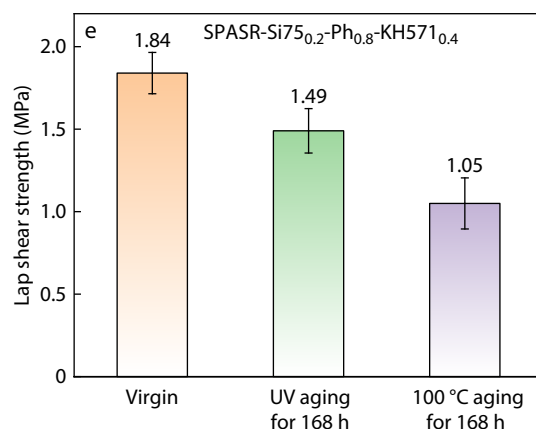
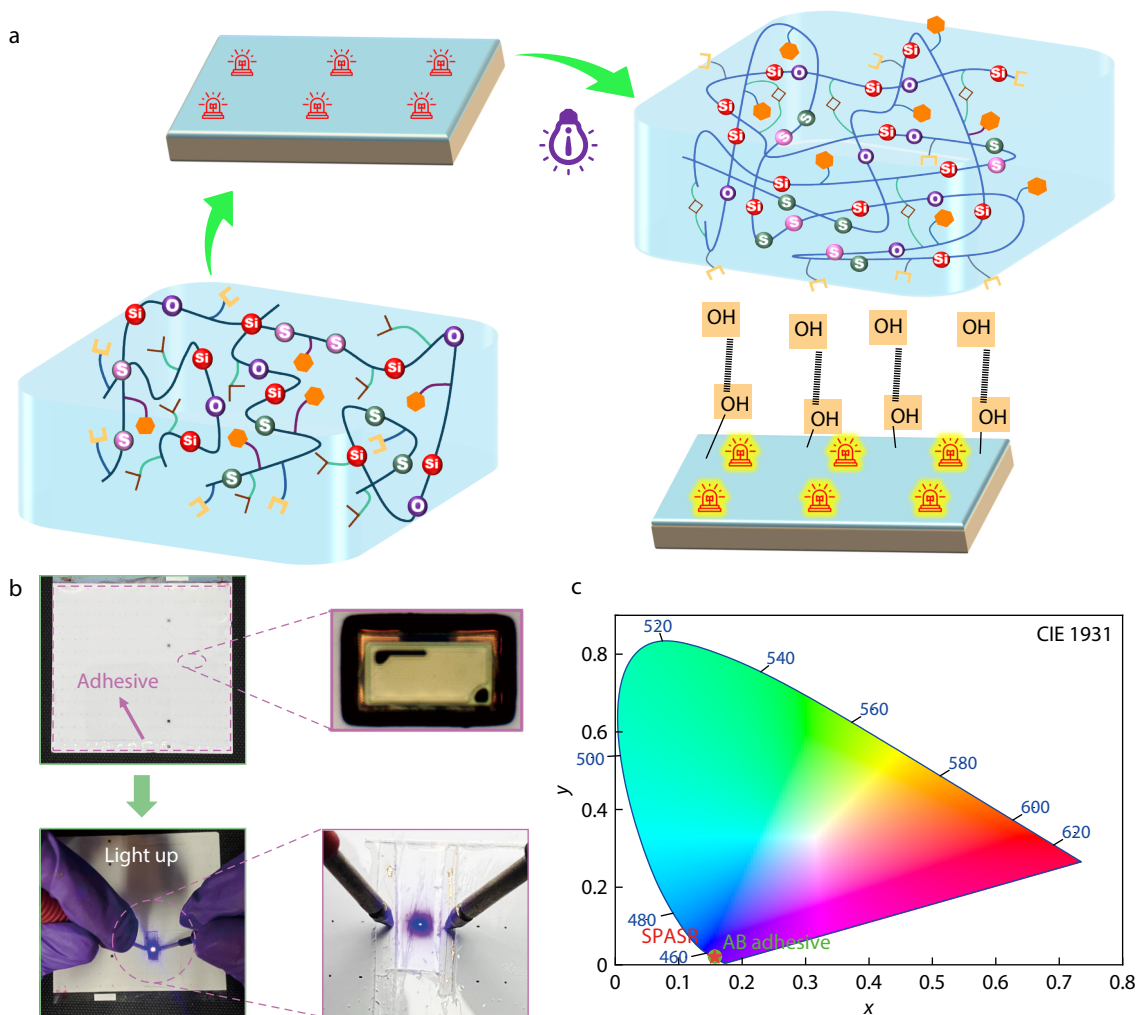


Fig. 5 Lap shear strength of (a) SPASR silicone resins on glass; (b) SPASR-Si75_{0.2}-Ph_{0.8}-KH571_{0.4} on other substrates; (c) Images showing the bonding and debonding of UV-curable SPASR-Si75_{0.2}-Ph_{0.8}-KH571_{0.4} for glass-glass, glass-Al, and glass-Fe, and SEM images of resins after debonding; (d) Photographs showing the SPASR silicone resins before and after thermal aging at 100 °C for 168 h; (e) Lap shear strength of SPASR-Si75_{0.2}-Ph_{0.8}-KH571_{0.4} for UV aging and thermal aging (100 °C) for 168 h.

Mini-LEDs Encapsulation and Aging Resistance of SPASR Silicone Resins

To explore their encapsulation feasibility, SPASR-Si75_{0.2}-Ph_{0.8}-KH571_{0.4} is coated on a Mini-LED panel and rapidly cured under

UV irradiation (Fig. 6a). Luminance and electroluminescence spectra are used to determine light output and chromaticity. A commercially available AB adhesive cured at 150 °C for 1 h is used as the positive control. Fig. 6(b) shows that the encapsulat-



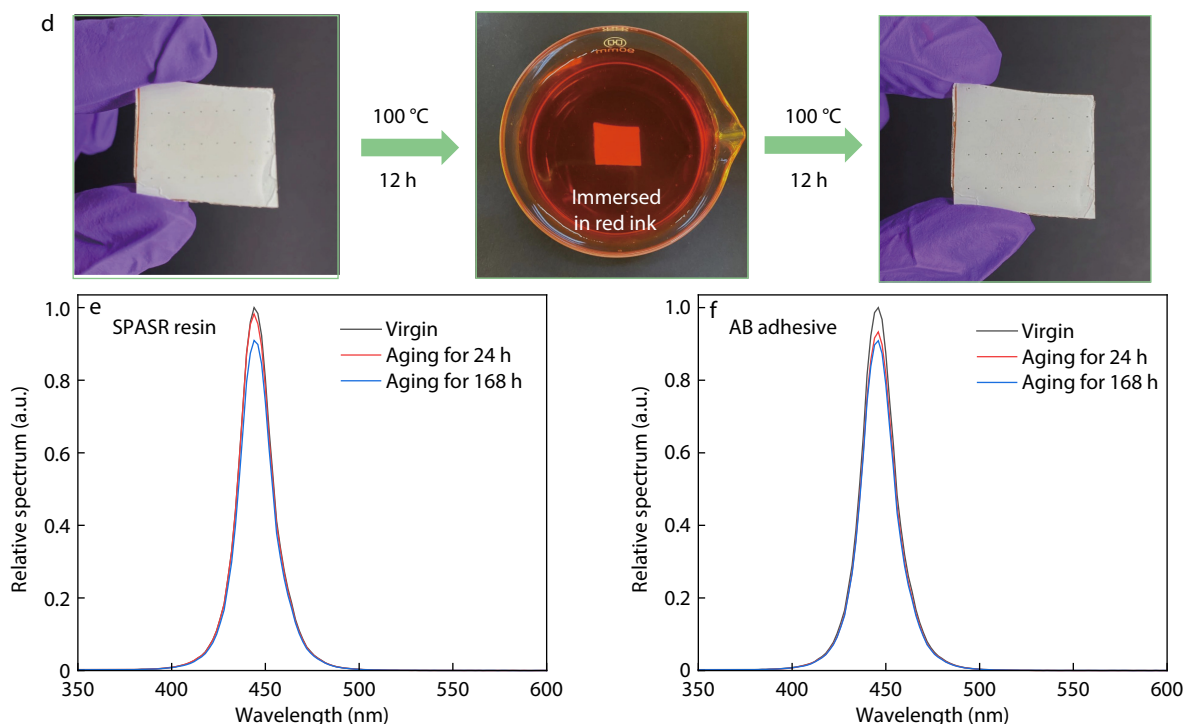


Fig. 6 (a) Underlying bonding mechanism of SPASR silicone resins; (b) Photographs of Mini-LEDs encapsulated with SPASR-Si75_{0.2}-Ph_{0.8}-KH571_{0.4}; (c) Chromaticity diagram of Mini-LEDs encapsulated with SPASR silicone resin and AB adhesive; (d) Photographs showing the sealing capacity of Mini-LEDs by this silicone resin; The normalized electroluminescence spectra of virgin, aged Mini-LEDs after different “double 85” test time: (e) SPASR-Si75_{0.2}-Ph_{0.8}-KH571_{0.4}, and (f) commercially available thermally cured AB adhesive.

ed Mini-LEDs function normally. The CIE coordinates of virgin (0.1561, 0.0202), SPASR-encapsulated (0.1570, 0.0195), and AB-encapsulated (0.1572, 0.0208) Mini-LEDs are similar (Fig. 6c), indicating that the SPASR resin has a minimal impact on color temperature and is suitable for Mini-LED encapsulation. Fig. 6(d) shows that after thermal aging at 100 °C for 12 h and immersion in red ink for 12 h, the encapsulated Mini-LEDs show no ink permeation. Furthermore, hydrothermal aging is performed on both SPASR and AB adhesives. Figs. 6(e) and 6(f) and Table S2 (in ESI) indicate that the electroluminescence spectra of both encapsulants degrade to different extents under “double 85” conditions. After 168 h, the SPASR-encapsulated Mini-LEDs retain 91% of their luminance with a maximum wavelength ($\lambda_{\max}$) of approximately 444 nm, whereas the AB adhesive-encapsulated devices retain 90% of their luminance with a $\lambda_{\max}$ of approximately 446 nm. The outstanding aging resistance mainly depends on the low surface energy and excellent hydrophobicity of the polysiloxane (Fig. S5 in ESI), as well as the structural stability conferred by the high energy of the Si—O bond within the polysiloxane backbone. Compared to the AB adhesive, the SPASR resin not only enables rapid, energy-efficient UV curing, but also maintains a certain luminance after aging. In addition, SPASR-Si75_{0.2}-Ph_{0.8}-KH571_{0.4} exhibits a low dielectric constant (3.02 at 1 MHz, Fig. S6, in ESI), suggesting its potential for integrated circuit and chip applications. These results confirm that SPASR silicone resins possess excellent adhesion and sealing capabilities for Mini-LEDs, highlighting their substantial potential in the electronics industry.

Silicone exhibits excellent optical properties, and its easy modification enables the incorporation of various functional

groups. Consequently, SPASR silicone resins can be engineered with phenyl groups to enhance the refractive index, while dynamic disulfide bonds are simultaneously incorporated to release stress and reduce volume shrinkage during curing.^[56,57] Therefore, controlled chemical synthesis, tunable structures and properties, and efficient packaging engineering are required for the future application of advanced electronic encapsulants.

CONCLUSIONS

In this study, UV-curable, transparent, and low volume-shrinkage silicone resins (SPASR) are synthesized for Mini-LED encapsulation. The resins can be UV-cured within 30 s, and exhibit a high lap shear strength of 1.84 MPa on glass substrates. UV-curable silicone resins possess excellent optical transparency (> 92%), high refractive index (>1.5), and low volume shrinkage (about 4.83%), making them suitable for commercial Mini-LEDs with a wavelength range of 400–800 nm. Moreover, SPASR resins show superior thermal stability ($T_{5\%}>265$ °C) and excellent encapsulation properties for Mini-LEDs. Notably, encapsulated Mini-LEDs retains approximately 91% of their luminance after 168 h of hydrothermal aging. These properties underscore the significant potential of this UV-curable transparent silicone resin for Mini-LED encapsulation and other optical fields.

Conflict of Interests

The authors declare no interest conflict.

Electronic Supplementary Information

Electronic supplementary information (ESI) is available free of charge in the online version of this article at <http://doi.org/10.1007/s10118-025-3506-4>.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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REFERENCES

- Chen, Z. Y.; Sheng, B. W.; Liu, F.; Liu, S. F.; Li, D.; Yuan, Z. X.; Wang, T.; Rong, X.; Huang, J. S.; Qiu, J. Y.; Liang, W. J.; Zhao, C. L.; Yan, L.; Hu, J.; Guo, S. P.; Ge, W. K.; Shen, B.; Wang, X. Q. High-efficiency InGaN red mini-LEDs on sapphire toward full-color nitride displays: effect of strain modulation. *Adv. Funct. Mater.* **2023**, *33*, 2300042.
- Huang, Y. G.; Hsiang, E. L.; Deng, M. Y.; Wu, S. T. Mini-LED, Micro-LED and OLED displays: present status and future perspectives. *Light Sci. Appl.* **2020**, *9*, 105.
- Wang, Y. J.; Tang, W. Y.; Zhang, C.; Molokeev, M. S.; Ming, H.; Zhou, Y. Y.; Peng, S.; Song, E. H.; Zhang, Q. Y. Structure-based machine learning enables discovery of Mn⁴⁺-activated red-light fluorides for ultrawide-gamut mini-light-emitting diodes. *Adv. Funct. Mater.* **2024**, *34*, 2313490.
- He, K.; Chen, D. J.; Yuan, L. F.; Xu, J. M.; Xu, K. Y.; Hu, J.; Liang, S. S.; Zhu, H. M. Crystallization engineering in PVDF enables ultrastable and highly efficient CsPbBr₃ quantum dots film for wide color gamut Mini-LED backlight. *Chem. Eng. J.* **2024**, *480*, 148066.
- Lee, H. E.; Shin, J. H.; Park, J. H.; Hong, S. K.; Park, S. H.; Lee, S. H.; Lee, J. H.; Kang, I. S.; Lee, K. J. Micro light-emitting diodes for display and flexible biomedical applications. *Adv. Funct. Mater.* **2019**, *29*, 1808075.
- Deng, Z. T.; Wang, M. L.; Zhu, C. Z.; Li, C. H.; Liu, J. H.; Tu, M. L.; Xie, L.; Gui, D. Y. Study on light aging of anhydride-cured epoxy resin used for RGB LED packaging material. *Polym. Test.* **2019**, *80*, 106131.
- Gao, H.; Wang, M. M.; Mao, Y. F.; Zhao, Q. S.; Zhang, C.; Jin, L.; Xia, Y. Y.; Li, W. J.; Zhang, K.; Zeng, H. B. Intramolecular-catalyzed vitrimers with white-light emission for light-emitting diode encapsulation. *Adv. Mater.* **2023**, *35*, 2300616.
- Reddy, P. M.; Chang, C. J.; Lai, C. F.; Su, M. J.; Tsai, M. H. Improved organic-inorganic/graphene hybrid composite as encapsulant for white LEDs: role of graphene, titanium (IV) isopropoxide and diphenylsilanediol. *Compos. Sci. Technol.* **2018**, *165*, 95–105.
- Lin, G. H.; Yin, J. F.; Lin, Z. Q.; Zhu, Y. W.; Li, W. J.; Li, H. Z.; Liu, Z.; Xiang, H. P.; Liu, X. X. Facile thiol-epoxy click chemistry for transparent and aging-resistant silicone/epoxy composite as LED encapsulant. *Prog. Org. Coat.* **2021**, *156*, 106269.
- Jung, S.; Kim, Y. S.; Kim, Y. N.; Jeong, S.; Naqvi, S. M.; Hassan, T.; Narayanasamy, M.; Cho, S.; Jung, Y. C.; Kin, J.; Koo, C. M. All-in-one epoxy/MXene nanocomposites with bead-type polymeric imidazole latent curing agent for enhancing storage stability and flame retardancy. *Adv. Mater.* **2024**, *36*, 2408674.
- Tang, Y.; Zhang, X. Y.; Liu, X. Y.; Wei, W.; Li, X. J. Facile synthesis of hyperbranched epoxy resin for combined flame retarding and toughening modification of epoxy thermosets. *Chem. Eng. J.* **2024**, *482*, 148992.
- Du, W. T.; Cai, M. Y.; Cao, J.; Huang, H. Q.; Luo, Q. H.; Xiang, H. P. High-strength, impact-resistant, transparent and aging-resistant silicone/epoxy composite as LED encapsulant via thiol-epoxy click chemistry. *Polymer* **2025**, *337*, 128932.
- Fan, X. L.; Miao, J. T.; Yuan, L.; Guan, Q. B.; Gu, A. J.; Liang, G. Preparation and origin of thermally resistant biobased epoxy resin with low internal stress and good UV resistance based on SiO₂ hybridized cellulose for light emitting diode encapsulation. *Appl. Surf. Sci.* **2018**, *447*, 315–324.
- Jiang, B.; Shi, X. R.; Zhang, T.; Huang, Y. D. Recent advances in UV/thermal curing silicone polymers. *Chem. Eng. J.* **2022**, *435*, 134843.
- Deng, H. Y.; Liu, Y. Y.; Du, W. T.; Huang, H. Q.; Zhang, L. Y.; Xiang, H. P. Transparent, high-strength, resistant, recyclable silicones based on dual dynamic thiourethane and hydrogen bonds. *Chem. Eng. J.* **2025**, *517*, 164309.
- Yu, T. X.; Liu, Y. Y.; Tian, F. Y.; Ning, N. Y.; Yu, B.; Tian, M. Silicone elastomer with high elongation at break used in digital light processing 3D printing. *Chinese J. Polym. Sci.* **2023**, *41*, 1786–1795.
- Briesenick, M.; Gallei, M.; Kickelbick, G. High-refractive-index polysiloxanes containing naphthyl and phenanthrenyl groups and their thermally cross-linked resins. *Macromolecules* **2022**, *55*, 4675–4691.
- Badur, T.; Dams, C.; Hampp, N. High refractive index polymers by design. *Macromolecules* **2018**, *51*, 4220–4228.
- Rodríguez, R.; de las Heras Alarcón, C.; Ekanayake, P.; McDonald, P. J.; Keddie, J. L.; Barandiaran, M. J.; Asua, J. M. Correlation of silicone incorporation into hybrid acrylic coatings with the resulting hydrophobic and thermal properties. *Macromolecules* **2008**, *41*, 8537–8546.
- Cong, Y.; Li, Z. X.; Bian, P.; McCarthy, T. J. Isomeric silicones: reactive phenylsilsesquioxane-based MT resins and comments concerning the structure of the phenylsilsesquioxane homopolymer. *Macromolecules* **2022**, *55*, 5803–5815.
- Liu, Z.; Hong, P.; Huang, Z. Y.; Zhang, T.; Xu, R. J.; Chen, L. J.; Xiang, H. P.; Liu, X. X. Self-healing, reprocessing and 3D printing of transparent and hydrolysis-resistant silicone elastomers. *Chem. Eng. J.* **2020**, *387*, 124142.
- Chen, X. Y.; Fang, L. X.; Wang, J. J.; He, F. K.; Chen, X. R.; Wang, Y. Q.; Zhou, J. F.; Tao, Y. Q.; Sun, J.; Fang, Q. Intrinsic high refractive index siloxane-sulfide polymer networks having high thermostability and transmittance via thiol-ene cross-linking reaction. *Macromolecules* **2018**, *51*, 7567–7573.
- Ye, P. R.; Hong, Z. H.; Loy, D. A.; Liang, R. G. UV-curable thiol-ene system for broadband infrared transparent objects. *Nat. Commun.* **2023**, *14*, 8385.
- Liang, Y. M.; Liu, M.; Wang, T. T.; Mao, J. Y.; Wang, L. C.; Liu, D. Z.; Wang, T. Y.; Hu, W. P. UV-curing-enhanced organic long-persistent luminescence materials. *Adv. Mater.* **2023**, *35*, 2304820.
- Jin, H.; Zhong, X. X.; Zhong, C. C.; Dai, W. S.; Xiang, H. P.; Zhang, L. Y. UV-curable, 3D printable, thermally conductive polysiloxane composites for thermal interface devices. *Addit. Manuf.* **2025**, *99*, 104658.
- Sun, Y. H.; Long, L.; Li, B. J.; Kong, D. F.; Liang, C. L.; He, M.; Liu, R. Enhancement of mechanical and thermal properties of UV-curable wood coatings by cellulose nanofibrils and carboxylated organo-montmorillonite. *Polym. Compos.* **2024**, *45*, 8005–8015.

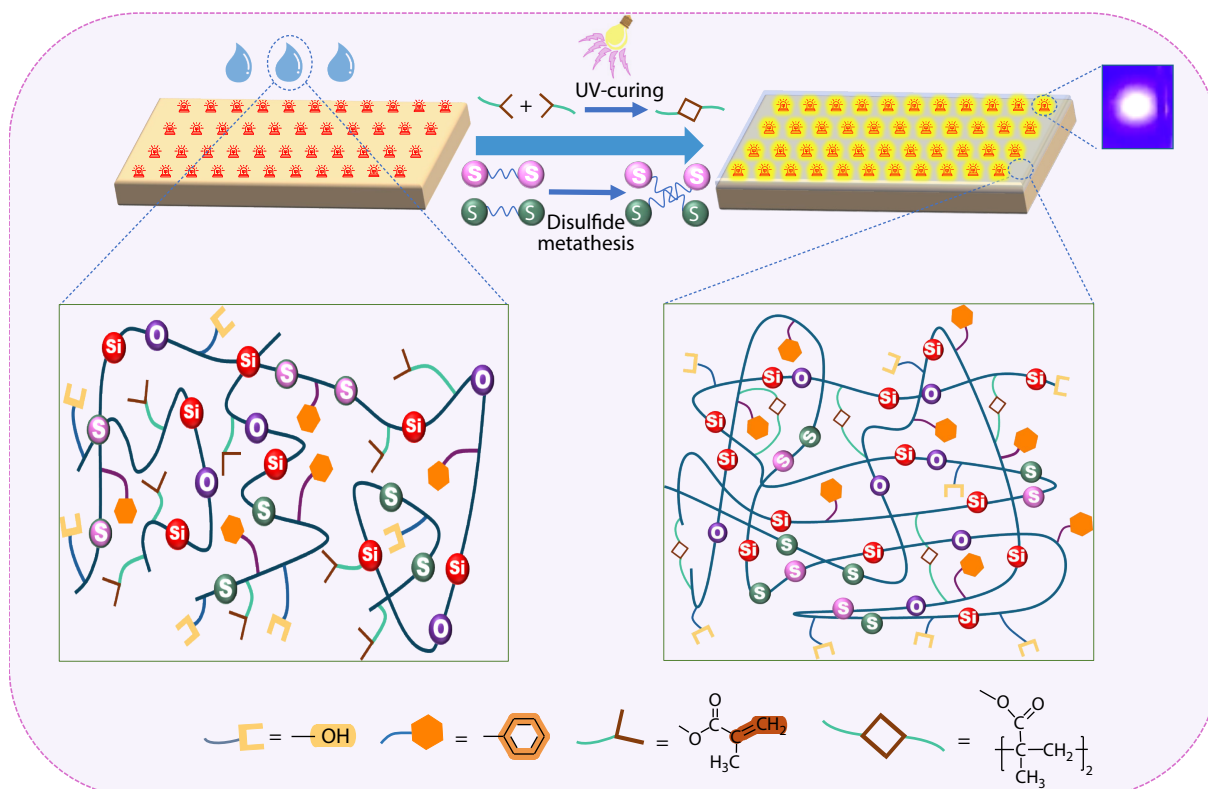
Graphical Abstract

UV-curable, Transparent, and Low Volume-shrinkage Silicones for Efficient Mini-LED Encapsulation

Zi-Hua Zhang, Juan Ye, Wei-Shan Wen, Qing-Hong Luo, and Hong-Ping Xiang

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This work develops a novel UV-curable silicone resin containing phenyl, disulfide, and acryloyl groups. It can be rapidly UV-cured within 30 s, exhibiting a high optical transparency (>92%), a high refractive index (>1.5), and a low volume shrinkage (< 4.83%), providing an effective encapsulation solution for Mini-LEDs.



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- 27 Huang, S. J.; Huang, H. Q.; Liu, X. X.; Xiang, H. P. Free-radical/cationic hybrid UV-curable silicone resin for age-resistant coatings. *Ind. Eng. Chem. Res.* **2024**, 63, 14657–14667.
- 28 Ye, J.; Zhang, Z. H.; Huang, S. J.; Liu, Y. Y.; Wen, W. S.; Xiang, H. P. UV-curing silicone-based adhesives with improved adhesion strength and aging resistance. *Ind. Eng. Chem. Res.* **2024**, 63, 21300–21311.
- 29 Yang, X. F.; Liu, J.; Wu, Y. F.; Liu, J. L.; Cheng, F.; Jiao, X. J.; Lai, G. Q. Fabrication of UV-curable solvent-free epoxy modified silicone resin coating with high transparency and low volume shrinkage. *Prog. Org. Coat.* **2019**, 129, 96–100.
- 30 Berg, O.; Nguyen, L. T. T.; Teixeira, R. F.; Goethals, F.; Ozdilek, C.; Berghmans, S.; Du Prez, F. E. Low modulus dry silicone-gel materials by photoinduced thiol-ene chemistry. *Macromolecules* **2014**, 47, 1292–1300.
- 31 Lu, Y.; Zhao, Z. H.; Fan, X. P.; Cao, X. Y.; Hai, M. T.; Yang, Z.; Zheng, K.; Lu, J. X.; Zhang, J. N.; Ma, Y. M.; Zhang, R. B.; Fang, S. B. Zirconia/phenylsiloxane nano-composite for LED encapsulation with high and stable light extraction efficiency. *RSC Adv.* **2021**, 11, 18326–18332.
- 32 Zeng, Y. S.; Xia, J. H. Preparation of ultraviolet-cured silicone elastomer reinforced by SH-POSS crosslinker for light emitting diode encapsulant. *J. Appl. Polym. Sci.* **2025**, 142, e56327.
- 33 Kim, Y. H.; Kim, J.; Baek, J. J.; Chang, K. C.; Park, B. S.; Bae, G. Y.; Koh, W. G.; Shin, G. Fabrication and characterization of UV-curable thiol-functionalized siloxane elastomers with enhanced adhesion for flexible substrates. *Chem. Eng. J. Adv.* **2024**, 20, 100679.
- 34 Jones, B. H.; Wheeler, D. R.; Black, H. T.; Stavig, M. E.; Sawyer, P. S.; Giron, N. H.; Celina, M. C.; Lambert, T. N.; Alam, T. M. Stress relaxation in epoxy thermosets via a ferrocene-based amine curing agent. *Macromolecules* **2017**, 50, 5014–5024.

<https://doi.org/10.1007/s10118-025-3506-4>

- 35 Chen, J.; Fu, Z.; Huang, H.; Zeng, X.; Chen, Z. Preparation and properties of vinylphenyl-silicone resins and their application in LED packaging. *RSC Adv.* **2016**, *6*, 71924–71933.
- 36 Yang, X.; Shao, Q.; Yang, L.; Zhu, X.; Hua, X.; Zheng, Q.; Song, G.; Lai, G. Preparation and performance of high refractive index silicone resin-type materials for the packaging of light-emitting diodes. *J. Appl. Polym. Sci.* **2013**, *127*, 1717–1724.
- 37 Wang, S. Q.; Peng, Z. B.; Huang, Y. H.; Zhu, M. Q.; Liu, Y. Y.; Zhang, Y. Synthesis, characterization and properties of vinyl-terminated poly[dimethylsiloxane-co-methyl (phenyl) siloxane]. *Polymer* **2024**, *311*, 127554.
- 38 Chen, J. T.; Jiang, S. L.; Gao, Y. J.; Sun, F. Reducing volumetric shrinkage of photopolymerizable materials using reversible disulfide-bond reactions. *J. Mater. Sci.* **2018**, *53*, 16169–16181.
- 39 Xiang, Z.; Chu, C. Z.; Xie, H.; Xiang, T.; Zhou, S. B. Multifunctional thermoplastic polyurea based on the synergy of dynamic disulfide bonds and hydrogen bond cross-links. *ACS Appl. Mater. Interfaces* **2020**, *13*, 1463–1473.
- 40 Zhao, D.; Shan, S. X.; Zhang, M.; Zhang, X. A.; Jiang, S. L.; Lyu, Y. F. Preparation of titanium-silphenylene-siloxane hybrid polymers with high refractive index, transmittance, and thermal stability. *Chinese J. Polym. Sci.* **2020**, *38*, 973–982.
- 41 Zhong, Y. M.; Liu, S.; Luo, L. B.; Huang, Q. Influence of chemical side groups containing aromatic rings: flow-induced friction enhancement or reduction. *Macromolecules* **2024**, *57*, 4833–4841.
- 42 Hong, S. M.; Kim, O. Y.; Hwang, S. H. Synthesis of 9, 9-bis[4-(2-hydroxyethoxy) phenyl] fluorene di(mercaptopropionate) for high-luminance and refractive prism sheets. *Prog. Org. Coat.* **2024**, *196*, 108700.
- 43 Li, L.; Feng, W. Q.; Welle, A.; Levkin, P. A. UV-Induced Disulfide Formation and Reduction for Dynamic Photopatterning. *Angew. Chem. Int. Ed.* **2016**, *128*, 13969–13973.
- 44 Yang, Z.; Bai, Y. P.; Wei, B. X.; Cui, Y. T.; Wang, R. L.; Zhang, W.; Li, Y. Y.; Meng, L. H.; Wang, Y. Facile synthesis of UV-curable fluorosilicone polymers and coatings with good corrosive resistance on account of the reaction of disulfide bonds with vinyl groups. *Prog. Org. Coat.* **2024**, *188*, 108236.
- 45 Khudyakov, I. V.; Turro, N. J. Cage effect dynamics under photolysis of photoinitiators. *Des. Monomers Polym.* **2010**, *13*, 487–496.
- 46 Liu, S. H.; Zhang, X. Q.; Bu, M. L.; Lei, C. H. Properties tailoring of biobased epoxy resins by regulating the degree of polymerization of oligomers. *Eur. Polym. J.* **2022**, *173*, 111253.
- 47 Andrzejewska, E. Photopolymerization kinetics of multifunctional monomers. *Prog. Polym. Sci.* **2001**, *26*, 605–665.
- 48 Otsuka, H.; Nagano, S.; Kobashi, Y.; Maeda, T.; Takahara, A. A dynamic covalent polymer driven by disulfide metathesis under photoirradiation. *Chem. Commun.* **2010**, *46*, 1150–1152.
- 49 Yang, H.; Chen, X.; Sun, B.; Tang, J.; Vlassak, J. J. Fracture tolerance induced by dynamic bonds in hydrogels. *J. Mech. Phys. Solids* **2020**, *169*, 105083.
- 50 Watanabe, S.; Tsunekawa, Y.; Takayama, T.; Oyaizu, K. Diverse side-chain transformation of high refractive index methylthio-substituted poly(phenylene sulfide)s. *Macromolecules* **2024**, *57*, 2897–2904.
- 51 Ogliani, E.; Yu, L. Y.; Mazurek, P.; Skov, A. L. Designing reliable silicone elastomers for high-temperature applications. *Polym. Degrad. Stabil.* **2018**, *157*, 175–180.
- 52 Park, H. W.; Park, J. W.; Lee, J. H.; Kim, H. J.; Shin, S. Property modification of a silicone acrylic pressure-sensitive adhesive with oligomeric silicone urethane methacrylate. *Eur. Polym. J.* **2019**, *112*, 320–327.
- 53 Ou, S. N.; Zhang, J. Q.; Gu, L. J.; Wen, T.; Cao, M. T.; Olonisakin, K.; Yang, W. B.; Li, R.; Zhang, X. X. Click chemistry of PMHS for fabrication of robust, transparent and hydrophobic silicone resin coating on wood substrate at room temperature. *Prog. Org. Coat.* **2024**, *186*, 107976.
- 54 Wu, J.; Niu, K. F.; Su, B. L.; Wang, Y. S. Effect of combined UV thermal and hydrolytic aging on micro-contact properties of silicone elastomer. *Polym. Degrad. Stabil.* **2018**, *151*, 126–135.
- 55 Marin, E.; Boschetto, F.; Zanoocco, M.; Doan, H. N.; Sunthar, T. P.; Kinashi, K.; Iba, D.; Zhu, W. L.; Pezzotti, G. UV-curing and thermal ageing of methacrylated stereo-lithographic resin. *Polym. Degrad. Stabil.* **2021**, *185*, 109503.
- 56 Pan, Z.; Cheng, Y.; Li, B.; Zhang, Z. A Hydrogen-Containing Di-Phenyl Siloxane Cross-Linker for Ultra-High Hardness and High Refractive Index Silicone Resin and its Application in LED Encapsulation. *Silicon* **2023**, *15*, 3647–3655.
- 57 Xiang, H. P.; Rong, M. Z.; Zhang, M. Q. A facile method for imparting sunlight driven catalyst-free self-healability and recyclability to commercial silicone elastomer. *Polymer* **2017**, *108*, 339–347.