Epoxy Molding Compound Lead Frames With Silicone Resin for Encapsulating AlGaN-Based UVB Light-Emitting Diodes

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ABSTRACT In this paper we report epoxy molding compound lead frames (EMC-LFs) with encapsulated silicone as a simple and inexpensive packaging for AlGaN-based ultraviolet-B (UVB) light-emitting diodes (LEDs) displaying high light extracting efficiencies (LEE) and long operation lifetimes. The convex surfaces and beveled shapes obtained after curing the encapsulated silicone surrounding the UVB-LED chips significantly enhanced the light output power (LOP). With silicone present inside the EMC-LFs having bonding cavity diameters of 1.7 and 1.45 mm, the LOPs of the UVB-LEDs improved by 26 and 42%, respectively; reliability tests performed over a period of 1000 h revealed, however, that the LOPs decreased to 70 and 71%, respectively, of their initial values, but no cracks appeared in the silicone during such long-term operation. Thus, the stability of silicone-encapsulating EMC-LFs for UVB-LEDs was acceptable. When compared with AlN-based direct plating copper ceramic lead frames (AlN-DPC-LFs), our proposed packaging structure and method have the potential to lower the manufacturing cost of UVB-LEDs.

INDEX TERMS AlGaN, AlGaN-based ultraviolet-B LEDs, packaging, light output power.

I. INTRODUCTION

III-Nitride–based deep-ultraviolet (DUV) light-emitting diodes (LEDs) have a wide range of applications. By alloying GaN with AlN, the emission of AlGaN-based LEDs can be tuned to cover almost the entire ultraviolet (UV) spectral range (200–365 nm), making them perfectly suited to applications in biological, environmental, industrial, and medical fields [1], [2]. AlGaN-based ultraviolet-B (UVB) LEDs began attracting great attention after implementation of the Minamata Convention on Mercury. Such LEDs have much potential for use in medical (e.g., cancer immunotherapy; treatment of psoriasis, vitiligo, and pemphigus vulgaris) and agricultural (e.g., plant growth under UVB lighting; production of phytochemicals in the green leaves of vegetables) applications [3]–[7]. Verhaeghe et al. found that narrow-band (NB-UVB) emission therapy at 310 nm was more effective than broad-band (BB-UVB) therapy at 280–320 nm in the treatment of psoriasis and atopic dermatitis; furthermore, NB-UVB phototherapy with emission at 310 nm appears suitable for cancer therapy and skin cure therapy [8], [9]. Several reports have disclosed high external quantum efficiencies (EQEs: 2–5%) for UVB-LEDs prepared using a combination of low-dislocation-density AlN template substrates, an electron injection layer, a transparent p-AlGaN layer, and reflective electrodes [10]–[13]. Because it has not been possible to prepare high-hole-density p-AlGaN layer, and reflective electrodes [10]–[13]. Because it has not been possible to prepare high-hole-density p-AlGaN with a high Al content (>50%), it has remained necessary to use p-GaN as the contact layer to lower the series resistance of UVB-LEDs, although its presence significantly decreases...
the LEE as a result of the strong absorption of UVB light. Moreover, several reports have suggested the poor reliability of silicone, as an encapsulating material, against DUV light [14]–[16]. Therefore, to improve the reliability of UVB-LEDs, the mainstream design for packaging has involved flipping the LED chip bonded onto the AlN-based LFs and using an attached quartz glass as a hermetic cover. This kind of packaging structure for DUV-LEDs comes, however, with higher materials costs, severely decreased light extraction, and limited optical performance [17]–[20]. Some DUV-transparent encapsulation materials have been proposed to ameliorate these drawbacks such as sol–gel methyl siloxane hybrid material, fluorine resins, and liquid packaging structure [21]–[23]. In practical application, EMC-LFs have also been applied commonly in conventional packaging of semiconductors and LEDs because they can be introduced with low manufacturing costs [24]–[26]. And others have also proposed some special packaging methods such as microlens arrays and graphene oxide-based fluoropolymer interface encapsulant to improve the light extraction efficiency [27], [28].

In this study, we developed an inexpensive and highly durable packaging structure, using reliable silicone as the encapsulation material, to improve the LEEs of UVB-LEDs. Compared with AlN-DPC-LFs, the use of such EMC-LFs has the potential to decrease the cost of manufacturing UVB-LEDs.

**II. EXPERIMENTAL**

Fig. 1 provides a schematic representation of the AlGaN-based UVB-LED heterostructure.

![Schematic representation of the investigated AlGaN-based UVB-LED heterostructure.](image)

**TABLE 1.** The structures of the various packaging types. A1 and A2 denote EMC-LFs having a filling encapsulant in the cavity and bonding cavity diameters of 1.7 and 1.45 mm, respectively; A3 denotes an AlN-DPC-LF having a filling encapsulant in this study and obtained from Jusheng Optoelectronics (Shenzhen, China) [29]; the curing process took approximately 3 h at 150 °C in each case. The absorbance was less than 1% for wavelengths in the range from 280 to 320 nm. The dimensions of the EMC-LF and AlN-DPC-LF were 3.0 × 3.0 × 0.5 mm and 3.75 × 3.75 × 1.4 mm, respectively.

| Type | Description |
|------|-------------|
| A1   | EMC-LF with silicone resin, bonding cavity diameter of 1.7 mm, filling encapsulant in cavity |
| A2   | EMC-LF with silicone resin, bonding cavity diameter of 1.45 mm, filling encapsulant in cavity |
| A3   | AlN-DPC-LF with 20% silicone resin, bonding cavity diameter of 1.45 mm, filling encapsulant in cavity |

The prepared UVB-LED chips were separately flip-bonded on two types of EMC-LF having different bonding areas, and an AlN-DPC-LF was introduced through soldering to function as a thermal interface. The silicone (JS-UV200-L) shows good transmittance in UVB band was used as the encapsulant in this study and obtained from Jusheng Optoelectronics (Shenzhen, China) [29]; the curing process took approximately 3 h at 150 °C in each case. The absorbance was less than 1% for wavelengths in the range from 280 to 320 nm. The dimensions of the EMC-LF and AlN-DPC-LF were 3.0 × 3.0 × 0.5 mm and 3.75 × 3.75 × 1.4 mm, respectively.

**FIGURE 1.** Schematic representation of the investigated AlGaN-based UVB-LED heterostructure.
value of $I_f$ of 40 mA at room temperature (RT). To mimic feasible application conditions, the input power for each sample was selected to be close to 0.2 W.

### III. RESULTS AND DISCUSSION

Table 2 lists the values of $V_f$, the EL peak wavelength, the EL full width at half maximum (FWHM), and the LOP at a value of $I_f$ of 40 mA measured before and after filling silicone as the encapsulant into samples A1, A2, and A3. All of the EL spectra featured a near-constant peak wavelength of approximately 310 nm and a FWHM of approximately 9.3 nm. Furthermore, the average variations in the values of $V_f$ were all less than 2%. In contrast, significant enhancements in the LOP occurred for samples A1, A2, and A3 after encapsulation (26, 42, and 14%, respectively), presumably because of lower degrees of total internal reflection (TIR) after decreasing the refractive index ($n$) gap between the UVB-LED chip (sapphire; $n = 1.82$) and air ($n = 1$) by encapsulating silicone inside the cavity [30].

The different enhancement ratios arose from the variations in the form of the encapsulated silicone after curing. Fig. 2(a) and 2(b) present photographs of the UVB-LED chips and silicone structures in the cavities of the three package samples. The cured silicone in samples A1 and A2 had a convex surface; in contrast, it had a concave surface in sample A3. Furthermore, the shapes of the cured silicone structures surrounding the UVB-LED chips in samples A1 and A2 were obviously beveled (Fig. 2(a)). These phenomena were presumably caused by the distribution of soldering between the bonding pads of the UVB-LED chip and the bonding area of the EMC-LF. The more titled angle of the silicone around the chip in sample A2 resulted in its greater enhancement of LOP. Accordingly, in the active region of $c$-plane AlGaN, the transverse electric (TE) polarized light propagated mainly in the vertical direction, whereas the transverse magnetic (TM) polarized light propagated mainly in the lateral direction and underwent greater total internal reflection (TIR) than did the TE-polarized light [31]. Ryu reported a simulation in which the LEE of the TM mode was more than 10 times smaller than that of the TE mode in flip-chip DUV LEDs [32]. Enhancement in TM-polarized light of the UVB-LEDs occurred upon increasing the Al content in the AlGaN-based active region. Our present experimental results demonstrated, however, that the LEE from the UVB-LED chip to the environment could be enhanced in the lateral direction by controlling the shape of the cured silicone.
Fig. 3(a) and 3(b) display the relative LOPs of the package samples over time. The values were normalized to the initial value. During operation over an aging time of 1000 h, whether silicone was encapsulated in the cavity or not, the rates of degradation of A1/A2 and B1/B2 were faster than those A3 and B3, respectively. The LOP decreased more rapidly at the onset of operation and slowed down during operation between 200 and 1000 h. Such linear time-dependence of the LOPs of LEDs has been discussed previously [33]–[35]. The mechanism is usually associated with diffusion of the metal contact or dopant atoms having a faster degradation rate. Interestingly, while the LOPs decreased upon increasing...
The LOP of A1, A2, A3, B1, B2 and B3 after 1000 h aging is the degradation tendency of LOPs during the operation were for 1000 h. Similar behaviors of improving the LEE and but also slightly decrease the decay of the LOP after operation cavity of the AlN-DPC-LF could not only improve the LEE and decrease the radiation recombination rate [35]; the second reason could be attributed to breaking of Mg–H complexes in the p-layer close to the active region because this process might introduce electrically active point defects as non-radiative recombination centers [36], [37].

At the onset of operation, but before 200 h, the voltages decreased noticeably (average decrease: 6.4%), but remained relatively stable thereafter during operation between 200 and 1000 h. Fig. 4 and 5 suggest, however, that these tendencies could not be attributed to mechanisms involving degradation of the contacts due to metal migration, generation of point defects, or dislocations in the active region. Accompanied by the presence of the encapsulating silicone, we provided two possible mechanisms responsible for the degradation processes occurring in UVB-LEDs: the first one could be the result of decreases in the internal quantum efficiencies of the LED chips, caused by the thermal effect due to higher chip temperature, and that will increase the non-radiation rate and decrease the radiation recombination rate [35]; the second reason could be attributed to non-radiative recombination centers [36], [37].

Fig. 3(a) and 3(b) provide the results of an additional analysis performed after operation for 1000 h; the relative LOPs of samples A3 and B3 decreased to 78 and 75% of their initial values, respectively. Thus, the silicone within the cavity of the AlN-DPC-LF could not only improve the LEE but also slightly decrease the decay of the LOP after operation for 1000 h. Similar behaviors of improving the LEE and the degradation tendency of LOPs during the operation were observed for the EMC-LFs. The relative LOPs of samples A1, A2, B1, and B2 decreasing to 70, 71, 68, and 71%, respectively, of their initial values after operation for 1000 h. The LOP of A1, A2, A3, B1, B2 and, B3 after 1000 h aging is 2.478, 2.598, 2.735, 1.946, 1.972, and 2.52 mW, respectively. These greater decreases in LOPs might have been caused by the lower thermal conductivity of the EMC-LFs in comparison with the AlN-DPC-LFs.

Nevertheless, no cracks were evident in photographs of samples A1, A2, and A3 after aging for 1000 h (Fig. 2(b)). Thus, the main mechanism responsible for the degradation of the LOPs was not cracking of the silicone in the cavities [14]. Furthermore, our results suggest that EMC-LF packaging with encapsulating silicone is suitable for long-term operation of UVB-LEDs in applications requiring lower input power.

IV. CONCLUSION

In conclusion, with comparison to the conventional method by using AlN-DPC-LFs, we report that encapsulating silicone in EMC-LFs appears to be a simple and inexpensive packaging technology that can increase the LEEs and operation lifetimes of AlGaN-based UVB-LEDs. Convex surfaces and beveled shapes were formed after curing the encapsulated silicone surrounding the UVB-LED chips, leading to significant enhancements in the LOP. When silicone was present inside EMC-LFs having bonding cavity diameters of 1.7 and 1.45 mm, the LOPs of the UVB-LEDs improved by 26 and 42%, respectively. The lower enhancement in the LOP of the corresponding AlN-DPC-LF (14%) was due to the concave surface of the silicone over the UVB-LED chip. Nevertheless, reliability test performed over 1000 h revealed that the LOPs decreased to 70 and 71% of their initial values after encapsulating silicone in the 1.7- and 1.45-mm-diameter EMC-LFs, respectively, but no cracks appeared in the silicone during long-term operation. In comparison, the LOPs of the UVB-LED chips containing AlN-DPC-LFs prepared with and without encapsulating silicone decreased to 78 and 75%, respectively, of their initial values. These results suggest that our proposed packaging structure and method have the potential to further lower the manufacturing costs of UVB-LEDs.

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