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Microstructural and thermal characterizations of light-emitting diode employing a low-temperature die-bonding material

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ABSTRACT

A Sn/Bi bilayer was deposited on a hot air solder leveling (HASL)-treated metal-core printed circuit board (MCPCB) using electroplating as a low-temperature die-bonding material for light-emitting diode (LED). The eutectic feature of the Sn/Bi contact enabled the die-bonding process to accomplish through a liquid/solid reaction at 185 °C with a proper compression force. A high-temperature die-bonding structure composed of a Bi layer sandwiched by two intermetallic compounds (IMCs) formed after thermocompression. Employment of the Sn/Bi bilayer for low-temperature die-bonding prevented the LEDs from thermal stress problems, and the resulting high-temperature IMC/Bi/IMC die-bonding structure was capable of withstanding multiple bonding reactions and high temperature/current operation environment. Durability tests including mechanical, thermal, and optical performance were systematically performed and compared with other commercially available die-bonding materials (Ag paste and solder alloys).

1. Introduction

Due to many advantages such as low power consumption and long lifetime, light-emitting diode (LED) has become more and more popular in the applications of general illuminations. From small-scale display backlight to large-scale outdoor board, LED plays an important role as a stable and brilliant light source. Though LEDs have been widely applied in human daily life, some issues concerning materials and processing still need to be solved with new perspectives for the development of high-power LEDs. For example, metallic solder alloys (eutectic SnAgCu or AuSn) are employed as the die-bonding materials to replace polymer-based Ag paste in order to remove heat generated from the chip more efficiently [1–4]. The die-bonding process of solder alloy is accomplished through a liquid/solid reaction during which molten solder joins with the metallizations on both the chip and substrate sides [2,5]. The reaction temperature needs to exceed the melting point of the solder alloy; however, this temperature (>250 °C) is much higher than the bonding temperature used for traditional Ag paste and may bring about undesirable thermal stress issues. To solve the problem, some low-temperature solder alloys were employed in the die-bonding process such as Bi–In, Bi–In–Zn, Bi–In–Sn, and Bi–In–Sn–Zn so as to lower the liquid/solid reaction temperature (<110 °C) [5]. However, the die-bonding structure composed of a low-temperature solder alloy may suffer softening problem when the operation temperature approaches 70–80 °C [5]. More severely, the die-bonding structure collapses once the LED package undergoes multiple bonding reactions with a bonding temperature higher than the melting point of low-temperature solder alloys. Therefore, a subsequent solid/solid reaction at 80 °C for 0.5–3 h was suggested to perform to completely transform soft solder alloys into high-temperature intermetallic compounds (IMCs) so that the resulting high-temperature die-bonding structure was able to withstand multiple bonding reactions and harsh (high temperature/current) operation environment [5].

Besides the monolithic solder alloys, insertion of a multilayer of Sn/Bi/Sn in between the LED chip and substrate was also a promising method for low-temperature die-bonding [6]. The Sn/Bi system is a eutectic system with a eutectic temperature of 138 °C. The eutectic feature enabled the die-bonding process to accomplish at 175 °C which was much lower than the SnAgCu or AuSn solders. Though the die-bonding temperature for the Sn/Bi/Sn multilayer was higher than the low-temperature solder alloys (Bi–In, Bi–In–Zn, … etc), the die-bonding process only involved a single liquid/solid reaction without a second long-term solid/solid reaction. The Sn layer was as thin as 0.3–1 μm in the Sn/Bi/Sn multilayer so it was completely consumed to form the IMC after die-bonding. The resulting die-bonding structure comprised of a Bi layer sandwiched by two IMCs, forming a high-temperature die-bonding

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structure (IMC/Bi/IMC) capable of withstanding multiple bonding reactions and high temperature/current operation environment.

The above-mentioned study [6] demonstrated the feasibility of the IMC/Bi/IMC multilayer as a promising die-bonding structure for LEDs with the main emphasis on as-bonded LED samples. In this study, a systematic assessment of the IMC/Bi/IMC die-bonding structure was performed by investigating the microstructural evolution, mechanical strength, shear fracture modes, thermal management performance, and optical property under thermal aging. The results indicated that the die-bonding structure underwent a pronounced microstructural change with new IMC formation and IMC detachment upon thermal aging. Nevertheless, the LEDs with the IMC/Bi/IMC die-bonding structure displayed superior durability with good mechanical, thermal, and optical performance after long-term thermal aging.

2. Experimental procedures

2.1. Fabrication of a Sn/Bi bilayer as die-bonding material

A metal-core printed circuit board (MCPCB, KT-104-001A, K. T. Perfect, Taiwan) was used as the substrate for electrodeposition of a bilayer of Sn/Bi. The surface metallization of MCPCB was a Cu layer and, to avoid Cu oxidation, the Cu surface was pre-treated using hot air solder leveling (HASL). Bi (4 μm thick) and Sn (0.3 μm thick) were sequentially deposited on the HASL-treated Cu surface using electroplating to form a Sn/Bi bilayer as the die-bonding structure. A GaN-based LED chip (35 mil × 35 mil, ES-CADBV35A, EPISTAR, Taiwan) was placed on top of the MCPCB where the back-side metallization (Ti/Al/Cr/Pt/Au) of the LED chip was in direct contact with the Sn/Bi-coated Cu surface of the MCPCB. The die-bonding process was carried out by imposing proper forces (257 MPa) on the LED chip using a thermocompression machine at 185 °C for 20 min.

2.2. Characterizations of the Sn/Bi die-bonding material

The Sn/Bi bilayer as the die-bonding material for LEDs was systematically characterized including microstructural evolution, mechanical strength, optical performance, and thermal property. For the analysis of microstructural evolution, the die-bonded LEDs were placed in a furnace at 120 °C for 240 to 1000 h. After thermal aging, the LEDs were removed from the furnace and examined metallographically. The LED samples were mounted in epoxy resin and cross-sectioned to expose the die-bonding layer for microstructural observation using scanning electron microscopy (SEM) and transmission electron microscopy (TEM). Energy-dispersive x-ray spectrometer (EDX) was used to determine the elemental compositions of the die-bonding layer. The die-bonded LEDs were also mechanically examined using a DAGE-4000 shear tester with shear speed of 500 μm/s and tool height of 10 μm. The average shear forces of the die-bonded LEDs were obtained based on at least five measurements. The fracture mode of the LEDs subjected to shear test was determined based on SEM and EDX examination.

The LED chip was electrically connected with the MCPCB using a wire-bonding technique. To perform the high-temperature operation life (HTOL) test, the wire-bonded samples were injected with a current of 0.5 A at 85 °C following a standard of reliability test (JESD22 method A108-B, JEDEC Solid State Technology Association). After high-temperature operation for 1000 h, the luminous intensity decay of the LED samples was measured using an integrated sphere. The surface temperatures of the LED chips and the total thermal resistances were measured using a thermal infrared analyzer (TVS-500EX, AVIO, Japan) and thermal transient tester (T3Ster-Master, MicRed), respectively.

2.3. Other common die-bonding materials for comparison

Three other die-bonding materials were also used in the LED die-bonding process including Ag paste, SAC305 (Sn–3 wt.% Ag–0.5 wt.% Cu), and eutectic SnBi (Sn–58 wt.% Bi) solder pastes. The Ag paste was dispensed on the MCPCB and the other two solder pastes were coated on the MCPCB using screen printing. After placing the LED chip onto the die-bonding materials, the samples were placed in a furnace to conduct the die-bonding process, where the bonding temperatures and times were tabulated in Table 1. After die bonding, the LED samples were further wire-bonded to form electrical connection with the MCPCB. Then, the microstructural, mechanical, optical, and thermal characterizations were performed as mentioned above, and the results were compared with the LED samples die-bonded with a Sn/Bi bilayer.

3. Results and discussion

3.1. Microstructural characterization of die-bonding structures

Figs. 1(a) and (b) show the SEM images of the surface and cross section, respectively, of the Sn/Bi bilayer deposited on the HASL-treated MCPCB. In a typical HASL process, the MCPCB was dipped into a bath of molten Sn during which the molten Sn wetted the Cu surface of MCPCB and the Cu_6Sn_5 phase layer formed over the Cu surface as a result of the Sn/Cu interfacial reaction, as seen in Fig. 1(b). The Bi layer electroplated over the Cu_6Sn_5 phase layer was about 3 μm thick and adhered closely to the Cu_6Sn_5 phase layer. The surface Sn layer exhibited a granular structure, as seen in Fig. 1(a), and its thickness was about 0.3 μm. After die bonding with a LED chip using thermocompression, the die-bonding structure exhibited a multi-layered structure composed of three phase layers, $AuSn_2$, Bi, and Cu_6Sn_5, which stacked in between the LED chip and MCPCB as seen in Fig. 2(a). The formation of the $AuSn_2$ phase was a result of the reaction between the electroplated Sn layer and the back metallization layer (Au) of LED chip under thermocompression. In addition to above-mentioned three phase layers, the Cu–Sn–Bi–Au phase was observed at some local regions along the Bi/Cu_6Sn_5 interface [6].

Figs. 2(b)–2(d) are the SEM images showing the cross-sectional microstructures of the die-bonded LEDs with Ag paste, SAC305, and eutectic SnBi solder pastes, respectively. Overall, all die-bonding materials were capable of adhering the LED chip to the MCPCB without any noticeable defects like voids or delamination. The thicknesses of all die-bonding structures were measured as Table 1 listed. It was found that the Sn/Bi layer fabricated using electroplating was as thin as 3 μm and was much thinner than the other three die-bonding structures (10–40 μm). Strategically, the thickness of die-bonding structure should be as thin as possible so that heat generated from the chip can be removed to the MCPCB (Cu) side more efficiently. This also indicates that

Table 1
Four types of die-bonding materials and the parameters used for the die-bonding process including temperature, pressure, and time.

Die-bonding materials	Ag paste	SAC305	eutectic SnBi	Sn/Bi bilayer
Deposition	Dispensing	Screen-printing	Screen-printing	Electroplating
Die-bond method	Heating	Heating	Heating	Thermocompression
Temperature/pressure	150 °C/ 0 MPa	260 °C/ 0 MPa	160 °C/ 0 MPa	185 °C/ 257 MPa
Bonding time	60 min	0.5 min	1 min	20 min
Die-bonding layer thickness	30–40 μm	10–15 μm	10–15 μm	3–4 μm