Microelectronics Reliability 55 (2015) 2532–2541

Contents lists available at ScienceDirect

Microelectronics Reliability

journal homepage: www.elsevier.com/locate/mr

Degradation of high power single emitter laser modules using nanosilver paste in continuous pulse conditions

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ARTICLE INFO

Article history:
Received 23 May 2015
Received in revised form 17 July 2015
Accepted 20 July 2015
Available online 26 July 2015

Keywords:
Nanosilver paste
Laser module
Die-attach interface
Pulse mode
Reliability

ABSTRACT

This paper is mainly reported to a pulse reliability investigation of high power single emitter laser modules with nanosilver paste. Comparative experiments in continuous pulse conditions for the laser modules packaged with nanosilver paste, indium and AuSn solders were conducted. The results indicate that the laser modules attached by nanosilver paste have a longer-term lifetime than those with indium and AuSn solders in continuous pulse conditions. Transient thermal behavior and coupled thermo-mechanical behavior in continuous pulse conditions are simulated by finite element method (FEM). A semi-empirical model based on Arrhenius relationship is established to provide relative reliability assessments for laser modules by combining with the simulating results.

1. Introduction

Long-term reliability has always been concerned in high power laser modules (HPLMs). The reliability of HPLMs is affected greatly by heat dissipation capability, long-term mechanical integrity of die-attach interface, and thermo-mechanical stresses in operating conditions. Continuous wave (CW) mode is the most common operating condition for laser modules [1–3]. However, continuous pulse (CP) condition is continuously required for upcoming applications such as military weapons and fusion reactors in high-energy projects [4,5]. Compared to operation in CW mode, laser modules in CP condition experience substantial pulse thermal cycles, which can induce evident cyclic thermo-mechanical stress indie-attach interface and the laser active region due to mismatch of thermal expansion coefficients between laser diode and heat sink and then could result in poorer reliability for laser modules [6–8]. There may be some reliability issues in CP condition such as degradation of die-attach interface and gradual degradation of laser diodes. On the one hand, cyclic thermo-mechanical stress results in thermo-mechanical fatigue in the die-attach interface, which may destroy thermal and mechanical integrity of die-bonding interface due to formation and enlargement of voids/cracks. On the other hand, thermo-mechanical stress may induce the lifetime degradation of laser emitter. The critical degradation mechanism for HPLMs in CW mode has been widely evidenced such as catastrophic optical mirror damage (COMD) accelerated by the degradation of die-attach materials i.e., large voids and delamination of the package from the laser diode, especially under high optical output power conditions [9]. Nevertheless, the degradation mechanism for HPLMs in CP mode has not been clarified yet. As a novel alternative for HPLMs, the investigation of degradation mechanism in CP condition for laser modules with nanosilver paste is extremely significant.

Indium and gold–tin (AuSn) solders are widely used as die-attach materials for HPLMs because of some advantages [1,10]. For example, indium solder helps to relieve the stress in the active region of laser emitters due to its capability of plastic deformation. AuSn solder is free from thermal fatigue and creep deformation. However, indium solder is susceptible to high creep deformation and electro-migration [11,12] at high temperatures and high operating current, respectively. Voids could be initiated and propagated as cracks in die-attach interface due to the creep deformation and the electro-migration. Consequently, thermal resistance of laser modules increases significantly, causing COMD due to significant local heat near the facet of the laser modules [13–15]. For AuSn solder, it cannot release the operating stress because of the higher Young's modulus compared with the “soft” solders, e.g., indium solder [1,16]. As a result, the higher thermo-mechanical stress could be induced in the same operating condition and may impact the long-term reliability of HPLMs [17]. In order to alleviate the thermo-mechanical stress, an expansion-matching sub-mount like CuW is used

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http://dx.doi.org/10.1016/j.microrel.2015.07.037

commonly. The thermal resistance of the laser modules, however, could increase because the thermal conductivity of CuW (248 W/mK) is much lower than copper heat sink (398 W/mK). Therefore, we should pay more attention to develop new die-attach materials for operating HPLMs at environmental extremes reliably.

Recently, nanosilver paste emerges as a promising thermal interface material (TIM) for power electronics, especially at environmental extremes, because of its superior properties, e.g., high thermal conductivity (240 W/mK), high electrical conductivity ($2.6 \times 10^5\ \Omega \cdot \mathrm{cm}^{-1}$), low Young's modulus (about 9–20 GPa), and high melting point (961 °C) [18–21]. It is attractive to use it to bond laser diodes with heat sinks for fabricating reliable laser modules targeting to environmental extreme applications. As a result, we had joined high power laser diodes with heat sinks by sinter-bonding of nanosilver paste under the help of hydro-static pressure successfully in our previous work [18,22].

In this paper, 5 W, 808 nm laser diodes were mounted on heat sinks by sintering nanosilver paste, indium solder, and AuSn solder. The laser modules were then aged in continuous pulse mode in order to compare the module degradation with different die-attach materials. The induced cyclic thermo-mechanical stress was simulated by finite element method (FEM). The possible degradation mechanism was proposed based on the experimental and calculated results. The degradation of die-attach interfaces with nanosilver paste after continuous pulse aging was obtained by X-ray inspection. A semi-empirical Arrhenius relationship is established to estimate the lifetime of laser modules in CP mode.

2. Materials and methods

In this study, we used 5 W commercial GaAs-based single emitters coated with gold on backside as the dies. The emitters have a width of 0.5 mm and a cavity length of 1 mm. All laser emitters were packaged in a flip-chip way that means that the p-side of the emitter was connected with the heat sink. Three kinds of laser modules with different die-attach materials, i.e., sintered nanosilver, indium solder, and AuSn solder, were prepared for further aging tests.

The fabrication process of HPLMs using indium and AuSn solders are shown in Fig. 1. In the case of indium solder, 5–10 μm indium solder layer was placed between the laser diode and heat sink, and then the assembly was soldered at peak temperature of 156 °C [23]. In the case of AuSn solder, About 5 μm of AuSn solder layer was deposited on a copper–tungsten (CuW) submount which is inserted between the laser diode and the copper heat sink. The heat sink is deposited with indium or tin solder in die-attach region. And then the assembly was soldered at about 310 °C [24]. An expansion-match CuW submount (about 200 μm in thick) for the case is extremely essential to release the high stresses in the laser diode since the Young's modulus of AuSn solder is much higher than that of indium one.

In terms of the thermal and thermo-mechanical influence on the degradation of high power laser modules (HPLMs), the proper selection of thickness for the die-attach material is an important issue for the long-term reliability. From the perspective of thermal degradation, the die attachment may be as thin as possible to dissipate the heat from the active region of laser diode effectively and then alleviate the thermal degradation of laser diode. From the perspective of thermo-mechanical degradation, however, such a thin solder layer, e.g., 2 μm, may be harmful to the reliability of the laser diode because of the much higher fraction of inter-metallic compounds (IMCs) for such thin layer compared with that for the thicker solder layer. Such high fraction of IMCs, which is usually hard and brittle [25], cannot release the thermo-mechanical stresses effectively and then may accelerate the thermo-mechanical degradation of the laser diode. For commercial HPLMs, the common thickness of solder layer, i.e., AuSn and indium solder, is around 5 μm. Such thin films are usually pre-formed on the heat sink by physical vapor deposition [26]. For nanosilver paste, the die attachment may be suggested as thin as the solder layers or even lower since there should be no formation of IMCs in the sintered nanosilver joint. Unfortunately, it is impossible for us to obtain such thin bondline of nanosilver paste in stencil-printing way. As a result, we purposely set the as-printed bondline thickness of nanosilver paste as 20 μm. The paste could be shrinked to about 10 μm because of evaporation of the solvents and densification of the paste.

Therefore, in the case of nanosilver paste, 20 μm nanosilver paste is stencil-printed to the C-Mount heat sink (metalized Au/Ni) cleaning

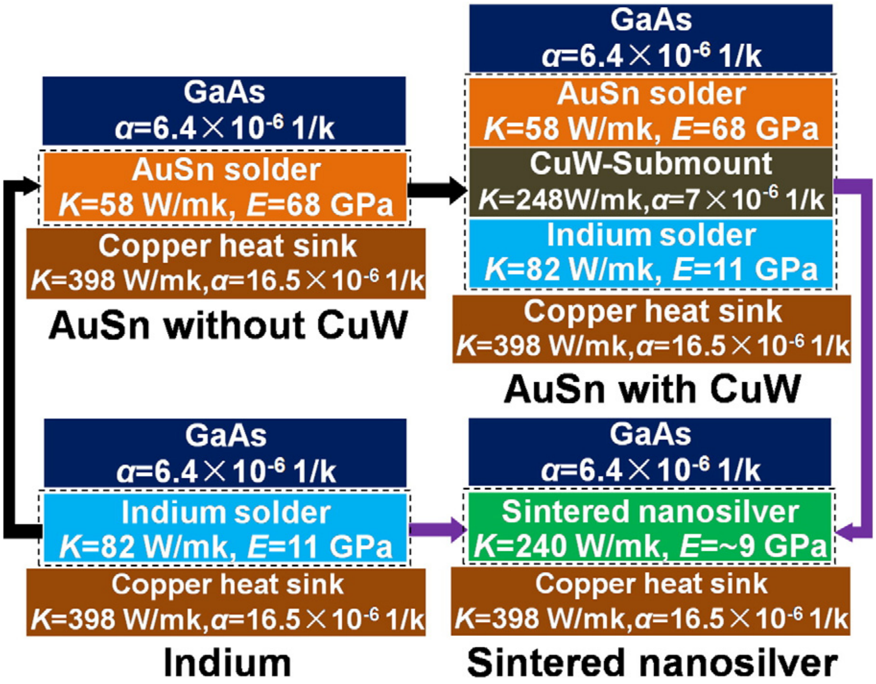

Fig. 1. Cross-sectional schema of typical samples using indium solder, sintered nanosilver, and AuSn solder with and without submount.