Investigation of the Mechanical Compliance of Highly Conductive and Durable Carbon Nanotube-Polymer Composite Thermal Interface Materials

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ABSTRACT

In the past several decades, the increasing performance of integrated circuits has put increasing demands on thermal management solutions. The thermal interface resistance of a typical electronics package can often comprise the majority of the total thermal resistance. While much effort has been put into developing high conductivity materials for thermal interface material (TIM) applications, in practice the observed thermal resistances are dependent on many other factors beyond the conductance of the material. A particularly important but somewhat overlooked factor in TIM performance is the mechanical compliance of the material. CTE mismatch between the various materials in typical packages can result in TIMs that need to accommodate chip center-to- edge warpages greater than 50 um. In multichip applications TIMs may need to accommodate chip- to- chip offsets of 100 um or more. These challenges are exacerbated in burn in and device testing applications where temperatures are often higher and contact with the device is a dynamic process sometimes requiring multiple insertions per device tested. There are many different types of TIMs to help mitigate the problem including solders, greases, adhesives, phase change materials, gels, and pads. In this work, carbon nanotube- polymer composite TIMs are investigated as a potential highly compliant, low thermal resistance solution. Vertically aligned carbon nanotubes grown on metal foils can deliver low thermal resistances due to their high in plane conductivity, mechanical compliance and achievable contact area for heat transfer. As carbon nanotube height increases, the TIM becomes more mechanically compliant, but also has a higher thermal resistance. This work focuses on how to make the CNT-polymer composites mechanically compliant while keeping thermal resistance low. Carbon nanotube-polymer TIMs will be stacked to improve compliance while keeping thermal resistance low. A variable force thickness gauge is used to measure the deformation of different TIM composites at different pressures. In addition to initial deformation, compression set and TIM rebound will be evaluated to understand how the candidate TIMs will perform over time and under changing mechanical conditions.

KEY WORDS: TIM, Thermal Resistance, Compression, Electronics Package, Burn in and Chip Testing

INTRODUCTION

While thermal interface materials (TIM) are used to reduce the total thermal resistance in an electronics package, there are many design requirements needed in order to accommodate different microchips across a wide range of applications. While conductance of the TIM is important, in many cases the limiting resistance of an interface is the contact resistance at the interface. Many materials can make good contact between two planar surfaces, however when the mating surfaces are not flat the task become significantly more difficult.

As a microchip heats up, it can warp leading to a center-to-edge warpage greater than 50 um [1]. In multichip applications TIMs may need to accommodate chip- to- chip offsets of 100 um or more[2]. To make up for the CTE driven die warpage, mechanically compliant TIMs are necessary. Not only is the initial compliance of the TIM important, but the rebound of the TIM after compressive force is removed is also key to determining how well the TIM performs over its lifetime. As the interface expands and contracts due to changing power consumption of the devices being cooled a TIM with poor rebound may tend to de-wet the interface as the bond line increases, resulting in poor cooling performance.

Conventional TIM materials such as greases, soft metals such as indium or graphite sheets, and elastomeric gap pads may provide the compliance needed to make up to non planarity in the package. In this work, carbon nanotube-(CNT) polymer composite TIMs are investigated as a potential highly compliant, low thermal resistance solution for cooling warped or otherwise non planar die. Compliance in the CNT array may be obtained by growing longer carbon nanotubes or by stacking the CNT TIMs on each other [3].

SAMPLE FABRICATION

Vertically aligned carbon nanotubes are grown on aluminum foil as the base substrate. Both sides of 50 um thick aluminum foil are coated with an iron catalyst and then the CNTs are grown via low pressure chemical vapor deposition. Acetylene and hydrogen act as precursor gases and growth is performed at 630°C in order to stay comfortably below the melting temperature of the Al substrate. CNTs are grown to 7-10 um with an 8 minute growth time.

To avoid some of the diffusion driven challenges associated with growing long CNTs on metal foils [4], one method of increasing the thickness as well as the compressibility of the CNT-TIM is to stack the TIMs on one another. Figure 2 shows a schematic of the single tier and multi-tier TIMs.

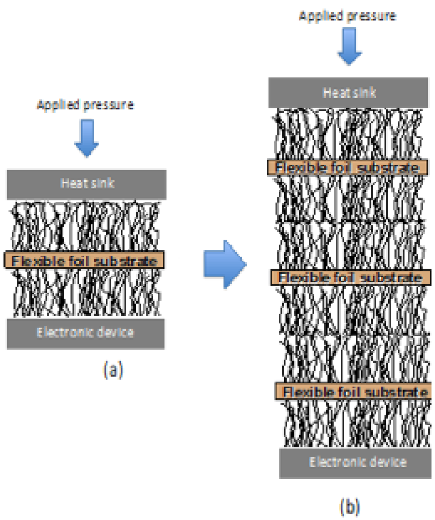

Figure 2: Schematic showing a 1 tier and a 3 tier stack up of the CNT based TIM

EXPERIMENTAL METHODS

In order to measure thickness, compression, and rebound of the candidate TIMs, the Precision Thickness Gauge – FT3V by Hanatek Instruments (Figure 3) is used to measure the thickness of a material at different applied pressures. Weights can be added to a weight platform that corresponds to an instantaneous change in pressure at the pressure foot that the material is placed under. The pressure foot comes down at a rate of 3 mm/s. The thickness is recorded when the material has reached steady state which typically takes 1-10 seconds. For a given user applied force, the tool measures thickness with an accuracy of +/- 0.1 micrometer. This machine meets ASTM-F36-99 standards to test compressibility and recovery of gasket materials. The minimum pressure the gauge is able to achieve is 7 psi - the datum pressure. The pressure is then taken up to 100 psi and the thickness is recorded. Then, all pressure is released from the TIM, and then the 7 psi is reapplied to measure the amount of rebound of the TIM.

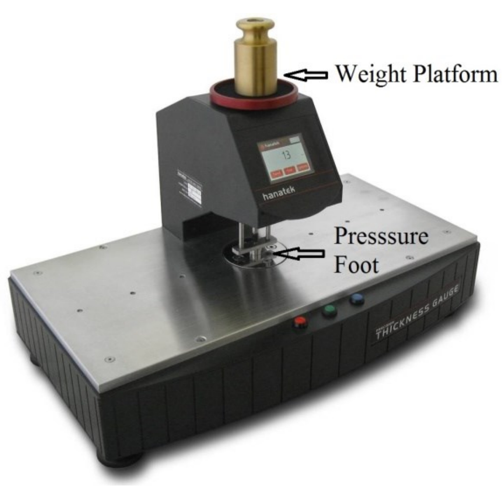

Figure 3: Hanatek Precision Thickness Guage FT3-V depicting the Weight Platform and the Pressure Foot.

To benchmark the CNT-TIM thermal performance as a function of number of tiers, 1 cm x 1 cm samples were measured in a modified ASTM- D5470 stepped bar apparatus designed to measure the steady state 1D thermal resistance of thermally conductive samples. The test apparatus, which is described in great detail in [5], improves upon more traditional 1D reference bar style test systems by removing uncertainty associated with proper alignment of the upper and lower reference bars. To properly position the performance of the CNT-TIM within the state of the art, a wide variety of commercially available TIMs were tested under the same conditions.

For all TIMs investigated, compressibility $(thickness_{100\,psi}/thickness_{original})$, and rebound $\left(\frac{thickness_{post\ compression} - thickness_{100\,psi}}{thickness_{original} - thickness_{\ 100\,psi}}\right)$ -the degree to which the TIM recovers to its original thickness - were measured. The commercial TIMs used for benchmarking are: TGARD 210 (silicone elastomer), T-Global PC94 (acrylic base), Pyrolytic Graphite - (PGS), Fujipoly SARCON XR-UM-Al (silicone putty backed with thin aluminum foil), and Indium Heat Spring (soft metal). These materials are chosen to represent different TIM compositions, and also all have a specified thermal conductivity greater than 4.0 (W/m*K), placing them at the state of the art for current TIMs.

RESULTS

The first metrics measured are the compressibility and rebound of the TIMs using the Precision Thickness Gauge. Figure 4 and Figure 5 show the normalized compression and rebound, respectively. When looking at commercial gap pads, most demonstrate a compressibility of 10% or less at 100 psi. Stacked CNT-TIM tiers show a slight drop in compressibility as compared to a single tier, owed to inter-digitation of the CNT tips during the stacking process.

Indium and the PC94 have notably higher compressibility at 100 psi at 33% and 16%, respectively. However these materials have comparatively little rebound after the initial compression. In applications with cyclic heating and cooling, this could lead to dewetting of the interface during expansion and contraction events.

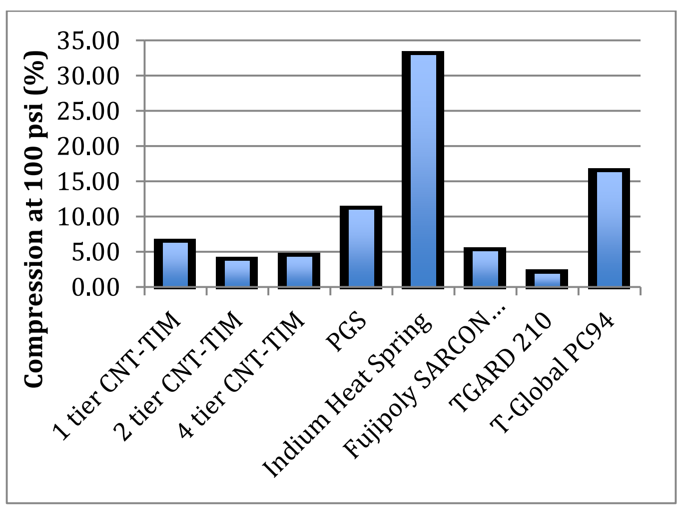

Figure 4: Normalized compression measured at 100 psi.

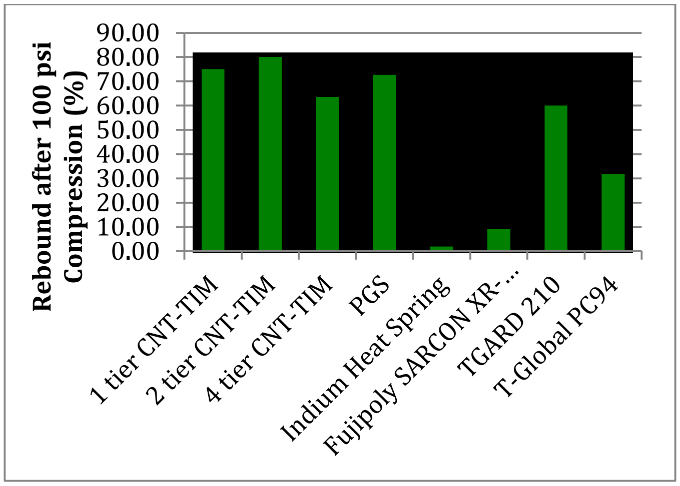

Figure 5: TIM normalized rebound measured at 7 psi after it has been compressed to 100 psi.

From a deformation mechanics perspective, the CNT-TIMS and PGS have a good combination of compressibility and rebound after compression. However a key challenge for thermal designers in selecting a TIM for applications requiring compliance is that the warpage of the die in the application is not always known. As a means of evaluating the required compliance of an application, one may consider stacking CNT-TIMs in the interface. Because the CNT-TIMs do not experience an inter tier thermal penalty, the effective conductance of the stack increases with each successive tier due to compliance driven increased contact area for applications with a curved interface. This is shown pictorially in Fig. 6, where CNT-TIMs of 1, 2 and 4 tiers were compressed in a curved interface. The resulting contact area clearly increases with each additional tier. At 4 tiers, contact appear to be approximately uniform across the interface suggesting that this may be an appropriate thickness for this application.

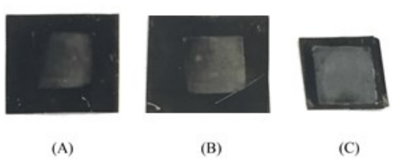

Figure 6: Imprint of a curved surface on a 1 tier CNT-TIM (A), 2 tier CNT-TIM (B), and 4 tier CNT-TIM (C).

When measured in the stepped bar apparatus, the conductance of the CNT-TIM increases by 95% when going from 1-2 tiers, and an additional 36% when going from 2-4 tiers (Fig. 7). As the bulk conductivity of the CNT-TIMs does not increase with stacking, this effect is driven by the increase in contact area that additional compliance allows.

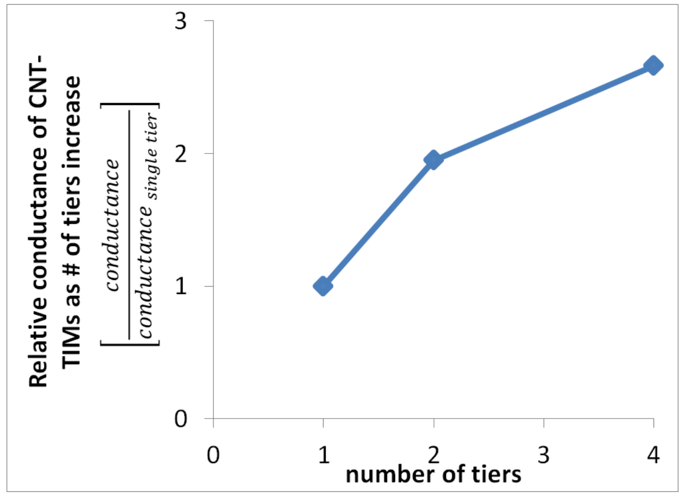

Figure 7: Effective thermal conductivity of TIMs are stacked compared to commercial TIMs.

CONCLUSION

Bulk conductivity alone is not sufficient to predict how a TIM will perform in an interface. The compressibility of a TIM is a key factor in evaluating the degree to which the TIM will be able to create good contact in an interface with nonflat surfaces due to warpage, manufacturing tolerances, 2.5D or 3D architectures or other scenarios typically seen in the field. Furthermore, in applications that may heat and cool cyclically or where the interface geometry may otherwise change on the microscale over time, TIM rebound must also be evaluated so that the interface does not de-wet with a resulting loss in performance during operation.

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