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Progress and Perspective of Near-Ultraviolet and Deep-Ultraviolet Light-Emitting Diode Packaging Technologies

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Abstract

Ultraviolet light-emitting diodes (UV-LEDs) have drawn considerable attentions in environment, life science, and industry fields, such as the applications of near UV-LEDs in resin curing, illumination, and identification, and deep UV-LEDs in disinfection, medical treatment, and biochemical inspection. However, due to the limitation of packaging technology, UV-LED devices exhibit low light efficiency and poor reliability compared with visible LEDs. The organic encapsulation materials are prone to UV aging, thermal degradation, and non-airtightness, which significantly reduce the performances of UV-LEDs. In order to solve this issue, UV-LED packaging technology have been proposed for UV-LED devices instead of conventional LED packaging. In this review, we detailedly investigated the overview and challenges of NUV-LED/DUV-LED packaging. For the packaging of UV-LEDs, all inorganic encapsulation materials, hermetic packaging structures with low-temperature bonding, reduced reflection losses, UV stable and transparent materials, and effective thermal management are key progresses to enhance the light efficiency and reliability of UV-LEDs. In addition, the summary and perspectives of NUV-LED/DUV-LED packaging were introduced and discussed.

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1. Introduction

III-V nitrides based ultraviolet light-emitting diodes (UV-LEDs) have been considered as promising UV light devices [1-4]. Unlike the conventional mercury lamps, UV-LEDs are compact, robust, wavelength-tunable, energy-saving, and environmentally friendly [5-9], as presented in Table 1. Currently, UV-LEDs are divided into near-ultraviolet LEDs (NUV-LEDs) with the emission wavelength of 300-400 nm and deep-ultraviolet LEDs (DUV-LEDs) with the emission wavelength of 210-300 nm [10-12]. Due to their different emission wavelengths and photon energies, UV-LEDs have attracted various applications in environment, life science, and industry, as shown in Fig. 1. The NUV-LEDs widely apply in ink-printing, resin curing, illumination, and identification, while the DUV-LEDs have broad application prospects in disinfection, air and water purification, medical treatment, and biochemical inspection [13, 14]. Yole Développement expects that the NUV-LED market will grow from 107 million dollars in 2015 to 357 million dollars by 2021, and the DUV-LED market will strongly grow from 7 million dollars in 2015 to 610 million dollars by 2021 owing to an increased penetration rate in all applications [15]. The gradual restriction of mercury-based light sources will further promote the market scale of UV-LEDs.

Table 1. Characteristics comparison of mercury lamps and UV-LEDs.

Characteristics	Mercury Lamps	UV-LEDs
Emission spectrum	Fixed, Broad	Tunable, Narrow
Input voltage	100-10,000 V	3-10 V
Heat Generation	High	Low
Structure	Bulky	Compact, Robust
Lifetime	3,000-5,000 h	>10,000 h
Environment	Mercury pollution	No-mercury

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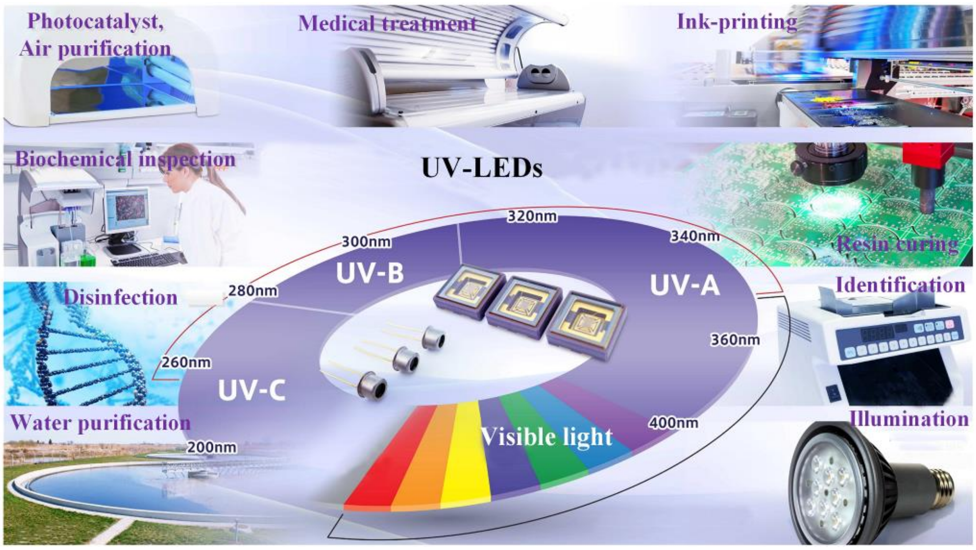

Fig. 1. Application fields of UV-LEDs.

Nowadays, it has high technical threshold to fabricate the UV-LEDs, which is markedly different from the visible LEDs in the equipment, epitaxy, chip, and packaging technologies. Due to the limitations of epitaxial material, Al-doping, and packaging technology, the light efficiency and reliability of UV-LEDs are inferior to those of visible LEDs, especially for the DUV-LEDs with the shorter wavelength below 280 nm [16-18]. So far, the external quantum efficiency (EQE) of DUV-LEDs is still lower than 25% and the lifetime is only 10,000 hours [19, 20]. Although the performances of UV-LEDs have been enhanced by the improved epitaxial and doping technologies, UV-LEDs still have some packaging issues in material, structure, and process. For the conventional packaging structure, a chip was bonded on a substrate and an encapsulation material (silicone or epoxy) was coated on the chip surface [21-23]. It should be noted that the organic materials have seriously thermal degradation and UV aging during long-term service [24-27]. Furthermore, the organic materials display breathable and permeable problems. These issues significantly reduce the long-term reliability of UV-LED devices. As a promising alternative, the glass packaging was proposed to enhance the reliability of LED devices due to its excellent thermal stability, high mechanical strength, low thermal expansion [28-30]. However, the glass packaging yields limited light extraction and complicated packaging process. Therefore, the UV-LED packaging should be deeply studied to enhance the light efficiency and reliability of UV-LED devices, which is the motivation for the present work. In this review, the overview and challenges of

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NUV-LED/DUV-LED packaging were discussed. The corresponding progresses of NUV-LED/DUV-LED packaging were investigated, followed by the summary and perspectives of NUV-LED/DUV-LED packaging.

2. Overview and challenges of UV-LED packaging

Packaging is a key process for the fabrication of LED devices, and its functions include mechanical protection, electrical interconnection, light extraction, and heat dissipation [31-33]. The packaging quality directly determines the light efficiency and reliability of LED devices, especially for the UV-LEDs applied in the harsh environment of high temperature and high humidity. Considering their photon energy and application field, the packaging types of NUV-LEDs/DUV-LEDs and their key technologies are distinctly different.

2.1 NUV-LED Packaging

Fig. 2 displays the four packaging types of NUV-LEDs, including organic material (silicone or epoxy resin) packaging and glass packaging. Currently, most of NUV-LEDs still continue to use the traditional organic material packaging, which does not require additional materials and equipment. For the organic material packaging, the encapsulation is coated onto the surface of chip for the protection of chip and gold wire. Although this traditional approach is simple and low-cost, the organic materials are prone to considerable UV absorption and photochemical decomposition, resulting in the reduction of transparency, the decrease of light efficiency, and the degradation of reliability [34-37]. These issues become profoundly serious for the DUV-LEDs due to the high photon energy of DUV light.

For this reason, some NUV-LEDs are retrofitted with a quartz glass [38, 39]. The glass packaging of NUV-LEDs can be processed by either bonding a glass lens on the chip surface (Fig. 2c) or bonding a glass plate on the dam of substrate (Fig. 2d). Although the quartz glass offers high UV transparency and excellent UV stability, the glass packaging of NUV-LEDs inevitably uses the organic material as an adhesive for the glass bonding. Due to the low refractive index of organic material, the emission light has serious reflection loss on the adhesive layer, which limits the light extraction of NUV-LEDs. Moreover, the organic material also display molecular dissociation and aging during long-term high temperature and

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high UV radiation. These packaging issues still affect the light efficiency and reliability of NUV-LEDs.

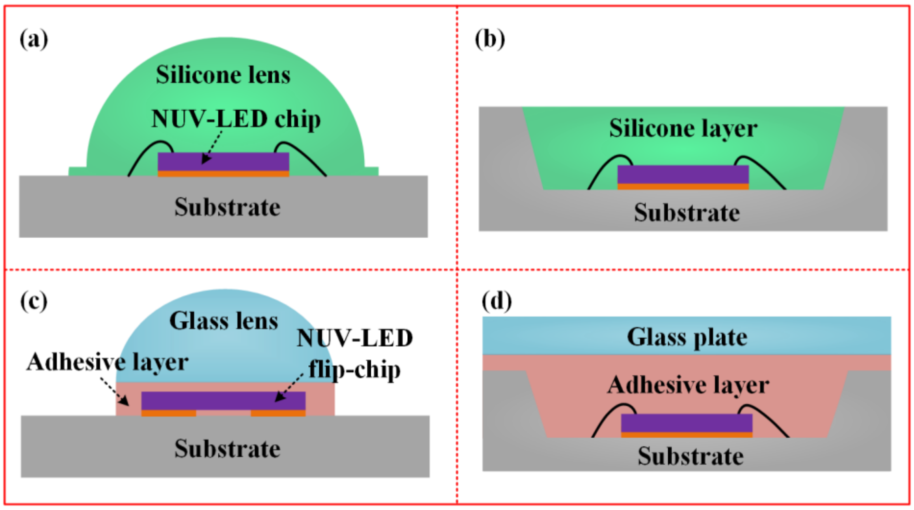

Fig. 2. Packaging types of NUV-LEDs.

2.2 DUV-LED Packaging

Since the DUV light exhibits a high photon energy of ~4.1 eV (at 300 nm), most organic materials are destructed by the UV-induced molecular dissociation [40]. The organic materials have low transmittance in the DUV region, which reduces the light extraction. Considering the inevitable shortcoming of organic materials, the DUV-LEDs must adopt inorganic materials (glass or sapphire) to realize the hermetic packaging for the enhancement of reliability [41]. Currently, two packaging types are applied in the DUV-LEDs, as presented in Fig. 3. The TO-style packaging uses a glass lens as the transparent window and a metal can as the heat dissipation and support structure (Fig. 3(a)). This packaging type achieves the hermetic packaging for the DUV-LEDs by soldering the metal can on the metal substrate, and the whole packaging structure has no organic material, which can effectively prevent UV aging and enhance the lifetime of DUV-LED devices. However, the TO-style packaging with lead is not suitable for high-power DUV-LEDs due to its poor heat dissipation. Furthermore, the complex fabrication process of the metal can with glass lens limits the application of TO-style packaging.

Aiming to solve this issue, another packaging type, in which a glass plate is bonded on a three-dimensional (3D) substrate, is proposed for DUV-LEDs (Fig. 3(b)). The packaging

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process of DUV-LEDs is shown in Fig. 4. First, the 3D substrate with metal interconnection is prepared by some approaches, such as sintering, electroplating, and adhesion [42, 43]. Then, the DUV-LED chip is soldered on the metal layer in the cavity of 3D substrate, following by gold wire bonding process. After that, the quartz glass plate is bonded on the dam of 3D substrate in the atmosphere or vacuum environment. Notably, the low-temperature bonding between the glass plate and the 3D substrate is a challenge for this packaging process. Since the die soldering and the wire bonding of chip have been accomplished before the glass bonding, the high bonding temperature of glass plate causes the thermal damage of chip and then affects the performances of LEDs (the resistance temperature of chip is lower than 300 ℃ and the resistance time is lower than 30 s) [44, 45]. The high bonding temperature also destroy the soldering layer of chip, resulting in the soldering failure. Thus, the bonding temperature of glass plate is greatly restrained, and it is necessary to realize the low-temperature bonding of glass plate for the hermetic packaging of DUV-LEDs. Furthermore, the reflection losses occur at the glass surface and the chip surface for this packaging structure, which reduces the light efficiency of DUV-LEDs.

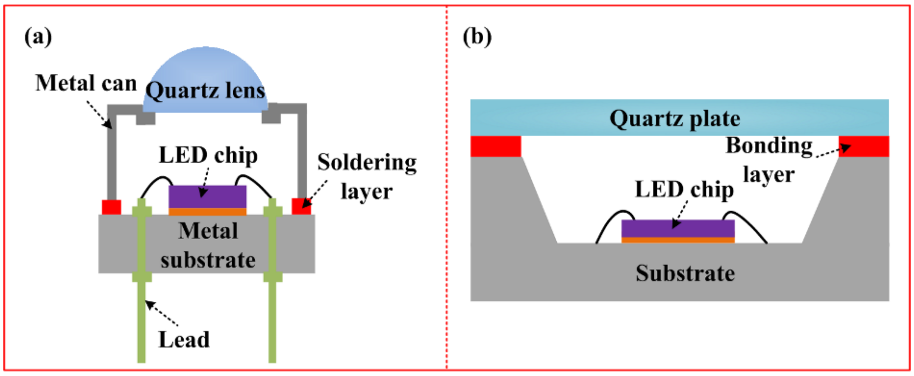

Fig. 3. Packaging types of DUV-LEDs.

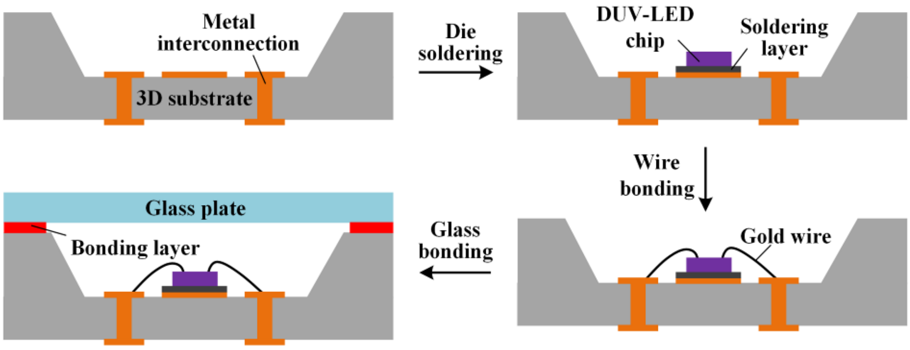

Fig. 4. Packaging process of DUV-LED with glass plate.

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3. Progresses of UV-LED Packaging

3.1 NUV-LED Packaging

For the glass packaging of NUV-LEDs with the organic adhesive layer, the reflection losses at the adhesive and chip interface reduce the light efficiency of NUV-LEDs. A hemispherical quartz glass lens bonded on the chip surface is a common method to reduce the reflection loss, as shown in Fig. 5. Due to the low refractive index of adhesive (silicone or epoxy resin), the emission light exhibits the reflection loss on the adhesive layer. Liang et al. [46] proposed a new packaging structure for the NUV-LEDs by introducing a thin silicone layer doped with AlN nanoparticles (NPs), as shown in Fig. 6. Due to the increased refractive index and light scattering ability of the adhesive layer by the doping of AlN NPs, the light output power of NUV-LEDs was enhanced. In addition, microlens array (MLA) surface is an effective method to inhibit the reflection loss [47-49]. Liu et al. [50] adopted a spin-on glass (SOG) with a good UV transmittance for the MLA fabrication. The SOG MLAs with different diameters were fabricated on the chip surface by thermal reflow and multiple replication process, as presented in Fig. 7. By applying the SOG MLA with optimized size and shape, the light efficiency of NUV-LEDs was increased by 21.86%.

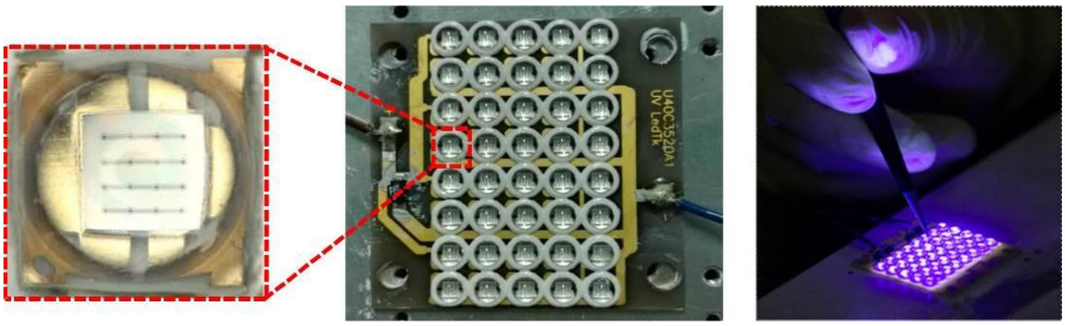

Fig. 5. NUV-LEDs packaged by bonding hemispherical glass lens.

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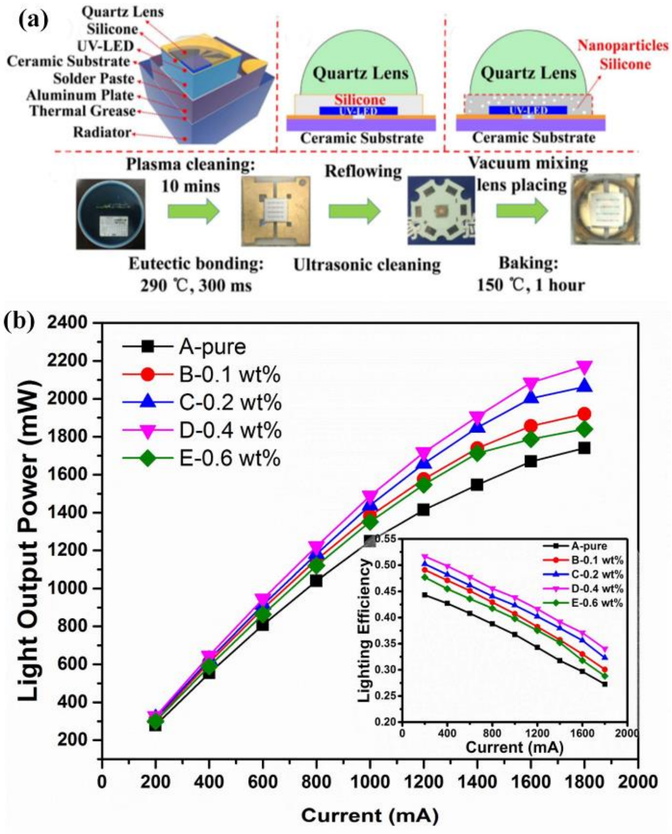

Fig. 6. (a) Packaging structure and process of NUV-LEDs with AlN NPs doped silicone adhesive layer. (b) Light output powers of NUV-LEDs with different AlN NPs doping contents.

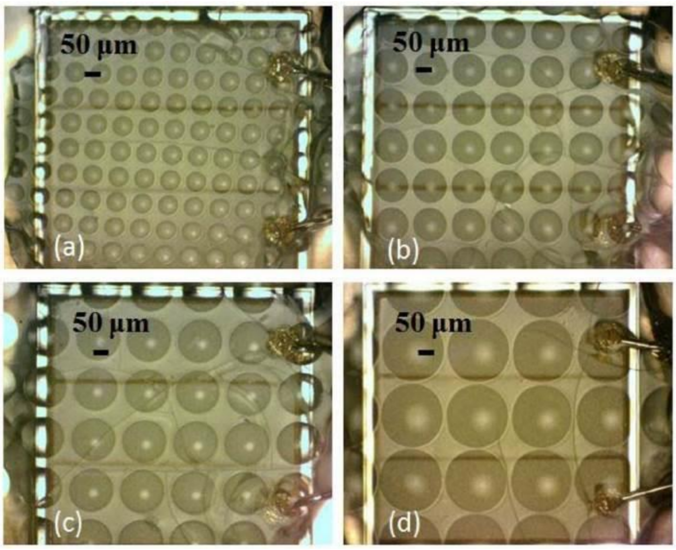

Fig. 7. Different-diameter SOG MLAs fabricated on the NUV-LED chip: (a) 50 µm, (b) 100 µm, (c) 150 µm, and (d) 200 µm.

The NUV-LEDs have a key requirement in thermal management due to their poor conversion efficiency and large input power. The optical performances and reliability of NUV-LEDs depend on the junction temperature and heat dissipation of packaging structure

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[51-54]. It is crucial to develop some thermal management methods for the reduction of overall thermal resistance. Nowadays, most of NUV-LEDs are fabricated by direct AuSn eutectic flip-chip bonding because of its excellent thermal performance and high reliability (Fig. 8) [55-57]. This packaging can provide a rapid and direct heat transfer path. Liang et al. [55] investigated the thermal characterization of eutectic NUV-LEDs and evaluated the effects of eutectic bonding voids on the thermal performance of NUV-LEDs. Consequently, the NUV-LEDs achieved lowest thermal resistance and junction temperature at the 3% bonding voidage. The results demonstrated that the low thermal resistance leads to the low junction temperature and the high light output power for NUV-LEDs.

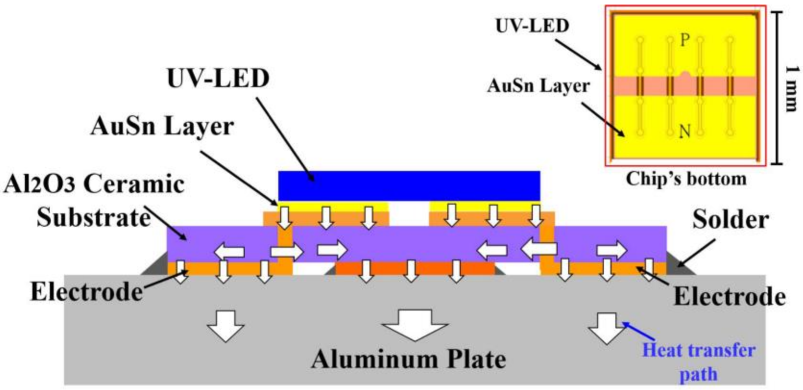

Fig. 8. Schematic of NUV-LED packaged by AuSn eutectic bonding and its heat transfer path.

In order to reduce the heat accumulation in the bonding layer of NUV-LEDs, Liang et al. [58] fabricated a highly efficient thermal interface of silicone composites with graphene oxide (GO). The GO-doped composite was used to embed the air gap between NUV-LED chip and substrate (Fig. 9(a)). The NUV-LEDs packaged by the silicone composite with 4 wt% GO exhibited excellent thermal and reliable performances by reducing the junction temperature and interface thermal resistance. The junction temperature decreased about 2.9 ℃ and the interface thermal resistance reduced about 34% (Fig. 9(b)). Moreover, the NUV-LEDs with the proposed structure achieved a low light failure rate compared to the traditional structure through the accelerated aging test, as shown in Fig. 9(c).

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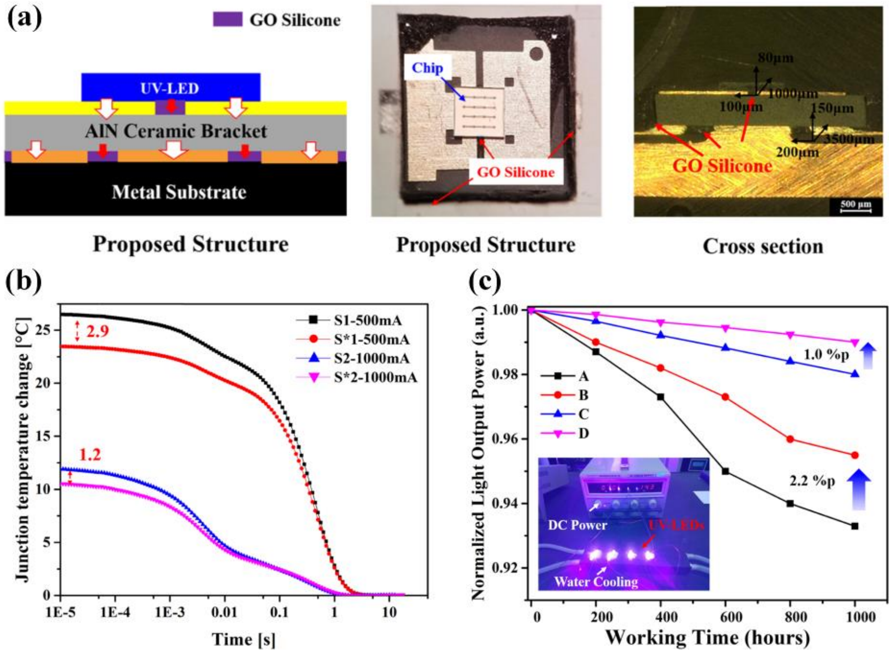

Fig. 9. (a) Proposed packaging structure of NUV-LEDs with GO-doped composite thermal interface. (b) Junction temperature change during cooling of sample 1 and sample 2 after embedding with the GO-based composite. (c) Normalized light output power of four samples as a function of the working time.

3.2 DUV-LED Packaging

In order to realize the hermetic packaging of DUV-LEDs, the 3D substrate with cavity is essential requirement for chip bonding. Currently, ceramic substrate is a common packaging substrate for power devices due to its robustness, high thermal conductivity, and low expansion coefficient [59-61]. The 3D ceramic substrate can be fabricated by ceramic sintering, repeated electroplating, and direct bonding methods. Although the ceramic sintering method can realize the 3D substrate with different sizes and shapes, this method requires screen-printing process and affects the precision of metal layer. The repeated electroplating is that a metal dam is directly plated on a plate ceramic substrate, which exhibits high mechanical strength and pattern precision [62]. Nevertheless, the internal stress of substrate and time-consuming process limit the practical application of this method. The direct bonding is that a dam is bonded on a plate ceramic substrate by using the adhesive or solder. The bonding layer influences the reliability of 3D substrate. To avoid these issues in the existed methods, Cheng et al. [63] fabricated the 3D ceramic substrates by molding alkali-activated aluminosilicate pastes on the direct plated copper (DPC) ceramic substrates, as presented in

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Fig. 10. By adjusting the viscosity and curing temperature of inorganic paste, the 3D ceramic substrates achieved low fabrication error and excellent thermal reliability. Furthermore, Sun et al. [64-66] developed a facile and low-temperature method of direct ink writing to fabricate 3D cavity. By writing kaolin suspensions, the 3D cavity structure with the height of 900 μm was fabricated on the ceramic substrate, as shown in Fig. 11. These 3D ceramic substrates have greatly potential applications for the hermetic packaging of UV-LED devices.

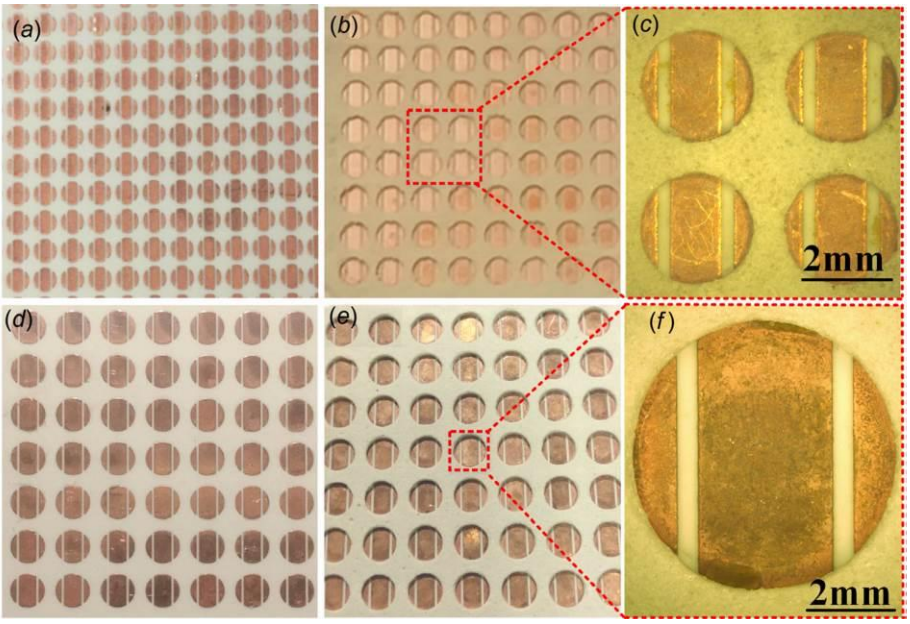

Fig. 10. Images of fabricated 3D ceramic substrates with different sizes by molding aluminosilicate pastes.

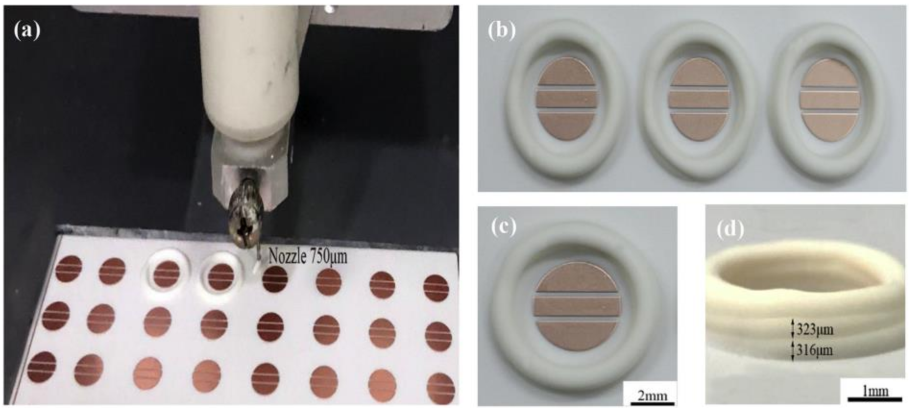

Fig. 11. Images of 3D ceramic substrates fabricated by the direct ink writing of kaolin suspensions.

After the fabrication of 3D substrate, the low-temperature bonding between glass plate and substrate is the key challenge for the hermetic packaging of DUV-LEDs. Currently, some low-temperature bonding methods have been proposed, such as adhesive bonding, laser

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heating, and localized heating [67-69]. The adhesive bonding is not suitable for the DUV-LED packaging due to the organic materials destroyed by DUV light. The laser heating is only suitable for light-absorbing materials and requires precise alignment. For the localized heating, the bonding layer is heated and other parts are at low-temperature, which can avoid the influence of heating temperature on the chip and microstructures. The low-temperature bonding method includes localized current heating, parallel seam welding, and localized induction heating [70-73]. By controlling the input current in the localized heating circuit, the air-tight material around the circuit is heated and then realizes the bonding of glass plate and substrate (Fig. 12(a)). Unfortunately, this method has complex process and low packaging efficiency. The parallel seam welding is an efficient method to realize the bonding of metal frame and metal dam (Fig. 12(b)). Although this method achieves high hermetic packaging, it requires the preparation of the glass window with metal frame and the reliability soldering between metal dam and substrate. The induction heating has been considered as a potential method for the low-temperature bonding by a combination of electromagnetic induction and heat transfer technologies (Fig. 13(a)). When an alternating current through an induction coil, joule heat generates on the bonding layer and then the solder layer is heated and melted, finally the glass plate and the substrate are bonded together. Thus, Peng et al. [74] used the induction heating to realize the reliable packaging of DUV-LEDs. As shown in Fig. 13(b), the highest temperature difference reaches to 180 ℃, which indicates that the induction heating can avoid the adverse effect of high temperature on the LED chip.

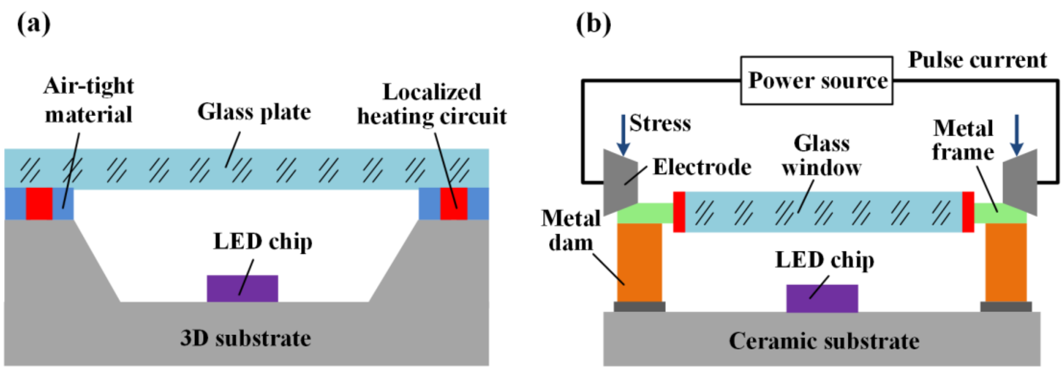

Fig. 12. (a) Localized current heating and (b) parallel seam welding technologies for low-temperature bonding between glass plate and substrate.

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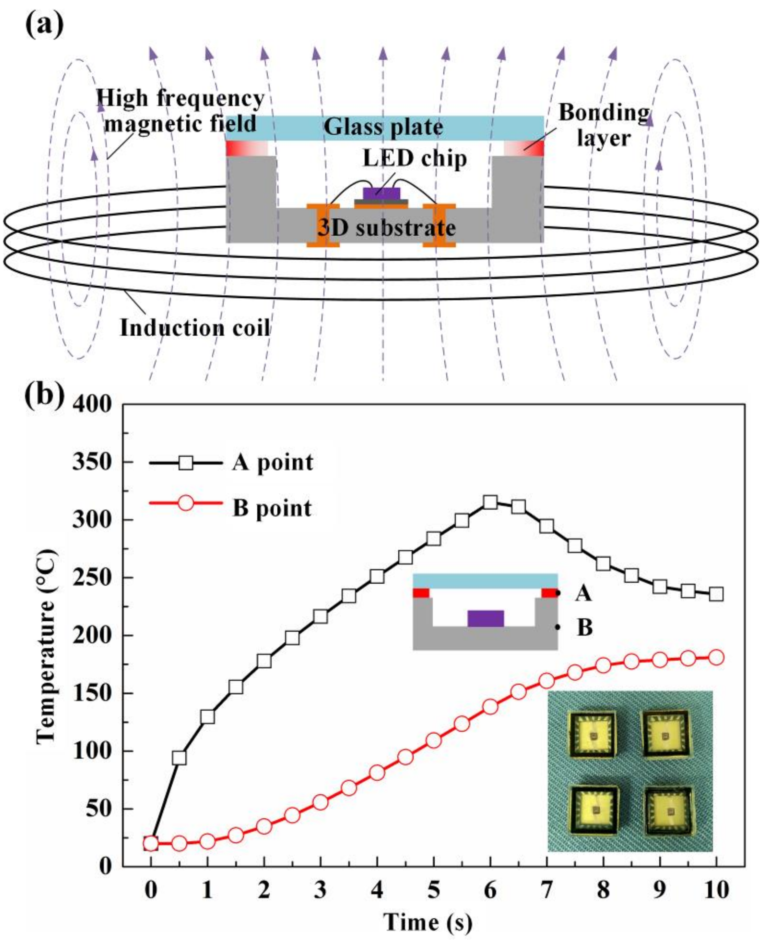

Fig. 13. (a) Schematic illustration of localized induction heating and (b) temperature variation of A, B points on the DUV-LED during induction heating process.

For the hermetic packaging structure of DUV-LEDs, the light extraction efficiency (LEE) is still low, which is insufficient for most practical applications. The reason is that the reflection losses are inevitably occurred on the glass-air and chip-air interfaces due to the large refractive index difference, as shown in Fig. 14. Many approaches have been proposed to reduce the reflection losses and enhance the LEE of DUV-LEDs. Peng et al. [75] fabricated the tailored nanostructures on the both sides of glass surface for the DUV-LEDs. When the nanostructures had a small dimension than the DUV wavelength, a gradient refractive index was generated on the glass-air interface, which can realize broadband and omnidirectional antireflection properties. By utilizing the dual-side nanostructures, the transmittance of the glass and the light efficiency of DUV-LEDs were increased. On the other hand, surface roughening is a feasible method to reduce the reflection loss on the chip-air interface, and then enhances the light extraction from LED chip [76-79]. Khizar et al. [80] fabricated

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microlens arrays (MLAs) on the sapphire substrate of DUV-LED chip by resist thermal reflow and plasma dry etching. The microlens surface profile reduced the total reflection loss, which enhanced the light output power of 55%. Since the etching process affected the photoelectric characteristics of LED chip, Peng et al. [81] developed a simple and economical approach to fabricate MLAs on an encapsulation layer for DUV-LEDs. Considering the UV aging and destruction of conventional encapsulation materials, C-F-based amorphous fluoropolymers with high UV transparency and excellent UV durability were used as the encapsulation layer. First, porous films were prepared by using a UV-assisted and initiative cooling based water condensing method. Then, the uniform porous films with different morphologies were treated as negative templates for the straightforward micromolding of MLAs with well-controlled curvature on fluoropolymer encapsulation layers. Consequently, the emission intensity and light output power of DUV-LEDs were increased because the scattering effect of MLAs increases the critical angle and more light can escape out (Fig. 15(a) and (b)). Furthermore, Liang et al. [82] fabricated nanolens arrays (NLAs) on sapphire lens by nano-photolithography and wet-etched techniques for the light extraction of DUV-LEDs (Fig. 15(c)). By optimizing the NLAs with a radius of 350 nm, the highest light output power of DUV-LED was achieved (Fig. 15(d)). Ichikawa et al. [83] fabricated the DUV-LEDs with high light output power by using direct bonding methods at room temperature, including atomic diffusion bonding (ADB) and surface activated bonding (SAB). The hemispherical sapphire lenses were directly bonded on the chip surface without other interface layer, as presented in Fig. 16. Although these direct bonding methods can increase the light efficiency and reliability, the bonding process requires harsh conditions. Yan et al. [84] reported the DUV antireflection (AR) coating with a discrete-refractive index for the DUV-LEDs. The AR coating effectively matched the refractive index between air and sapphire and eliminated the Fresnel reflection at the sapphire-air interface, which can improve the LEE of DUV-LEDs.

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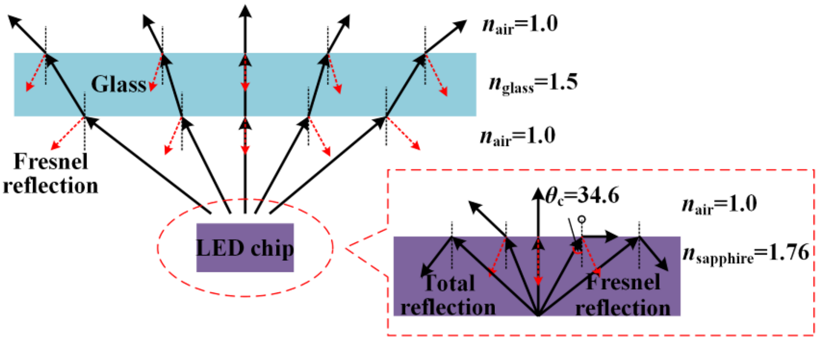

Fig. 14. Schematic of light transmission in the packaging structure of DUV-LED.

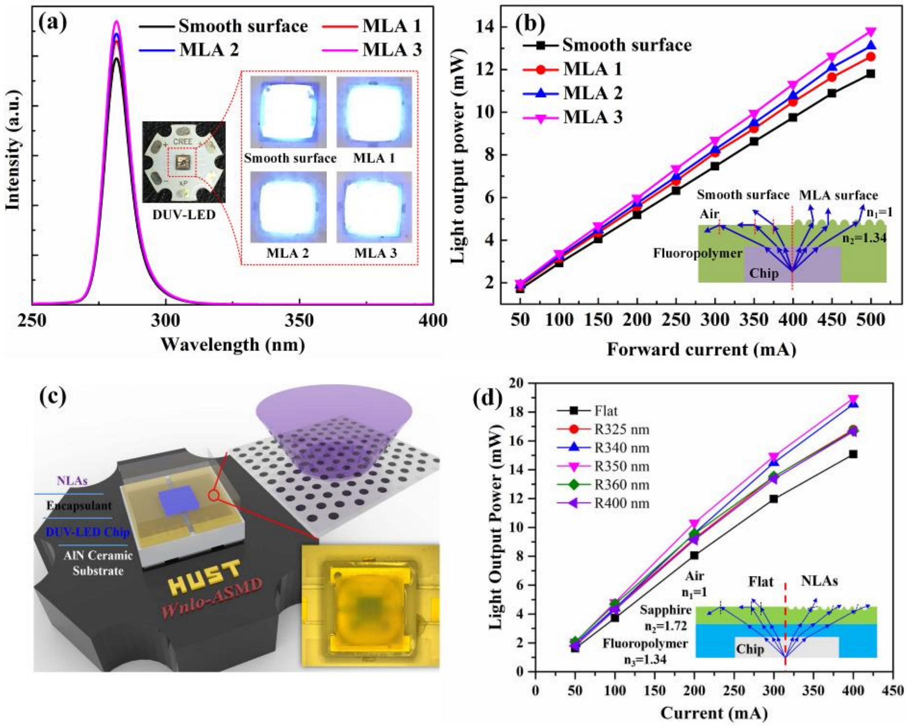

Fig. 15. (a) Emission spectra of DUV-LEDs packaged by fluoropolymer layers with different MLAs at a current of 350 mA. The inset shows the pictures of DUV-LEDs under operation. (b) Light output powers of DUV-LEDs packaged by different MLAs as a function of current. (c) Schematic of DUV-LED packaged by sapphire lens with NLAs. (d) Light output powers of DUV-LEDs packaged by different NLAs as a function of current.

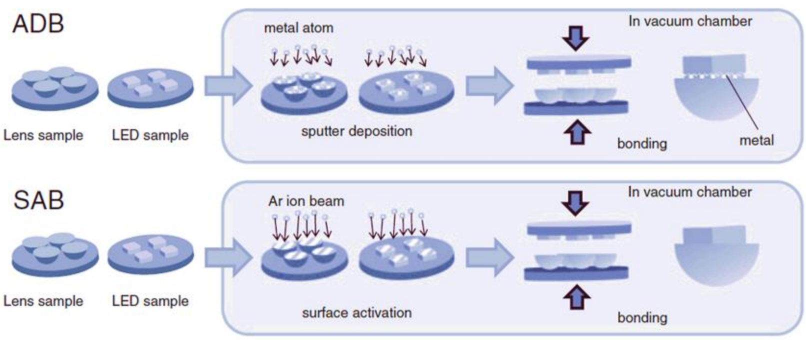

Fig. 16. Schematic illustration of the ADB and SAB processes for DUV-LED packaging.

Considering the difficult preparation of quartz lens, Nagai et al. [85] developed C–F-based fluoropolymers for DUV-LED packaging. The fluoropolymers have two terminal molecules of trifluoromethyl (-CF_3) and carboxylic acid (-COOH), which exhibit reasonably high transparency at the DUV region, as shown in Fig. 17. The aging tests indicated that no significant degradation was observed in the fluoropolymer with -CF_3 under DUV light, and the selected fluoropolymer can guarantee a lifetime of over 6,000 h at 265 nm [86, 87]. Unfortunately, the fluoropolymer with -CF_3 displays comparatively poor bonding ability, which is bad for the reliability of DUV-LED packaging. Liang et al. [88] proposed a graphene oxide (GO)-based fluoropolymer to achieve the better bonding ability of interface encapsulant and improve the LEE and working stability of DUV-LEDs, which is attributed to its superior interface performance based on an anchored effect (Fig. 18). Considering the low refractive index of fluoropolymer (~1.34), Peng et al. [89] proposed an AlN-doped fluoropolymer encapsulation layer to reduce reflection loss at the flat chip-encapsulation interface and then increase the light extraction from DUV-LED structure.

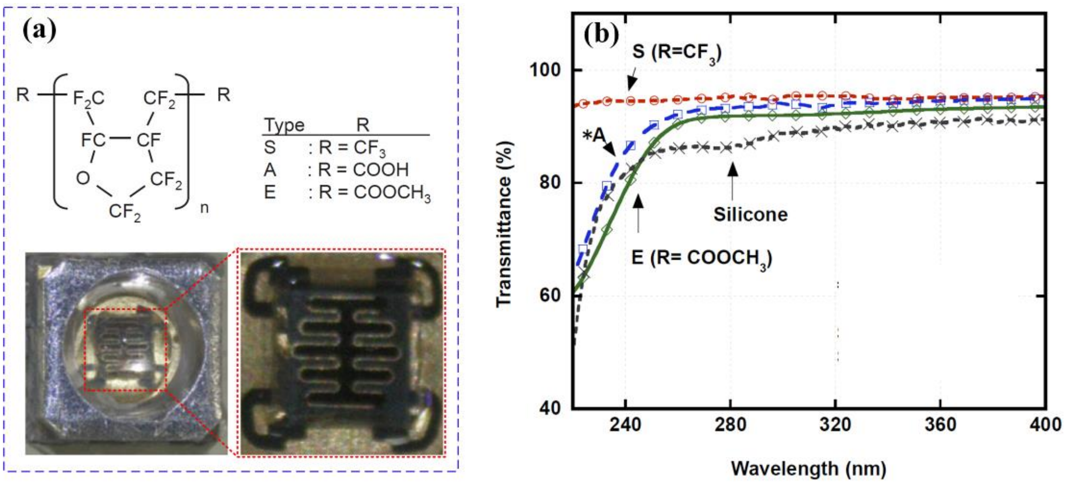

Fig. 17. (a) Molecular structures of amorphous fluoropolymers with various terminal ends and photographs of typical encapsulated DUV-LEDs. (b) Transmittance spectra of silicone and three types of fluoropolymers.

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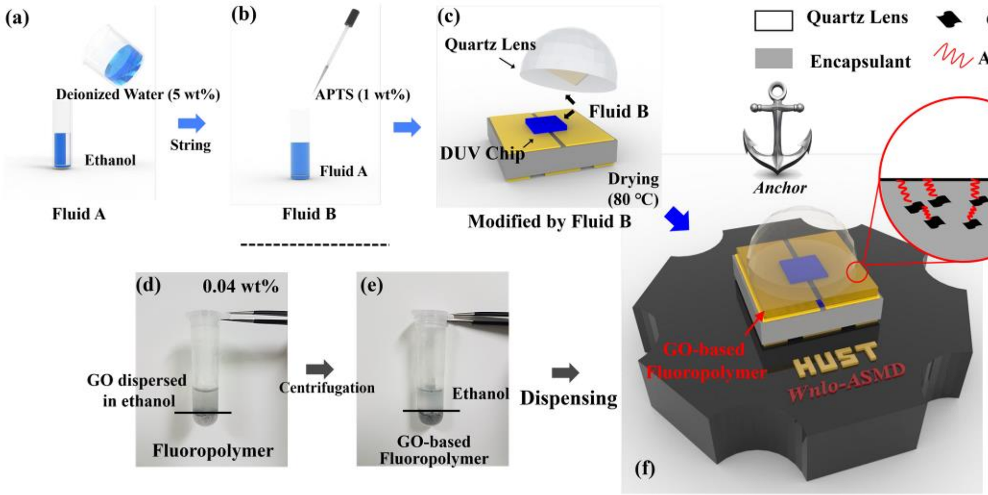

Fig. 18. Fabrication process of the DUV-LED packaged by GO-based fluoropolymer. (a) Fluid A: ethanol with 5 wt% deionized water; (b) fluid B: fluid A with 1 wt% APTS; (c) surfaces of sapphire and quartz lens modified using fluid B; (d) and (e) photographs of 0.10 wt% GO-based fluoropolymer; (f) typical packaging structure of DUV-LED.

4. Summary and Perspectives

The UV-LEDs have developed as promising UV sources in recent year due to their robustness, high efficiency, and environmental friendliness. The UV-LEDs exhibit widely applications in resin curing, general illumination, disinfection, and purification. In this review, we discussed the overview and challenges of UV-LED packaging. Due to their various UV photon energies, the packaging types of NUV-LEDs/DUV-LEDs and their key technologies are distinctly different. The corresponding progresses of NUV-LED/DUV-LED packaging were investigated. In order to enhance the light efficiency and reliability of UV-LEDs, the researches focus on the packaging materials, structures, and processes, including the all-inorganic packaging materials of ceramic substrate and quartz glass, the hermetic packaging structures with low-temperature bonding, the light extraction enhanced by reducing reflection losses, the UV stable and transparent fluoropolymers, and the effective thermal management.

The main objective of this review is to provide a comprehensive understanding of NUV-LED and DUV-LED packaging technologies. Many researches of UV-LED packaging that are worth exploring in the future, including but not limited to:

(1) Development of UV stable and transparent packaging materials. Due to the UV aging

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and disintegration, the common organic packaging materials of silicone and epoxy resin are inappropriate for UV-LED packaging. For this reason, the glass packaging is developed for UV-LED packaging. The glass packaging has several drawbacks such as limited light extraction and complex packaging process. Thus, it is highly desirable to develop new packaging materials that can meet the requirements of high UV transparency, excellent UV stability, and low-temperature process. Currently, the fluoropolymer with -CF_3 end group is an effective packaging material for UV-LEDs. However, this fluoropolymer still has some disadvantages, including low refractive index, poor affinity, and high preparation cost. Some intensive studies should be carried out on the fluoropolymers to realize the mass packaging of UV-LEDs.

(2) Exploration of new packaging structures and processes. In order to further improve the optical performances and reliability of UV-LEDs, new packaging structures need to be developed, such as surface roughing methods for reduced reflection losses, new lens structures for adjusted light distribution, and efficient heat managements of ceramic substrate, heat-conducting layer, and eutectic layer. Furthermore, effective and low-cost packaging processes should be explored for the mass-production of UV-LEDs, such as wafer packaging technologies of chip to wafer and wafer to wafer.

Many progresses have been achieved over the past years in UV-LED packaging, and further efforts to enhance the light efficiency and reliability of UV-LED devices remain necessary. This review provides a good summary of UV-LED packaging, which benefits to design and fabricate high-performance UV-LEDs and promotes their practical applications.

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Figure Captions List

Fig. 1 Application fields of UV-LEDs.

Fig. 2 Packaging types of NUV-LEDs.

Fig. 3 Packaging types of DUV-LEDs.

Fig. 4 Packaging process of DUV-LED with glass plate.

Fig. 5 NUV-LEDs packaged by bonding hemispherical glass lens.

Fig. 6 (a) Packaging structure and process of NUV-LEDs with AlN NPs doped silicone adhesive layer. (b) Light output powers of NUV-LEDs with different AlN NPs doping contents.

Fig. 7 Different-diameter SOG MLAs fabricated on the NUV-LED chip: (a) 50 μm, (b) 100 μm, (c) 150 μm, and (d) 200 μm.

Fig. 8 Schematic of NUV-LED packaged by AuSn eutectic bonding and its heat transfer path.

Fig. 9 (a) Proposed packaging structure of NUV-LEDs with GO-doped composite thermal interface. (b) Junction temperature change during cooling of sample 1 and sample 2 after embedding with the GO-based composite. (c) Normalized light output power of four samples as a function of the working time.

Fig. 10 Images of fabricated 3D ceramic substrates with different sizes by molding aluminosilicate pastes.

Fig. 11 Images of 3D ceramic substrates fabricated by the direct ink writing of kaolin suspensions.

Fig. 12 (a) Localized current heating and (b) parallel seam welding technologies for low-temperature bonding between glass plate and substrate.

Fig. 13 (a) Schematic illustration of localized induction heating and (b) temperature variation of A, B points on the DUV-LED during induction heating process.

Fig. 14 Schematic of light transmission in the packaging structure of DUV-LED.

Fig. 15 (a) Emission spectra of DUV-LEDs packaged by fluoropolymer layers with different MLAs at a current of 350 mA. The inset shows the pictures of DUV-LEDs under operation. (b) Light output powers of DUV-LEDs packaged by

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different MLAs as a function of current. (c) Schematic of DUV-LED packaged by sapphire lens with NLAs. (d) Light output powers of DUV-LEDs packaged by different NLAs as a function of current.

Fig. 16 Schematic illustration of the ADB and SAB processes for DUV-LED packaging.

Fig. 17 (a) Molecular structures of amorphous fluoropolymers with various terminal ends and photographs of typical encapsulated DUV-LEDs. (b) Transmittance spectra of silicone and three types of fluoropolymers.

Fig. 18 Fabrication process of the DUV-LED packaged by GO-based fluoropolymer. (a) Fluid A: ethanol with 5 wt% deionized water; (b) fluid B: fluid A with 1 wt% APTS; (c) surfaces of sapphire and quartz lens modified using fluid B; (d) and (e) photographs of 0.10 wt% GO-based fluoropolymer; (f) typical packaging structure of DUV-LED.

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Table Caption List

Table 1 Characteristics comparison of mercury lamps and UV-LEDs.