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RESEARCH ARTICLE

Ceramic-metal package for high power LED lighting

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Abstract High power light-emitting diodes (LEDs) lighting has drawn a great interest in the field of street light system in recent years. Key parameters for successful launching of LED street light in the commercial market are price and light efficiency, respectively, and they are greatly influenced by the materials and design factors used in high power LED package. This article presents a new design and materials processing technology to realize the solution of LED packaging with advantageous in price and performance. Cost effective materials and processing technology can be realized via thick film glass-ceramic insulating layer and silver conductor. Highly effective thermal design using direct heat dissipation to heat sink in LED package is demonstrated.

Keywords light-emitting diodes (LEDs) package, high-power, thick film, heat dissipation, thermal resistance

1 Introduction

Light-emitting diodes (LEDs) lighting solutions offer several enchanting benefits [1]; 1) longer lifetime as much as 2 to 10 times compared to the conventional sodium or mercury lamps, 2) lower power consumption: 52% over mercury lamp and 26% over sodium lamp, 3) higher efficacy: 50 lm/W over 31 lm/W in mercury lamp,4) more lux per watt: more than double that of mercury lamp. However, there are still remaining several issues for delaying market growth against the earlier expectation because of higher materials cost and bulky system due to thermally designed package housing and uncomfortableness due to low color rendering index (CRI) compared to the conventional bulb light.

Among those obstacles that make the slow introduction of LED lighting in our market, thermal management in the LED applications especially in the high power LEDs for outdoor or street light is still remains as a cumbersome issue which related to the lighting system cost, performance and design consideration.

There are a few text books that comprehensively guide the LED packaging for light applications [2,3]. However, there are many research articles which deal with in various aspects on thermal management in LEDs; 1) using thermal via in FR-4 (flame retardant-4) and CCL (copper clad laminate) [4], 2) thermal analysis, measurement, and enhancement of LED packages [5–11], 3) LED packages with cooling system such as heat pipe and water flow [12,13], and high thermal conductivity LED package substrate materials using ceramics and ceramic-polymer composites [14–16]. Most of the prior works afore mentioned deal with the thermal issues as a LED chip package level rather than a LED chip array module or package level which is closely related with high power street lighting.

Heat dissipation is one of the most important factors that rule the lighting performance of LED package. Thermal vias, metal-core printed circuit board (MCPCB) and chip-on-board (COB) technologies are most common design and materials solution for enhanced LED performance. And it has been known that the thermal resistance of LED chips on ceramic, specifically low temperature co-fired ceramic (LTCC), board was lower than that of MCPCB [4,14].

Even more, those known LED packaging solutions are using a FR-4 based epoxy polymer, alumina or LTCC based ceramics as an insulating substrate for multi LED chip array package. In this article, we introduce a new approach, hereafter designated as a ceramic-metal package, to fulfill the thermally effective design, cost and process effective materials and process technique for high power LED array module by applying conventional ceramic thick film and low-temperature co-firing technology which enable direct forming of ceramic insulation layer for LED array circuitry on aluminum heat sink plate.

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2 Experiments

2.1 Preparation of ceramic-metal based LED array module

The feature of this work is direct forming glass-ceramic insulation layer onto the aluminum plate which acts as a heat sink and heat spreading bed. Figures 1(a) and 1(b) illustrate the schematic structure of proposed ceramic-metal based high power LED array package and the process flow chart for fabrication. At first, flat aluminum plate with thickness of 1–4 mm was chosen for the heat sink and heat spreading substrate instead of fin type heat sink for easiness in preliminary experiment. Commercially available glass-ceramics and silver (Ag) paste with sintering temperatures ranging 500°C–560°C were used to form an insulation layer and conductor pattern for LED array circuitry.

The glass-ceramic layer and the silver conductor patterns are screen printed, dried, and co-fired at 500°C–560°C for 30 min in air. Then, solder paste (96Sn4Ag) was printed using metal mask for LED chip mounting, and it was cured at 240°C for 10 s under infra-red oven.

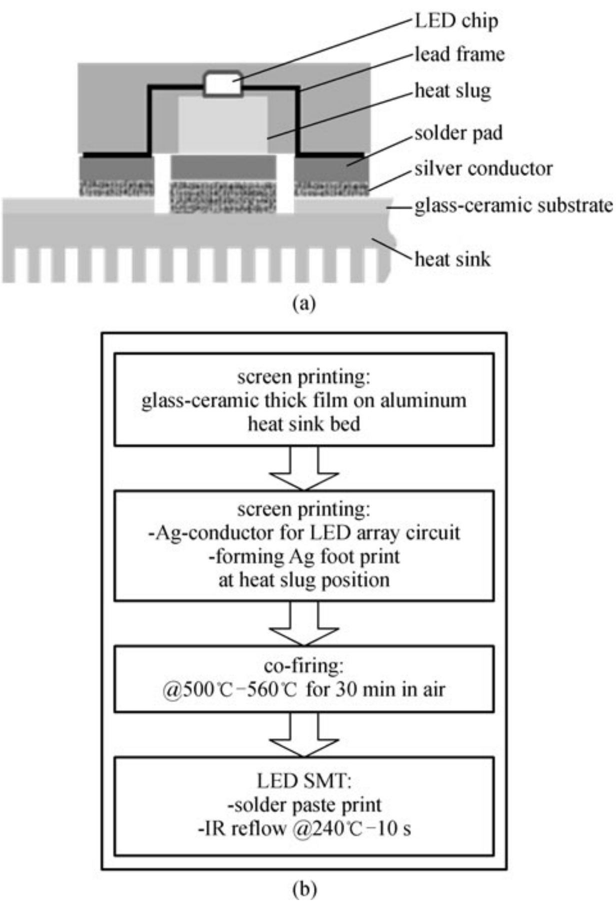


Fig. 1 (a) The illustration of a ceramic-metal based LED package and (b) a process flow chart

2.2 Evaluation of heat dissipation

Measurement of thermal resistance (R_{th}) as a heat dissipation property of fabricated LED array module was carried out using a thermal transient tester (T3Ster, www.micred.com) which complied with JEDEC-JEDS 51-1. To compare the thermal resistance of ceramic-metal package with prior art such as conventional FR-4 printed circuit board (PCB)and thermal-via PCB package, three types of one-chip mounted LED package test samples were designed as shown in Fig. 2.

Generally, thermal resistance of LED package is defined as the temperature difference between the junction temperature and ambient temperature at the heat sink or bed divided by applied power to the LED chip:

$$R_{th} = (T_j - T_a)/p = \Delta T/P \quad (°C/W), \tag{1}$$

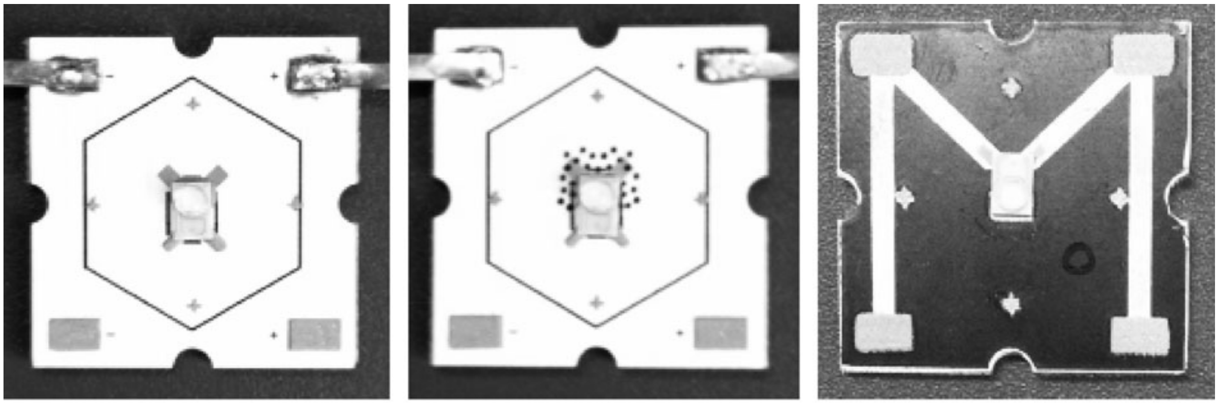
where P is the applied power to LED.

Figure 3 shows the test set-up for measuring thermal resistance of one-chip mounted LED test board. The one-chip LED test board used a surface mounting type LED chip supplied by Lumileds (LUXEON Rebel, Philips). The applied current range was 10–350 mA. Digital thermostat module (T3STERCALIB) with external heat sink was used for K-factor calibration and a thin bonding sheet with thickness of 0.5 mm and thermal conductivity of 0.9 W/m·K was used for attaching LED package test board to the cavity.

3 Results and discussion

3.1 Fabrication of ceramic-metal base 50 W rating LED package

For 50 W power rating LED array, 36 pieces of LED chips were used. The package was designed for 12 V DC operation with 4×12 array, i.e., 4 chips in series and 12 parallel connections. Stainless steel (SUS) meshed screens and metal mask were designed and fabricated for thick film process to make glass-ceramic insulation layer and silver conductor patterns. The process temperature of sintering ceramic-metal base LED package was limited to the metal heat sink material, in this case aluminum, such that the sintering condition was adopted at the sintering temperatures ranging 500°C–560°C as the melting temperature of pure aluminum is known to be 660.1°C. Figure 4 shows the optical images of heat-treated ceramic-metal LED package with different sintering conditions. The samples shown below are the glass-ceramic layer after sintering: under firing at less then 500°C showing delamination of brittle glass-ceramic layer from aluminum substrate (Fig. 4(a)), over firing at more then 560°C showing severely deformed aluminum substrate and crack generated at the glass-ceramic layer (Fig. 4(b)), and optimized firing at 500°C–



(a) (b) (c)

Fig. 2 One-chip mounted LED package test boards. (a) Conventional FR-4 PCB; (b) thermal-via PCB; (c) ceramic-metal PCB

Fig. 3 Photo imaging of test set-up for measuring thermal resistance

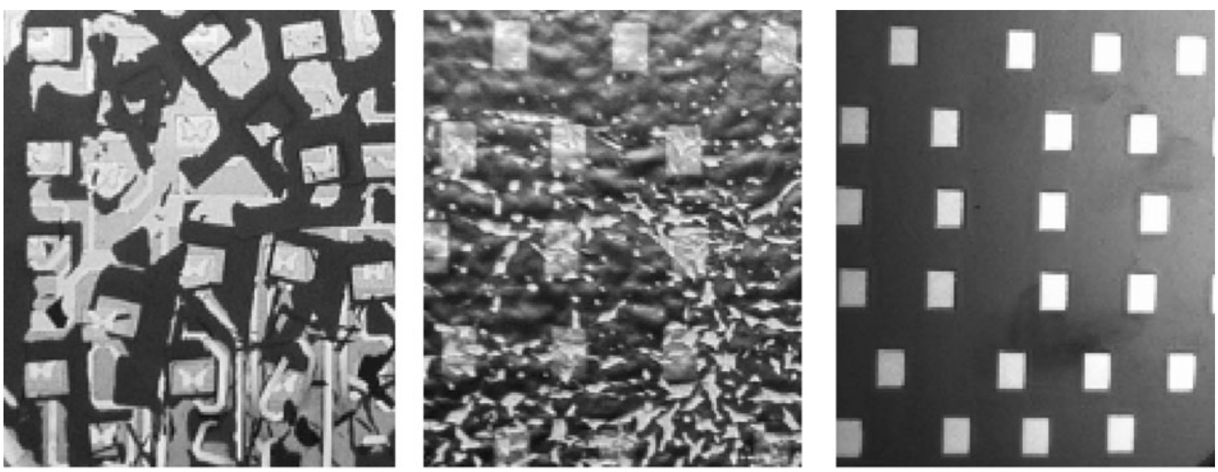
560°C showing well laminated glass-ceramic layer to the aluminum and dense film structure (Fig. 4(c)).

Figure 5(a) shows ceramic-metal based LED array module rating 50 W, where 36 LED chips are surface mounted, and the photo in the inset Fig. 5(b) shows the planar view of series connected 4 LED chips without top protection layer.

Although this paper deals with prototype samples using flat aluminum panel for simplicity and thermal performance evaluation, direct forming of glass-ceramic layer on a bulky aluminum heat sink block is also possible with this ceramic-metal packaging technique.

3.2 Heat dissipation performance of ceramic-metal base LED package

To compare the heat dissipation performance of ceramic-metal base LED package with conventional FR-4 PCB and thermal-via PCB, thermal resistances of the one-chip mounted LED test board were measured using T3Ster thermal transient tester. The results are presented in Fig. 6.



(a) (b) (c)

Fig. 4 Optical images of ceramic-metal LED packages. (a) Under-sintering; (b) over-sintering; (c) optimized sintering

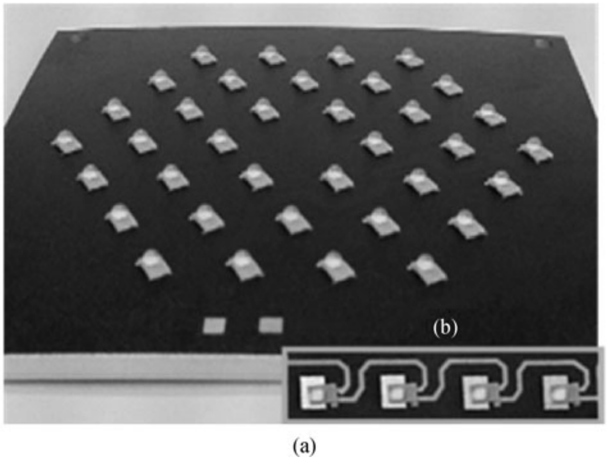


Fig. 5 Ceramic-metal based 50 W LED array module after LED chip mounting. (a) After top insulation layer coating; (b) before top insulation layer coating (inset)

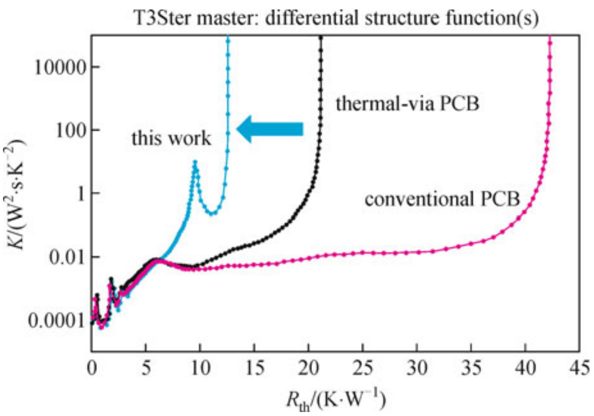


Fig. 6 Differential structure functions for types of LED one-chip LED test boards

The thermal resistances of the three types of LED packages that presented in Fig. 2 can be expressed as follows:

1) Conventional FR-4 PCB:

$$R_{th} = R_{js} + R_{sb} + R_{bm} + R_{mh} + R_{ha}, \quad (2)$$

where, R_{js}: R_{th} for junction to solder layer, R_{sb}: R_{th} for solder to FR-4 board, R_{bm}: R_{th} for FR-4 board to metal layer, R_{mh}: R_{th} for metal layer to heat sink, R_{ha}: R_{th} for heat sink to ambient.

2) Thermal-via PCB:

$$R_{th} = R_{js} + R_{sv} + R_{vh} + R_{ha}, \quad (3)$$

where, R_{sv}: R_{th} for solder to via, R_{vh}: R_{th} for via to heat sink.

3) Ceramic-metal PCB:

$$R_{th} = R_{js} + R_{sc} + R_{ch} + R_{ha}, \quad (4)$$

where, R_{sc}: R_{th} for solder to Ag conductor layer, R_{ch}: R_{th} for conductor to heat sink.

The thermal resistances measured for FR-4, thermal-via and ceramic-metal base package are 42.5, 22, and 12.5 K/W, respectively, as shown in Fig. 6. Therefore, the heat dissipation performance of ceramic-metal base LED package exhibits almost 2–4 times as that of a conventional PCB. The lower thermal resistance in the newly adopted ceramic-metal base LED package is attributed to both the minimal use of package inter layers and interfacial structures in LED package which hindering the heat transfer from the LED chips to the heat sink, and to the adoption of high thermal conductivity thermal interface material (TIM), for example using silver paste underneath of LED heat slug.

3.3 Assemblage of prototype LED lighting system

Finally, a prototype of 50 W LED down lighting system was assembled as shown in Fig. 7. High power LED lighting systems with 100 and 150 W can be fabricated if two or three sets of this 50 W basic LED array module are combined, depending on the application environment. However, though this ceramic-metal base LED package exhibits superior thermal performance compared to the conventional technology, further investigations on the reliability and field tests are under preparation. So, the complete evaluation of this newly adopted technology will be reported in the near future.

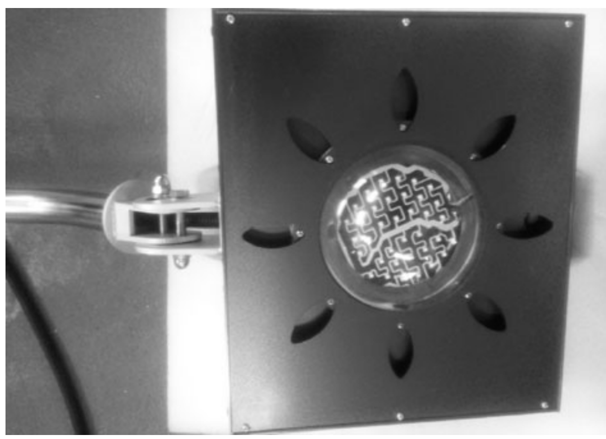


Fig. 7 Prototype 50 W LED down lighting system using ceramic-metal package

4 Conclusions

Ceramic-metal based high power LED package was developed via thick film LTCC technology using glass-ceramic insulation layer and silver conductor patterns directly printed on the aluminum heat sink plate. The thermal resistance measurement using thermal transient tester revealed that ceramic-metal base LED package exhibited a superior heat dissipation property to compare with the previously known packaging method such as FR-4 based PCB and thermal-via PCB. A prototype LED packages with 50 W power rating was fabricated using ceramic-metal base technology. However, further evaluations on reliability and field test are required for the feasibility of this newly proposed technology.

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