Characterization of a Novel Thermal Interface Material based on Nanoparticles for High Power Device Package Assembly

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ABSTRACT:

Thermal interface materials (TIM) are one of the key factors for an effective thermal management in packaged high-power electronic devices, hence the rapid growth of the TIM market. Novel TIMs based on nanoparticles are being developed to further ensure good heat conduction across interfaces in packages while ensuring a strong structural bond. Selecting the right thermal characterization technique for manufacturing feedback is challenging due to the lack of a widely accepted test method. In this work, low-frequency frequency domain thermoreflectance has been used to support material development and the process control of these novel nanoparticle-based TIMs.

INTRODUCTION:

Effective thermal management of high-power electronic devices is an on-going challenge; a lot of research effort is focused on improving the thermal interfaces between the key elements of the packaged device, mainly between the die and the flange, and between the flange and the heat sink. Thermal interface materials (TIM) are critical to minimizing thermal resistance and hence improve the heat conduction across these interfaces. To address the demands of various applications, many types of interface materials have been researched extensively and introduced to the market such as thermal adhesives, thermally conductive grease, thermal gap fillers and gel. Most TIMs consist of a polymer matrix, such as an epoxy or silicon resin, and thermally conductive fillers such as alumina and silver [1]. More recently, two-dimensional (2D) nanomaterials, such as graphene and boron nitride, are promising materials for enhancing the performance of TIMs, thermally and electrically. In this work, a novel TIM is presented; a novel thermal characterization technique is developed to support the TIM development; ultimately the developed TIMs are characterized and compared to a commercially available product.

BACKGROUND

Flange and heat sink baseplate surfaces have a typical roughness and non-flatness, causing a finite air gap between parts which is filled using a TIM layer [2]. Several TIM characteristics are desirable, such as high in-situ thermal conductivity for low thermal resistance, dielectric properties, processability, etc. [1]-[2]. Currently available commercial TIMs each have advantages and disadvantages [2]-[3], and will be selected depending on the targeted application. Their bulk thermal conductivities range from very low values of 0.4 W/m·K for some adhesive tapes, up to as high as 7 W/m·K for a silver filled adhesive [2].

The novel TIMs are based on mature nanotechnology products which have been incorporated through nano-modification approaches in polymers. They are intended to play an important role in structural assembly, as well accommodating thermal expansion mismatch, even between large parts. The nanoparticles are mechanically dispersed within the polymer matrix, enabling a solvent-less production route, and the resulting adhesive is then undergoing a filming process. Different nanoparticles-based TIM film samples were considered in this work, having a direct influence on the thermal conductivity through their chemical composition (from metallic to carbon-based nanoparticles) and their microstructures (such as spherical nanoparticles or flakes). Additionally, different filming processes were assessed, in order to evaluate their impact on the final properties. In this paper, eight samples are described and compared to a commercial TIM film, based on silver filler. The main goal is to reach a thermal conductivity of 10 W/m·K, which is higher than the best commercially available TIM for high power electronic devices assembly, benefiting the overall thermal performance of a packaged device.

EXPERIMENTAL SETUP

The TIM films developed are thin (75-150 μm) and come in a semi-cured state, which fully cures under heat to provide not only the thermal path but also a mechanical bond between the adherends. To study these products in application, as opposed to a self-standing material, all TIM films were sandwiched between an aluminum or copper foil (~20µm) and an aluminum substrate (~2mm). Additionally, this structure enables to study the presence of any high thermal boundary resistance at the foil/TIM and TIM/substrate interfaces, which is a very helpful information during assembly process.

Optimizing the thermal properties of TIMs through the material development process can be challenging. The current primary characterization method used is the ASTM D-5470 steady state test method. It is widely used by TIM suppliers to measure thermal properties of TIMs. The shortcoming of this method is the contact pressure used during the test of around 3MPa, which exceeds the contact pressures typically used in real applications (of around 0.1MPa) [4]-[5] and therefore underestimate the thermal resistance, i.e., thermal resistance decreases with increasing pressure. Comparing two TIM products through their datasheet values is often not possible due to the differences in testing, including the different preparation methods of materials [6]. Transient techniques have been also used to characterize TIMs such as laser flash or transient hot disk, to mention a few [6]. These transient techniques however measure bulk thermal conductivity (or the bulk thermal resistance) of the TIMs, therefore overestimate the TIM thermal performance when used in real application environment or after undergoing assembly process. Moreover, the application process of such films creates a challenge in standardizing the sample design (thickness, uniformity, parallelism).

Here we use the recently developed low-frequency frequency-domain thermoreflectance (FDTR) [7] which is an optical pump-probe system: while a modulated pump laser periodically heats the surface of a sample, a probe laser monitors the surface temperature change ΔT of the transducer which is proportional to the relative change in the transducer reflectivity ΔR ($\Delta R/R \propto \Delta T$). This FDTR system is operated at low modulation frequency from ~10Hz to 10kHz, to gradually increase the thermal penetration depth [7]. The reasons of choosing the FDTR as a characterization technique for the TIM are, firstly, it is simple and quick to use, similar to a flash technique. Secondly, its spatial mapping feature, enabling the TIM film uniformity study, which is not possible with the standard ASTM technique or the laser flash. Thirdly, and most importantly, the FDTR technique gives a repeatable results contrary to the other standard techniques, and the measurements are more representative of an actual packaged device assembly. For the subsequent thermal measurements, a 150 nm gold was deposited on the foil as a transducer on top of all the measured samples for the FDTR characterization. All samples have been measured under the same conditions at room temperature.

RESULTS AND DISCUSSION:

The measured effective thermal conductivity data, which takes into account the thermal boundary resistance at the foil/TIM and TIM/substrate interfaces, is presented in Fig. 1. The measured thermal conductivity of the commercial sample is 4.4 W/m·K which is lower than the datasheet value (6.5 W/m·K). This difference is expected since, on one hand, the datasheet gives the measured bulk thermal conductivity, which has been measured using a Photoflash technique. On the other hand, the thermoreflectance gives a value of an assembled TIM film. This highlights further the significant gap between the standard tests performed by the TIM manufacturers and real-life tests [5].

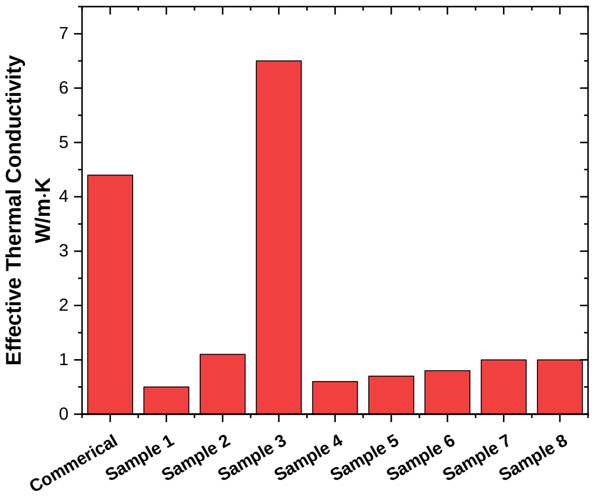

Fig. 1. Measured Effective thermal conductivity of all eight samples provided from Adamant Composite Ltd., along with commercial TIM film.

A fairly low thermal conductivity was measured for most of the TIMs samples developed here. However, Sample 3 has the highest measured thermal conductivity of around 6.5 W/m·K, which is higher than the value measured for the commercial film, i.e., a like for like comparison rather than data sheet value. The difference between the samples is attributed mainly to the composition of the TIM and to the preparation process. It has to be noted that these TIM samples are still in the development stage and the FDTR is assisting in determining the right composition and the right handling process.

CONCLUSIONS

A novel nanoparticle-based thermal interface material, which will enhance packaged device assembly, is under development. To understand and master the process control of these TIMs, different samples have been thermally characterized with the low-frequency FDTR, taking advantage of its representation of the TIM performance in an actual assembly. A promising thermal conductivity as high as 6.5 W/m·K has been measured, which outperforms an industry-standard material offering 4.4 W/m·K. Further material development and process control is needed in order to reach the 10 W/m·K target, aided using the FDTR technique.

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