the society for solid-state and electrochemical science and technology

Electrochemical and Solid-State Letters

Thermal Behavior of Sapphire-Based InGaN Light-Emitting Diodes with Cap-Shaped Copper –Diamond Substrates

Ray-Hua Horng, Hung-Lieh Hu, Re-Ching Lin, Kun-Cheng Peng and Yi-Chen Chiang

Electrochem. Solid-State Lett. 2011, Volume 14, Issue 5, Pages H215-H217.
doi: 10.1149/1.3559794

Electrochemical and Solid-State Letters, **14** (5) H215-H217 (2011)
1099-0062/2011/14(5)/H215/3/$28.00 © The Electrochemical Society

Thermal Behavior of Sapphire-Based InGaN Light-Emitting Diodes with Cap-Shaped Copper–Diamond Substrates

Ray-Hua Horng,[a,b,*,z] Hung-Lieh Hu,[b] Re-Ching Lin,[c] Kun-Cheng Peng,[d] and Yi-Chen Chiang[b]

[a]*Department of Electro-Optical Engineering, National Cheng Kung University, Tainan 701, Taiwan*
[b]*Institute of Precision Engineering and* [c]*Research Center for Advanced Industry Technology and Precision Processing, National Chung Hsing University, Taichung 402, Taiwan*
[d]*Department of Materials Engineering, Ming-Chi University of Technology, Taipei 243, Taiwan*

Light-emitting diode (LED) packages with various heat spreaders were developed to examine the heat dissipation property of sapphire-based LEDs. A cap-shaped copper–diamond sheet was fabricated by composite electroplating and directly contacted to the sapphire surface to enhance heat dissipation from the chip. The thermal diffusivity of the copper–diamond sheet was 0.7179 cm^2/s, as measured using the laser-flash method. LEDs with the copper–diamond sheet presents low surface temperature (49°C at 700 mA injecting current) and low thermal resistance (5.8 K/W). These findings suggest that the copper–diamond sheet helped reduce LED thermal resistance, and thereby prevented heat accumulation. The LED package also exhibited high light output power.
 [DOI: 10.1149/1.3559794]

Manuscript submitted January 17, 2011; revised manuscript received February 7, 2011. Published March 4, 2011.

Recently, there have been considerable improvements in the internal quantum efficiency and light extraction of InGaN light-emitting diodes (LEDs) for high-brightness applications. However, most studies have focused on epitaxial structures or thin GaN LED processing. Developments in sapphire-based, high-power InGaN LEDs have been hampered mainly by their poor heat dissipation.[1] On the other hand, sapphire-based chips in LED packages are always mounted on a heat sink by silver paste. The Joule heat generated is dissipated from the sapphire to the silver paste and then to the heat sink. As both sapphire and the silver paste possess high levels of thermal resistivity, sapphire-based InGaN LEDs suffer from power saturation at high-currents due to elevated junction temperature.[2] Direct contact of sapphire with a cap-shaped pure copper sheet has been demonstrated to enhance thermal extraction from sapphire-based LEDs.[3] Diamond is a material with high thermal conductivity (2300 W/mK); likewise, diamond-based solder pastes also have high thermal conductivity.[4] Previous work focused on either chip resistance minimization or package designs for thermal management.[3–7] In the present study, use of a cap-shaped sheet consisting of a diamond-added copper (DAC) heat spreader for chip heat dissipation was explored and is herein proposed. The composite electroplating technique was adopted to fabricate a sapphire-based LED with the DAC substrate. The thermal conductivity of the DAC substrate was measured, and the thermal and optical properties of the LED with the DAC substrate were also evaluated.

Experimental

Blue InGaN LEDs ($\lambda_p = 455$ nm) were grown on a sapphire substrate by low-pressure metal-organic chemical vapor deposition. The LED structure was composed of a low-temperature GaN buffer layer (30 nm), an undoped GaN layer (1.5 μm), a Si-doped n-type GaN layer (3 μm), an InGaN/GaN multiple-quantum well stack, and an Mg-doped p-type GaN layer (0.3 μm). After LED chip (with 1 mm^2 area) processing, the back side of the sapphire substrate was lapped, polished, and coated with an Ag reflector. Composite electroplating and self-aligned lithography were then used to fabricate the sapphire-based InGaN LEDs with cap-shaped heat spreaders. In composite electroplating, the copper plate with 5 N purity was used as the anode. The electrolyte solution consisted of copper sulfamate (200 g/L, 0.5 M), hydrochloric acid (1 mL/L), sulfuric acid (65 g/L, 0.38 M), sodium dodecyl sulfate (1 mL/L), poly(ammonium acrylate) (1 mL/L), and thallium sulfate (1 g/L). Commercial diamond powder (5 g/L) with a 0.5 μm particle diameter of was mixed into the solution for composite electroplating. The electrolyte solution was circulated by pump during this process. Note that, it is hard to calculate or measure the mass ratio of copper to diamond particles in the finished, plated DAC substrate due to the related low amount of diamond particles. However, the amount of diamond powder can be controlled by the electroplating current density. The electrolyte was maintained at room temperature using a control module. A square pulse current with a peak of 0.3 A (40 ms)/−0.05 A (20 ms) for the duty cycle was adopted in the plating process. The DAC heat spreader was electroformed with a thickness of 250 μm and a base area of 3 mm × 3 mm, which is nine times the base area of conventional sapphire-based LED power chips. For comparison, a sapphire-based LED with a cap-shaped heat spreader of pure Cu was also prepared. The fabrication process for cap-shaped heat spreaders has been previously described in detail.[3,4] Finally, these devices were attached to a metal-core printed circuit board (MCPCB, with 2 cm diameter and 1.5 mm thickness) by SnAgCu solders. LEDs with the cap-shaped copper heat spreader and the conventional sapphire substrate packaged on MCPCBs were also used to evaluate the performance of the LED with the DAC heat spreader. The current–voltage characteristics and light output power of the LEDs were measured at room temperature using an Agilent 4155B semiconductor parameter analyzer and an integration sphere detector (CAS 140B, Instrument Systems), respectively. The surface thermal property of the LEDs was evaluated by thermal infrared imaging at thermal equilibrium using a measuring current of 700 mA under a close ambient. A T3Ster Master system was used to analyze the total thermal resistance based on thermal transients. The thermal diffusivity of the DAC substrate was measured using the laser-flash method.

Results and Discussion

The sapphire-based LED with the DAC substrate packaged on the MCPCB is shown in Fig. 1a. The Ag reflector on the DAC substrate is shown in Fig. 1b, which magnifies the image shown in panel (a). Figure 1c shows a cross-sectional image of the above-mentioned package as observed by scanning electron microscopy (SEM). The DAC substrate was closely contacted to the sapphire substrate without any voids. The cap-shaped reflector was well controlled by self-aligned lithography.

Substrate cross-sections were observed by SEM and measured by elemental analysis (Fig. 2) to characterize the diamond present in the DAC heat spreader. Diamond powders (particle size <5 μm) were distributed uniformly on the copper substrate and they do not cluster into a large particle size (>10 μm). Results from the elemental analysis indicate that diamond was present in the DAC heat spreader.

* Electrochemical Society Active Member.
z E-mail: rhhorng@mail.ncku.edu.tw

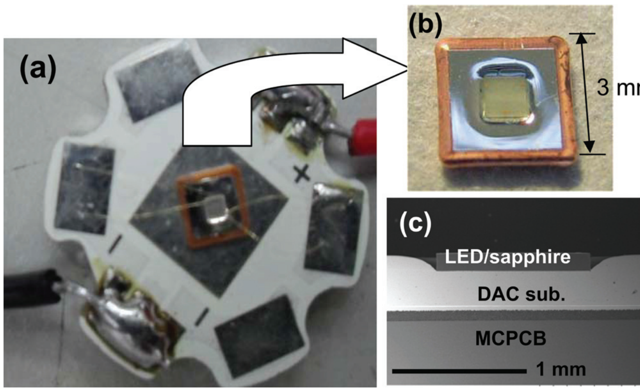

Figure 1. (Color online) (a) Packaged LED sample, (b) magnified image of the sapphire-based LED with the DAC heat spreader, and (c) cross-sectional SEM image.

Evaluating the thermal behaviors of LEDs with and without cap-shaped DAC and copper heat spreaders is important. The most straightforward method for this purpose is measuring the thermal resistance.[8] Figure 3 depicts the thermal capacitance as a function of

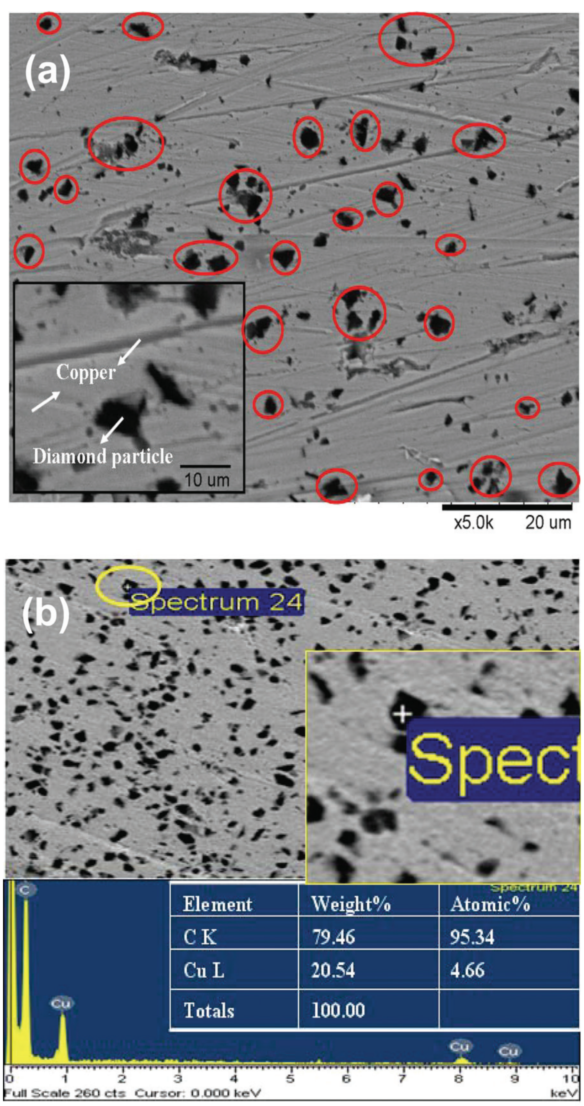

Figure 2. (Color online) (a) Substrate cross-sectional SEM image and (b) elemental analysis results for the LED with a DAC heat spreader.

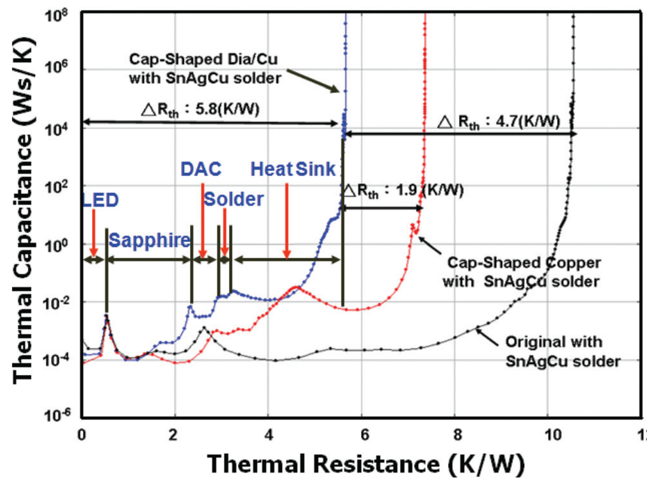

Figure 3. (Color online) Thermal capacitance as a function of total thermal resistance for the LEDs with DAC, copper, and sapphire substrates packaged on MCPCB by SnAgCu solder.

the total thermal resistance for the LEDs with the DAC heat spreader, the copper heat spreader, and the sapphire-based original structure. The total thermal resistance of the LED surrounded with the DAC substrate was 5.8 K/W, which was lower than the total thermal resistance of the LED surrounded with pure copper (7.7 K/W) and of the LED with the sapphire substrate only (10.5 K/W). The differences among the three samples depended on the presence of DAC or Cu, which contributes to thermal resistance reduction. In particular, the total thermal resistance of the LED with the DAC heat spreader considerably decreased. This indicates that the DAC was useful in reducing the LED thermal resistance.

Figure 4 displays the surface temperature distribution of LED chips (700 mA, 3 W) with the DAC heat spreader, the pure copper heat spreader, and the original structure. The surface temperature of the LED with the DAC heat spreader was 49.0°C, which was lower than the surface temperatures of the LED with the pure copper heat spreader (52.75°C) and the LED with the sapphire substrate (59.16°C). Thermal accumulation also occurred in the LED with a sapphire substrate. In contrast, the LEDs with DAC and copper heat spreaders had more rapid temperature grading. The surrounding temperatures were approximately 65, 45, and 42°C for the sapphire-based LED, the LED with the copper heat spreader, and the LED with the DAC heat spreader, respectively. These results suggest that the thermal LED junction temperature can be effectively dissipated by Cu or a DAC heat spreader.

In general, thermal dissipation is dependent on the thermal conductivity (k) of materials. The thermal conductivity of the DAC substrate thus had to be evaluated. On the other hand, it is well known that thermal conductivity and thermal diffusivity are the most important thermophysical material parameters for the description of the heat transport properties of a material or component. For the precise measurement of thermal diffusivity, the laser flash technique has proven itself as a fast, versatile and precise absolute method. In this method, a short pulse (<1 ms) of heat is applied to the front face of a specimen using a laser flash, and the temperature change of the rear face is measured with an infrared (IR) detector.[9] The thermal diffusivity of the specimen can be obtained. This property was calculated from the following equation[10]

$$k = D \times \rho \times c \quad [1]$$

where D, ρ, and c denote thermal diffusivity, mass density, and specific heat, respectively. The thermal diffusivity of the DAC substrate was 0.7179 cm^2/s, which was higher than that of pure copper (0.117 cm^2/s), as measured using the laser-flash method. The thermal conductivity of the DAC substrate obtained from Eq. 1 was

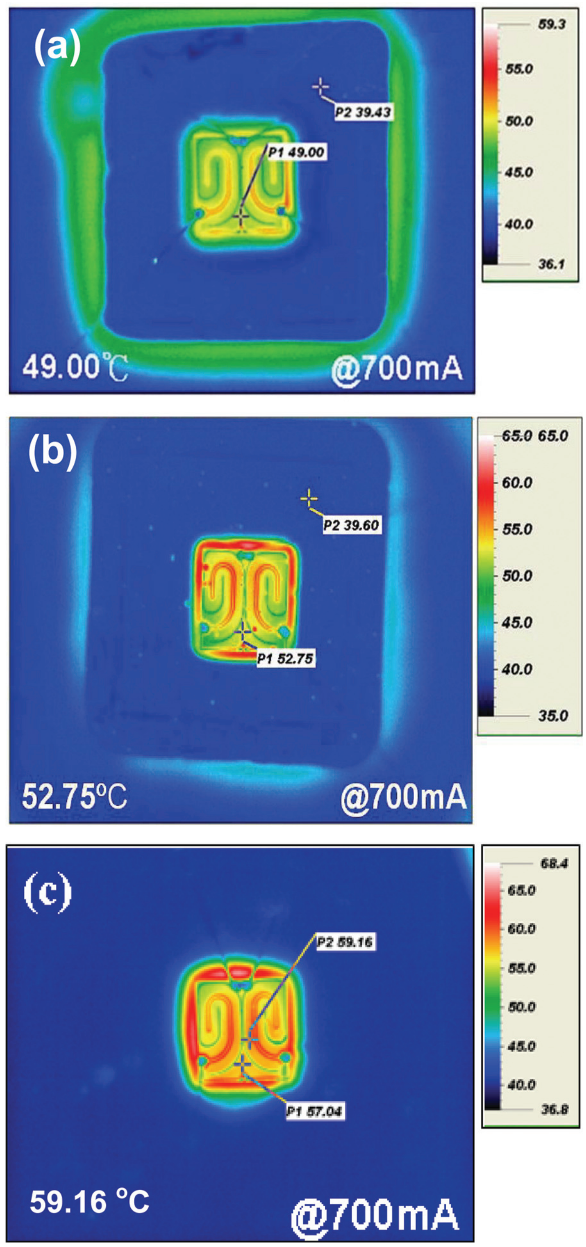

Figure 4. (Color online) Surface temperature distribution of LEDs under 700 mA (3 W) injected current for the LEDs with (a) DAC, (b) pure copper, and (c) sapphire substrates.

492.4 W/mK, also higher than that of pure copper (457.4 W/mK).[10] These results demonstrate that the DAC substrate can provide better thermal dissipation than the pure copper and sapphire substrates. This finding is consistent with the data on thermal resistance and surface temperature of LED chips shown in Figs. 3 and 4. It is worthy to mention that the measurement of thermal resistance is different from that of surface temperature. For the former, it is measured based on thermal transient. On the contrary, the surface temperatures of LEDs were measured under a thermal equilibrium and close ambient. Thus the obtained surface temperature could be higher than the calculated temperature using the thermal resistance. Nevertheless, the tendency of the junction temperature behaviors for these samples obtained from thermal resistance and IR microscope are almost the same.

Measuring device performance is another method to characterize the thermal dissipation properties of LEDs. Figure 5 shows the output power of the three LED samples as a function of the injected current. The LED packaged with the DAC substrate showed supe-

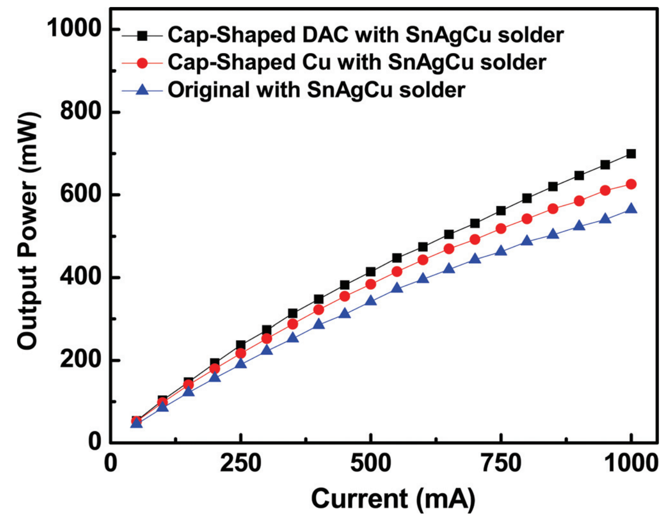

Figure 5. (Color online) Light output power of the LEDs with DAC, copper, and sapphire substrates packaged on MCPCB by SnAgCu solder.

rior performance in terms of output power because of its preformed reflector and high thermal dissipation. The output power levels were approximately 313, 287, and 253 mW for the LED (350 mA) with the DAC heat spreader, the LED with the copper heat spreader, and the LED with a sapphire substrate, respectively. The light output of LED with DAC substrate among the LEDs was highest under 1 A injected current. As all the LEDs were grown with the same epitaxial structure and fabricated with equal chip sizes, the observed power enhancement might be primarily attributed to the relatively high capacity of the DAC substrate to dissipate heat.

Conclusions

In this study, composite electroplating was adopted to form a sapphire-based LED with a DAC composite on a cap-shaped sheet. The heat dissipation ability of the LEDs improved as a result of the high thermal conductivity of the cap-shaped copper–diamond sheets. Low chip temperature enhanced the output power of the LED with the DAC heat spreader. The DAC reduced the LED thermal resistance and improved the light output power.

Acknowledgments

This work was supported by the Ministry of Economic Affairs (Contract No. 99-EC-17-A-07-SI-158) and the Electronics and Optoelectronics Research Laboratories of the Industrial Technology Research Institute (Contract No. 99-B-08).

National Cheng Kung University assisted in meeting the publication costs of this article.

References

1. Y. S. Choi and S. J. Kim, *Solid-State Electron.*, **50**, 1522 (2006).
2. E. Fred Schubert, *Light-Emitting Diodes,* Cambridge University Press, New York (2003).
3. R. H. Horng, C. C. Chiang, H. Y. Hsiao, X. Zheng, D. S. Wuu, and H. I. Lin, *Appl. Phys. Lett.*, **93**, 111 907 (2008).
4. R. H. Horng, J. S. Hong, Y. L. Tsai, D. S. Wuu, C. M. Chen, and C. J. Chen, *IEEE Trans. Electron. Device*, **57**, 2203 (2010).
5. T. Fujii, Y. Gao, R. Sharma, E. L. Hu, S. P. DenBaars, and S. Nakamura, *Appl. Phys. Lett.*, **84**, 855 (2004).
6. T. Gessmann, H. Luo, J. Q. Xi, Klaus P. Streubel, and E. Fred Schubert, *Proc. SPIE Int. Soc. Opt. Eng.*, **5366**, 53 (2004).
7. R. H. Horng, H. Y. Hsiao, C. C. Chiang, D. S. Wuu, Y. L. Tsai, and H. I. Lin, *IEEE J. Sel. Top. Quantum Electron.*, **15**, 1281 (2009).
8. G. Molnár, G. Nagy, and Z. Szőcs, *Proceedings of the 14th International Workshop on Thermal Investigations of ICs and Systems (THERMINIC'08)*, Rome, Italy (2008).
9. S. Graham, D. L. McDowell, E. L. Curzio, R. B. Dinwiddie, H. Wang, and W. Porter, *J. Compos. Mater.*, **37**, 73 (2003).
10. K. Yoshida and H. Morigami, *Microelectron. Reliab.*, **44**, 303 (2004).