Electrochemical and Solid-State Letters

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Electrochem. Solid-State Lett. 2011, Volume 14, Issue 11, Pages H453-H456.
doi: 10.1149/2.008111esl

Electrochemical and Solid-State Letters, **14** (11) H453-H456 (2011)
1099-0062/2011/14(11)/H453/4/$28.00 © The Electrochemical Society

Diamond-Added-Copper Heat Spreader for UV LED Applications

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

[a]*Graduate Institute of Precision Engineering, National Chung Hsing University, Taiwan*
[b]*Department of Electro-Optical Engineering and Advanced Optoelectronic Technology Center, National Cheng Kung University, Tainan 701, Taiwan*
[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*
[e]*Electronics and Opto-electronics Research Laboratories, Industrial Technology Research Institute, Hsinchu 300, Taiwan*

In this study, composite electroplating technique is used to fabricate the diamond-added copper (DAC) heat spreader for UV LED applications. Thermal dissipation characteristic and optical performance are improved as the composite DAC heat spreader adoption. The low thermal resistance of 18.4 K/W with UV LED using DAC heat spreader was measured. Surface temperature of UV LED using the DAC heat spreader is 45.32°C (at 350 mA injecting current), which is lower than those of LEDs using pure copper heat spreader (50.11°C) and only sapphire substrate (62.49°C). The thermal diffusivity of the DAC is 0.7179 cm^2/s measurement by laser flash method. Output power and power efficiency of UV LEDs are also enhanced to 71.81 mW and 4.32%, respectively, at 350 mA injection current. The optimal structure design and materials fabrication will be discussed.
 [DOI: 10.1149/2.008111esl]

Manuscript submitted June 23, 2011; revised manuscript received July 22, 2011. Published September 23, 2011.

Ultraviolet (UV) spectral range light emitting diodes (LEDs) are extensively studied for many applications. UV exciting sources for solid-state lighting based on various phosphors for white light generation are considerable effort in the development.[1] Backlight source for cell phones, and liquid crystal display televisions have become possible as the brightness increasing based on UV LEDs.[2] To improvement the power efficiency of UV LED is an important assignment, recently. Especially, the low power efficiency of UV LED leads more high heat generation. Therefore, high thermal dissipation design of spreader for UV LED is great urgency. In our pervious research, the cup-shape copper spreader has been developed to enhance thermal dissipation of high power LEDs, successfully.[3] The direct contact of sapphire with cup-shaped copper sheet was explained to improve heat dissipation from sapphire-based LEDs. It is well known that the diamond is a highly thermal conductive (2300 W/mK) material, and diamond-added solder pastes has been demonstrated to present excellent thermal conductive capability.[4] Diamond is a perfect thermal dissipation material, but it is difficult to fabricate in LED spreader application. Thus, composite materials of diamond and copper are to propose in high thermal dissipation application.[5] In this paper, an optimum materials for cup-shaped material consisted of diamond-added copper (DAC) heat spreader for UV LED chip heat dissipation was proposed.

Experiment

In this study, the UV-LEDs with 395-400 nm wavelength were fabricated on 2-inch c-axis orientation sapphire substrates using an metalorganic chemical vapor deposition (MOCVD) system. The UV LED structure consisted of 30-nm-thick low temperature GaN buffer layer, a 2-μm-thick undoped GaN layer, a 50 nm heavily Si-doped GaN layer, a 2.5 μm *n*-AlGaN contact layer, MQW active region, a 15 nm Mg-doped AlGaN cladding layer, and a 0.2 μm Mg-doped GaN contact layer. The ITO current speading layer, p electrode pads and n electrode pads were deposited by E-beam evaporator. The inductively coupled plasma (ICP) etching system was used in mesa etching processes to define the n-region. The backside of sapphire substrate was lapped, polished and deposited with reflector. In order to evaluate the ability of thermal dissipation, all the UV-LEDs have been measured and presents the same performance before cup-shaped electrplating processing. The composite DAC volume ratio of diamond to copper is 2: 100. It is the maximun ratio of diamond addition. If the ratio is further increased, the diamond could be precipitated. In this study, the heat spreader using DAC and pure copper were fabricated with thickness of 250 μm and a base area of 3×3 mm^2.[3,4] After the heat spreader electroforming processes, UV LED device with DAC, pure copper heat spreader and only sapphire substrate were attached on metal-core printed circuit board (MCPCB, with 2-cm diameter and 1.5 mm thickness) using SnAgCu solders. UV LED with DAC heat spreader, pure copper heat spreader and only sapphire substrate packaged on MCPCBs were prepared to evaluate performance. Detailed fabrication process of the cup-shaped heat spreader has been published elsewhere.[3,4] Current–voltage (*I–V*) characteristic and light output power of LEDs were measured at room temperature using an Agilent 4155B semiconductor parameter analyzer and integration sphere detector (CAS 140B, Instrument Systems), respectively. A thermal property was evaluated using thermal infrared image in thermal equilibrium at measurement current of 350, 500 and 700 mA under close ambient. A T3Ster Master system was used to analyze total thermal resistance based on thermal transient. The thermal diffusivity of the DAC substrate was measured by laser flash method.

Results and Discussion

Figure 1 indicates the UV LED chip attachment to cup-shape heat spreader rigidly precise. The interface between LED chip and spreader appears an absolutely faultless performance as shown in Fig. 1b. The strongly combination of LED chip, heat spreader and MCPCB provides that unimpeded thermal conduction path. On the other hand, the Ag mirror was coated on cup-shape heat spreader that will reflect principally generated light from LED chip. The cup-shape mirror is well controlled by the self-aligned lithography.

It is easy to perceive the contrast between thermal dissipation and various heat spreader structures as shown in Fig. 2. The highest thermal resistance of 58.4 K/W was obtained as the only sapphire substrate UV LED directly was packaged on MCPCB. This could be due to the contact area of chip with DAC and pure copper heat spreaders to the MCPCB can be extended to 9 mm^2, but the contact area of chip with only sapphire substrate to the MCPCB is only 1 mm^2. It results the thermal resist of solder can be obviously reduced for the LED with DAC and pure copper substrate. However, the thermal resistance of UV LED with DAC heat spreader and pure copper heat spreader are measured of 18.4 K/W and 24.8 K/W, respectively. Heat spreader for UV LED using with cup-shape pure copper improves

* Electrochemical Society Active Member.
z E-mail: huahorng@nchu.edu.tw

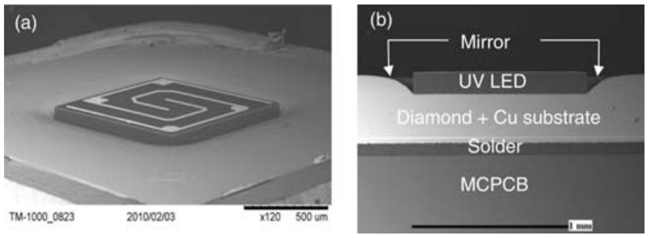

Figure 1. (a) SEM micrograph of UV LED chip mounted with DAC heat spreader and (b) corss section image.

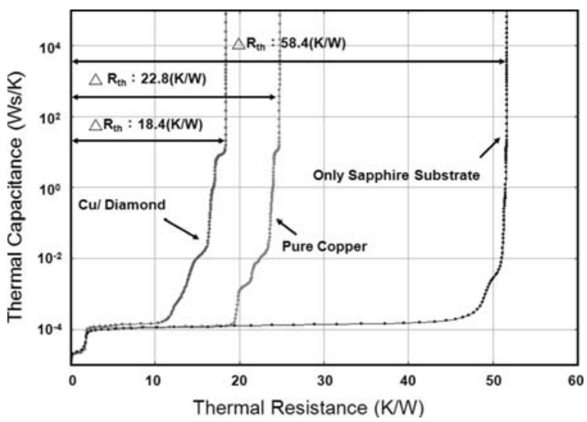

Figure 2. Cumulative structure functions for the LEDs packaged using DAC heat spreader, pure copper heat spreader, and original sapphire substrate.

thermal resistance as a result of nice thermal dissipation of copper heat spreader. The thermal resistance of UV LED with DAC heat spreader is even lower than with pure copper heat spreader. The high thermal dissipation characteristic of diamond powder doping in copper heat spreader is emerged obviously.

To evaluate the performance of package is not only utilized the thermal resist measurement, it also can be comfirmed by surface temperature maesurement. Figure 3 displays the surface temperature distribution of LED chips with DAC heat spreader, pure copper heat spreader and only sapphire substrate. It is worthy to mention that the orientation of chip shown in Fig. 3c is anti-clockwise 90º as compared with those of chips shown in Fig. 3a and 3b. The pads shown in Fig. 3c are the same with those of LEDs shown in Figs. 3a and 3b. It was found that the surface temperature of LED with DAC heat spreader always presented the most lowest among these three samples. The 57.95°C surface temperature for the LED with DAC heat spreader is lower than those of LEDs with pure copper heat spreader (74.71°C) and only sapphire substrate (115.25°C), respectively, as the LEDs derived at 700 mA. Thermal distribution is uniform with the cup-shape heat spreader due to the perfect thermal dissipation apparatus as shown in Figs. 3a and 3b. As the DAC heat spreader adpation, the fine heat conduction from LED chip to MCPCB via DAC heat spreader that is observed in Fig. 3a. On the contrary, the temperature distribution of the UV LED chip directly contacted to MCPCB is very non-uniform. There always exists the hot spot in the chip surface. The obtained results indicate that the DAC or pure copper heat spreaders can play a well thermal dissipation.

In general, the ability of thermal dissipation is dependent on the thermal conductivity (k) of materials. Thus, it is important to evaluate the thermal conductivity about the DAC substrate. The thermal conductivity can be calculated from the following equation:[8]

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

where D, ρ and c denotes the thermal diffusivity, mass density and specific heat respectively. The thermal diffusivity of the DAC substrate is 0.7179 cm^2/s higher than 11.7 mm^2/s of pure copper measured by laser flash method. The thermal conductivity of of DAC substrate is 492.4 W/mK obtained from equation 1. It is higher than pure copper of 457.4 W/mK.[6] This is a direct demonstration that DAC heat spreader can provide better thermal dissipation than the pure copper and only sapphire substrate. It is consistent with the data of thermal resistance and surface temperature shown in Figs. 2 and 3.

Thermal dissipation ability of these three spreader structures can be futher demonstrated from LED device performance. The output power

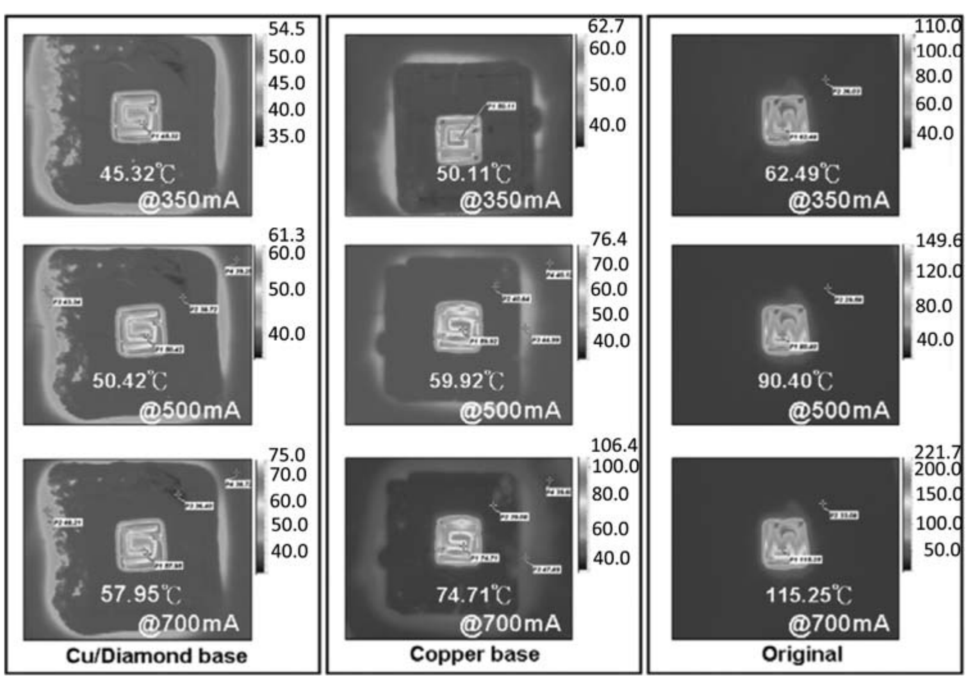

Figure 3. Surface temperature distribution at injection current of 350, 500 and 700 mA for the LEDs with (a) DAC heat spreader, (b) pure copper heat spreader and (c) original sapphire substrate.

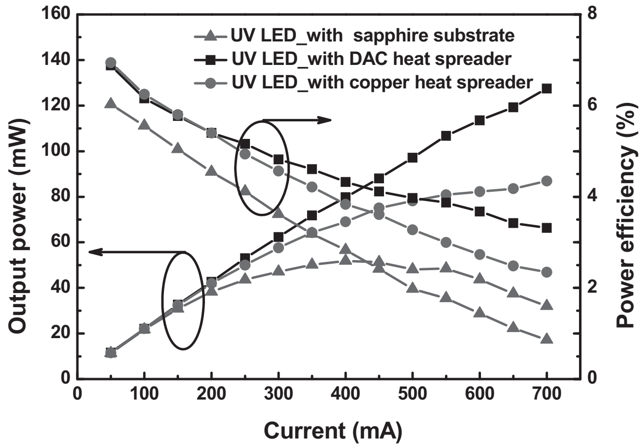

Figure 4. Light output power and power efficiency as a function of injection current for the UV LEDs packaged using DAC heat spreader, pure copper heat spreader, and original sapphire substrate.

and power efficiency of packaged LEDs with only sapphire substrate, pure copper heat spreader and DAC heat spreader as a function of injected current is shown in Fig. 4. The output power is about 50.18, 64.24 and 71.81 mW for the LEDs (@350 mA) with only sapphire substrate, pure copper and DAC spreaders, respectively. The corresponding power efficiency is 4.6, 4.2 and 3.18%. The LED packaged using DAC heat spreader exhibits the largest light output power than other two samples, yielding the power enhancement factor of 43% as compared with that of the UV LED without heat spreaders. The light output power with LED injection current less than 200 mA are almost the identical for LED with only sapphire substrate, pure copper and DAC heat spreaders. As a result of the small injection current leads the equivalent junction temperature.[4] The LED output power with only sapphire substrate is decreased obviously with injection current increasing as the injection current over 400 mA. Nevertheless, the output power is still increased with injection current as the LED using DAC heat spreader. Because of the heat is dissipated with high thermal conduction of DAC heat spreader. However, there exists a large heat accumulation, and it results in output power decreasing as the UV LED with only sapphire substrate package. Generally, the output power of a LED strongly relates to the carrier confinement in quantum wells. As the temperature increases of LED chip, the carrier confinement in quantum wells becomes less efficient, leading to deterioration in the output power.[7]

In LEDs device, the total input power equals light output power and thermal. The waste heat will result in junction temperature increasing. The difference between junction temperature and room temperature (25°C) is shown in equation 2.[8]

$$\Delta T = R_{\rm th} \times H_{\rm w} \quad [2]$$

The waste heat H_w is given by

$$H_{\rm w} = P_{\rm e} - P_{\rm op} \quad [3]$$

in which, R_{th}, P_e and P_{op} denote the thermal resistance, input power and optical output power, respectively. For three kinds of LED package structures, the input power is 1W at 350 mA injection current. Table I shows the thermal, optical and electrical characteristics with various package type of LEDs. The waste heat and junction temperature are calcuated by equation 2 and 3. The output power and thermal resistance are measured by semiconductor parameter analyzer, integration sphere detector and T3Ster Master system, respectively. The calculated surface temperature of LED chip for DAC, pure copper and only sapphire substrate heat spreader are 42, 48.2, and 80.5°C. Comparison the calculated surface temperature by thermal infrared microscopy, the calculated temperatures of LEDs for DAC and pure

Table I. Thermal, optical and electrical characteristic with various package types of LEDs

	LED with DAC	LED with pure copper	LED with sapphire
P_{op} (mW)	71.82	64.24	50.18
P_e - P_{op} (mW)	928.18	935.76	949.82
ΔT (°C)	17.08	23.2	55.47
R_{th} (W/K)	18.4	24.8	58.4
T (°C)	42	48.2	80.5

copper heat spreader are lower than the measured surface temperature. It could be attributed to the surface temperature measured by thermal equilibrium and the R_{th} measured by transient (around microseconds). It results in the surface temperature measured by infrared microscopy being higher than the junction temperature measured by R_{th}. In original sapphire package, the tendency of surface temperature for measured and calculated is opposite with DAC and pure copper spreader because the thermal dissipation area is small to lead heat distribution not uniform. In Fig. 3, the heat concentrates in a specific area and the thermal dissipation is poor. Therefore, the calculated value is higher than measured value of surface temperature. However, the tendency of the surface temperature and R_{th} is the same.

Conclusion

Low power efficiency of UV LED induces large heat generation. The vicious circle of relationship between thermal generation and low power efficiency will reduce the life cycle of LED device. To improve the light output performance and increase the reliability of UV LED, the high heat dissipation apparatus is developed and discussed in this study. Cmposite electroplating technique is adopted to devise DAC heat spreader for cup-shaped sheet of a sapphire-based UV LED, successfully. As a result of high heat conductivity of DAC heat spreader, the thermal dissipation is improved obvious. The output power of LEDs with DAC heat spreader is enhanced due to the low chip temperature. Especially, the cup-shape spreader can dissipate the heat generated from LED chip uniform and avoid heat congregated. The improvement DAC high thermal dissipation materials fabricated by composite-electroplating for heat spreader to replace the pure copper can descreas the thermal resistance and surface temperature, effectively. The optimal structure of cup-shape heat spreader and high thermal conductivity composite materials of diamond-added copper using in UV LED package are proposed approach in this study.

Acknowledgments

The authors would like to thank the National Science Council of the Republic of China, Taiwan, for financially supporting this research under contract NSC-96-2628-E-005-011-MY3, no. NSC96-2628-E-005-091-MY3, no. NSC98-ET-E-005-002-ET, and the Ministry of Economic Affairs under contract no. 97-EC-17-A-07-SI-097 and by Electronics and Opto-electronics Research Laboratories, Industrial Technology Research Institute under Contract 99-B-08.

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