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Fabrication of alumina/copper heat dissipation substrates by freeze tape casting and melt infiltration for high-power LED

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ABSTRACT

With the wide application of high-power LED, heat dissipation substrate not only demonstrates a high thermal performance but also requires a low thermal expansion coefficient that matches that of the chip. Metal/ceramic composite materials can combine the excellent heat dissipation performance of metals and low thermal expansion property of ceramics, satisfying the requirement for high-power LED. In this study, alumina/copper composite substrates were fabricated through freeze-tape casting and melt infiltration. Morphologies, infiltration rates, thermal properties, and heat dissipation properties of the fabricated composite substrates were investigated. This study found that copper was distributed in the lamellar pore channels of alumina substrates, and the infiltration rate of copper in alumina/copper composite substrates increased under increasing Ti content, infiltration temperature, and time. Furthermore, thermal conductivity and thermal expansion coefficient decreased as alumina content in the composite substrates decreases. The thermal resistance, junction temperature, and increase in junction temperature of the alumina/copper composite substrate when 57.33 vol% copper was used as heat dissipation substrates for 2W LED lamps are 22.5 $K \cdot W^{-1}$, 80.5 °C, and 40.5 °C, respectively. The heat dissipation performance of the LED module with the copper/alumina composite substrate with copper infiltration rate of 57.33 vol% was significantly better than that of the commercial alumina substrate. Fabricated composite substrate (57.33 vol% infiltration rate of copper) has a junction temperature of 80.5 °C and thermal resistance of 24.6 $K \cdot W^{-1}$, which are lower than the junction temperature (93.2 °C) and thermal resistance (32.1 $K \cdot W^{-1}$) of the commercial alumina substrate tested at same conditions. The reduction of junction temperature is important to improve the service life of the LED lamp.

1. Introduction

The light-emitting diode (LED) lamp is a type of lighting device that is constructed from semiconductor materials, such as GaN and GaAs [1]. Compared with traditional lighting lamps, LED lamps offer numerous advantages, such as high efficiency, long life, energy saving, environmental protection, and absence of radiation and pollution [2,3]. At present, the luminous efficiency of high-power LED is only 10%–20%, and the remaining 80%–90% of the energy is converted into heat energy [4,5]. Heat energy produced by LED cannot be dissipated in time, resulting in the increase in LED junction temperature, thus resulting in shortened life span of the LED lamp, decrease in luminous intensity, and fluorescence powder degradation [6]. Therefore, heat dissipation materials for use in high-power LED are particularly important. Printed circuit boards (PCBs) are used as heat dissipation materials for low-power LEDs because of lower heat dissipation [7]. However, PCB can support only the heat dissipation of 0.5 W LEDs [8]. Numerous researchers have attempted to use different heat dissipation materials for high-power LED, which are common in Cu or Al alloys because of good thermal conductivity [9,10]. The thermal expansion coefficient of the metal material is considerably higher than that of the LED, which can lead to cracking. Then, several scholars proposed the use of the thermal expansion coefficient of ceramic materials, such as alumina, as heat dissipation substrate [11,12]. Although alumina presents certain advantages, such as high insulation and thermal stability, thermal conductivity is low and difficult to use as heat dissipation substrate for LEDs. Therefore, the above problems can be solved by combining the thermal conductive metal and ceramic with composite materials. However, numerous studies have shown poor wettability between alumina and Al, Cu [13,14]. The alumina/Al or Cu composite is usually fabricated by an internal oxidation

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process and powder metallurgy because of the large melting point difference [15,16]. These methods limit the added amount of Al or Cu, which cannot form an effective heat conduction network [17,18]. Thus in this work, a new method is explored to increase conducting materials into these substrates.

2. Methodology

2.1. Fabrication

In the current study, alumina/copper composite substrates were fabricated by freeze-tape casting and melt infiltration. The copper in the composite substrates formed a directional thermal conduction path owing to the special pore structure of the alumina substrates, resulting in high thermal conductivity and low thermal expansion coefficient. The porous alumina substrates and the composite substrates were characterized by X-ray diffraction (XRD), scanning electronic microscopy (OM), and energy dispersive spectrometer (EDS). Thermal properties and heat dissipation properties of the fabricated composite substrates were also investigated. In addition, copper/alumina composite substrates with different copper infiltration rates were used for the LED module. The thermal resistances and junction temperatures were tested to determine whether a substrate could be used as the heat dissipation substrate of high power LEDs.

Fig. 1 shows the flow chart of the fabrication of alumina/copper composite substrates. The raw materials include alumina powder with a median size of 4.0 μm, copper sheet, titanium powder, organic additives (carboxymethyl cellulose (CMC, binder), polyethylene glycol (PEG, plastic plasticizer), polyacrylate sodium (PAAS, Dispersant)), and deionized water.

PAAS, CMC, and PEG were dissolved in distilled water, and then alumina powders were added. Aqueous alumina slurries were obtained after ball milling at 300 $r \cdot min^{-1}$ for 24 h. The slurry was cast in the pre-freezing substrate and then immediately placed in a cold source until alumina slurries were completely frozen unidirectionally. Freeze tape casting films were dried in low pressure after the substrate was completely frozen, and the porous green body with thickness of 1.5 mm is obtained. Organic additives were decomposed at 600 °C for 2 h. Porous alumina substrates were obtained after sintering at 1600 °C for 2 h and cooling in the furnace. The whole process of freeze tape casting as shown in Fig. 2. The residue products of organic additives were removed by washing with water. Ti powders were mixed with a dispersant and a binder in deionized water for 4 h to obtain the Ti slurry. The fabricated porous alumina substrates were dipped in the Ti slurry and then dried at 70 °C. After surface impurities are removed, copper is placed above porous alumina substrates and will enter pore channels by melt infiltration at 1100 °C–1400 °C for 1–5 h in vacuum atmosphere. Finally, alumina/copper composite substrates were obtained after cooling in the vacuum furnace.

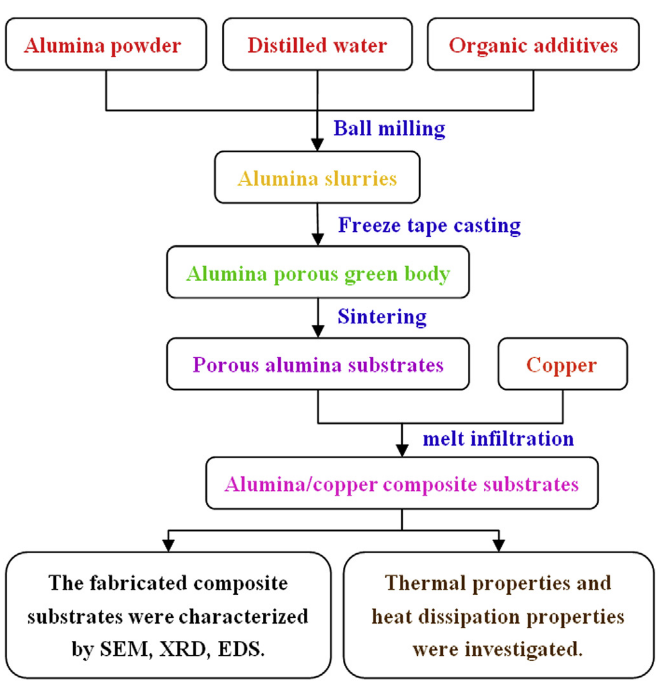

Fig. 1. Flow chart of alumina/copper composite substrate fabrication using the freeze tape casting and melt infiltration.

2.2. Characterization

The samples were polished for clear observation of their microstructure. XRD (Shimadzu Model 7000) analysis with Cu K_α radiation was used to identify the phases present at the copper/alumina interface. The morphologies of porous alumina substrates and alumina/copper composite substrates were characterized by SEM (JSM 6700F), whereas elemental distribution of the resulting heat dissipation substrates was characterized by EDS (Oxford INCA). Open porosity of porous alumina substrates was measured using Archimedes principle, and total porosities were determined by weighing. The infiltration rates of copper in the composite substrates were characterized by using the percentage (η) of copper volume in the total composite volume, which is given in Formula (1):

$$\eta = \frac{M_2 - M_1}{\rho_{Cu} V} \times 100\% \quad (1)$$

where M_1 is the weight of porous alumina substrate, M_2 is the weight of the composite substrates, V is the volume of composite substrates, and ρ_{Cu} is the density of copper. The thermal conductivity coefficients and thermal expansion coefficients of composite substrates were determined by a laser thermal conductivity analyzer (LFA457) and a thermal expansion apparatus (DIL402C), respectively. The junction temperature and thermal resistance of the composite substrates were characterized. The studied LED chips are provided by a commercial LED company (Guangzhou Hongli Opto-Electronic Co., Ltd.). Copper/alumina composite substrates (size: 10 × 10 × 1 mm), with different copper infiltration rates of 32.52%, 43.25%, 49.13%, 55.67%, and 57.33% as heat dissipation substrates of LED and the corresponding LED modules were defined as A, B, C, D, and E, respectively. The thermal resistances and junction temperatures of LED modules (A, B, C, D, and E) were tested by a thermal transient tester (T3Ster, SIMUCAD Info Tech Co., Ltd.). The thermal resistances and junction temperatures of the composite substrates were obtained by calculations. The principle of thermal resistance measurement is based on the Joint Electronics Device Engineering Council (JEDEC) and the JESD51-1 standards. The thermal resistance and junction temperature were obtained by measuring the transient temperature response curve of the chip and removing the structure function. The delay time of the test system is set to 1 μs, and the junction temperature resolution is 0.01 °C. The heat dissipation performances of LED modules were measured for the same input power of 2 W. The first step was to obtain the *K* factor. The *K* factor was calibrated with a 10 mA bias current from 25 °C to 85 °C. The *K* factor was −8.934 mV/°C; the forward voltage decreased by 8.934 mV when the junction temperature increased by 1 °C. The chip was charged by 10 mA for