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Research Paper

Thermal performance of low melting temperature alloys at the interface between dissimilar materials

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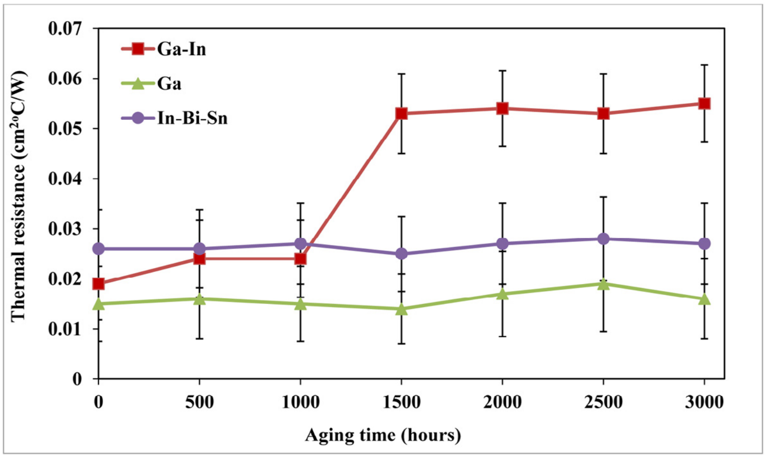
HIGHLIGHTS

- This paper presents the thermal performance comparision of a wide variety of TIMs
- Results show that LMAs offer extremely low thermal resistance
- LMAs survive 3000 hours of aging at 130 °C
- LMAs withstand 1500 cycles from -40 °C to 80 °C

GRAPHICAL ABSTRACT



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ABSTRACT

This paper describes the thermal performance and practical concerns of using a variety of thermal interface materials (traditional: greases, phase change materials, gels, and thermal pads; emerging: carbon nanotubes, graphene, low melt alloys, and metallic nanosprings) and investigated the reliability of low melt alloys (LMAs) containing gallium, indium, bismuth, and tin as thermal interface materials (TIMs). The analysis presented herein involved the thermal performance evaluation of LMAs placed between different surfaces (copper and nickel) after accelerated life cycle testing, which included high temperature aging at 130 °C and thermal cycling from –40 °C to 80 °C. Three alloys (75.5 Ga and 24.5 In, 100 Ga, and 51 In, 32.5 Bi, and 16.5 Sn) were chosen as candidate LMA TIMs. The testing methodologies followed ASTM D5470 protocols. Measurements showed that the proposed alloys survived as long as 3000 hours of aging at 130 °C and 1500 cycles from –40 °C to 80 °C without significant thermal performance degradation. The obtained results show that the performance of LMAs is significant as TIMs.

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1. Introduction

When two solid surfaces are brought into contact, surface asperities (roughness, waviness) limit their actual contact to 1–2% of the apparent contact at a low pressure [1]. The remaining interspace is filled with air which has a very low thermal conductivity (0.026 W/m-K at room temperature). Heat transfer across these solid contacts would result in significant temperature drop at the interface. By improving the quality of these contacts, the heat transfer can be enhanced. One option is to apply a very high pressure, which would crush all the peaks and increase the area of contact; however, the application of pressure is somewhat restricted considering the load constraints of the components attached. Furthermore, mating surfaces can be polished to a high degree to remove much of the roughness and waviness. Again, this is not a good option from an economic point of view because the surface preparation would make the components expensive. Another feasible option is to place a highly conductive material at the interface, which would fill those gaps at a lower pressure by displacing air from the interface. This material, which is placed at the interface between two objects to facilitate the heat transfer, is known as thermal interface material (TIM). The thermal performance of the TIM is characterized by the thermal conductivity and thermal resistance. The ultimate goal is to find TIM materials that are compatible, reliable, and offers lower interfacial thermal resistance. An ideal TIM would fill all the microscopic irregularities that exist at the interface. However, an actual TIM will leave some air gaps at the interface depending on the conformability of the TIM. A desirable TIM should offer low thermal resistance at a thin bond line thickness (BLT), high thermal conductivity, conformability at low to moderate pressures, good wetting properties, ease of manufacturing, and reasonable cost while also being environmentally and health friendly [2,3]. In addition to these properties, compliant TIMs must also be able to withstand the mechanical stresses resulting from the coefficient of thermal expansion (CTE) mismatches that occur between the adjoining materials (e.g. silicon-copper for processor-heat sink attachment). If the CTE strain overwhelms the mechanical properties of the TIM, the joint will ultimately fail. Therefore, high performing compliant TIMs are an essential design option for better thermal performance and improved reliability. In the next two sections, current status of some high-performing traditional and emerging TIMs are discussed.

1.1. Traditional TIMs

1.1.1. Thermal grease

Greases are usually made by mixing silicone or hydrocarbon oil with conductive particles such as silver, zinc oxide, aluminum oxide, or boron nitride to enhance the thermal conductivity. Greases flow quite well at the interface and fill most of the interstitial voids and irregularities which would otherwise be filled with air. Traditional greases have thermal resistance ranging from 0.1 to 0.55 cm^2 °C/W [1,2,4]. Today's high performing grease such as ShinEtsu X23-7921-5, has a thermal conductivity >6 W/m °C [5] and can offer thermal resistance as low as 0.07 cm^2 °C/W [5]. Dow Corning claimed the thermal resistance of their grease, TC 5026, to be as low as 0.032 cm^2 °C/W; however, Wasneiski et al. [4] found the thermal resistance of the same compound to be about 0.2 cm^2 °C/W at a thickness of 38 µm. Gwinn and Web [2] reported thermal resistance of Arctic Silver grease was 0.018 cm^2 °C/W. However, Wasneiwski et al. [4] and Roy et al. [5] could not reproduce that result with the same grease; the reported thermal resistance was about 0.1 cm^2 °C/W [4,5]. Thus, there is a large discrepancy between the manufacturer's claimed resistance and experimental results by different investigators. Chung [6] reported that polyethylene glycol (PEG) based thermal pastes are superior to silicone-based pastes due to the low viscosity of PEG. PEG-based paste can offer thermal resistance as low as 0.053 cm^2 °C/W when mixed with boron nitride particles (optimum concentration was found as 18 vol.%). Although greases offer low thermal resistance, there are practical concerns with greases. Greases are messy, difficult to apply and remove during re-work, and have reliability issues such as pump out, phase separations, and dry out, which limit the use of greases as an efficient TIM over a nominal lifespan of use [1,2]. In addition, greases can be electrically conductive; excess grease that extrudes out of the interface can cause electrical shorts [2].

1.1.2. Phase change material (PCM)

Phase change materials (PCMs) are made of highly conductive particles suspended in a base material, which can be a natural material such as fully refined paraffin, a polymer, a co-polymer, or a combination of these [7]. PCMs soften and start to flow above a certain temperature. The temperature at which the phase change occurs is called the phase change temperature or the transition temperature. When the temperature is below the transition point, PCMs act like a solid material, and above the transition point, the material starts to flow like greases and try to fill the irregularities that exist at the interface. The typical phase change temperature of the commercial PCMs ranges from 50–90 °C [7]. Gwinn and Web [2] reported the thermal resistance of PCMs was in the range 0.14–0.58 cm^2 °C/W, while Blezie [8] reported in the range 0.3–0.7 cm^2 °C/W. Honeywell claimed the thermal resistance of their PCM (PTM 6000 and PTM 5000) to be as low as 0.07 cm^2 °C/W. Roy et al. [9,10] reported the thermal resistance of Laird Tech. Tpcm 585 and Tpcm 5810 to be about 0.10 cm^2 °C/W and 0.16 cm^2 °C/W, respectively, at 50 psi. In general, PCMs have lower thermal conductivity and higher thermal resistance compared to the greases. Besides, PCMs can form a strong bond with the mating substrates, which hinder them from being applied between sophisticated components.

1.1.3. Gel

Typically, gels consist of silicone oil, a cross-linker, and thermally conductive particles [11]. Gels have similar properties to grease before being cured. However, gels are cured to a partially cross-linked structure, which keeps them from pump-out and migration from the interface like greases. Blazie [8] reported that the thermal resistance of gels falls in the range 0.4–0.8 cm^2 °C/W; Roy et al. [9] reported the thermal resistance of Chomerics Gel 30 was about 0.3 cm^2 °C/W. Samson et al. [12] reported the thermal resistance of an undisclosed gel to be as low as 0.1 cm^2 °C/W. Since gels are cured, they do not flow like greases and cannot offer thermal resistance as low as the greases. In addition, delamination (due to the CTE mismatch of mating substrates) is a major concern with gels [11].

1.1.4. Thermal pad

Thermal pads are composed of silicone or other similar elastomers loaded with thermally conductive ceramic particles, and may include a woven fiberglass or dielectric film reinforcement to improve handling [8]. Pads are easy to apply and remove and can be reused. They don't suffer from "pump-out" or "dry-out' problem as the greases do [13]. However, their thermal performance is not as good as greases, PCMs, and gels. In addition, moderate to high pressure is required to conform to the mating surfaces. Thermal resistance ranges from 1–3 cm^2 °C/W [8]. Wasneiwski et al. [4] and Roy et al. [5] reported the thermal resistance of a Bergquist Gap pad 5000S35 was in the range 0.82–0.90 cm^2 °C/W at 50 psi, whereas, the reported thermal resistance of a Bergquist Sil pad A2000 was about 1.65 cm^2 °C/W at 50 psi [9].