Influence Of Aluminum Particles On Thermal Interface Material Hardness And Thermal Conductivity

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Abstract : Electronic device heat dissipation is crucial and challenging because it limits the performance of the device. The electronic device is processing data at high speed, significantly generate heat and requires to be dissipated into the environment. Therefore, this experiment aims to investigate the influence of thermal interface material hardness on thermal conductivity. The results were analyzed by using conductivity measurement set-up and scanning electron microscopy (SEM) with energy dispersive x-ray spectroscopy (EDX). In the present study, thermal interface material (TIM) is hardened by aluminium oxide (Al@Al₂O₃) and thermal coefficient are measured for different hardness and the heat rate of 3W and 7W. The results show TIM hardness is significantly improved the thermal conductivity coefficient up to 10 times compare to pure TIM. The results also show that the Al@Al₂O₃ particles distribution inside the TIM is well distributed. The outcomes of this paper can be a guideline to the semiconductor industries especially for the usage of TIM in product development.

Keywords: Thermal interface material, thermal conductivity, aluminum particles, hardness, heat rate

1. INTRODUCTION

Due to demanding high performance and highly integrated functionalities of electronic package ranging from manufacturing to consumer product, the power of the electronic component is rising over the years. Such electronic devices process data at high speed, generating heat significantly that has to be dissipated into the ambient. Miniaturization and lightweight nature of electronic system components, higher demands on materials with high thermal conductivity and low density are constantly raised and become more challenging [1][2]. Thus, electronic device thermal management becomes very critical to ensuring functional, improved reliability and longer life span.

The thermal interface material (TIM) between silicon die and heat spreader or heat sink and the use of an external heat sink is to provide more efficient thermal conductivity. The TIM solution can be in various forms, such as adhesive, grease, gels, phase change material and sheets. Majority of TIM are of polymer matrix such as an epoxy or silicone resin and thermally conductive filler such as boron nitride [3], zinc oxide [4], aluminium nitride and alumina [5]. The TIM mixed with ultra-thin full carbon films with extraordinarily high thermal conductivity (k) and promising mechanical power, but the fragility (approximately 0.5-3.0 percent break elongation) limits their applications. In addition to the high k, superior TIM required excellent durability, low thickness and low hardness in order to ensure good thermal management [6]. Thermally conductive and insulating thermal interface materials composed of core-shell structured aluminium/aluminium oxide (Al@Al₂O₃) and epoxy resin. The composite exhibit 0.92W/mK thermal conductivity at 60wt percent filler content, which is about 4.2 times higher than the epoxy resin content. The oxidation of Al particles results in the formation of dense nanoscale Al₂O₃ shell isolating which effectively restricts the transfer of electrons, resulting in very high electrical resistivity and composite puncture voltage. The polymer composites filled with Al@Al₂O₃ particles have excellent insulation property, high thermal conductivity and outstanding thermal-mechanical performance, which could be a potential thermal interface material in advanced electronic packaging techniques [7].
but contact thermal resistance can be minimized by applying high compressive pressures to mechanically deform surfaces and interface contact region [14], [15]. An efficient way to reduce thermal contact resistance without using high pressure is to fill the holes with wet thermal interface materials, such as greases and pastes [16]. Another useful approach for these liquidation TIMs is to build high-performance thermal interfaces using nano-structured materials [17], [18]. Particle-laden polymers (PLPs) [19] have the same characteristics as the polymer matrix, while nano-filling particles of high thermal conductivity enhance the thermal conductivity of the polymer matrix. Higher filler particle ratio results in better thermal conductivity, but with the mechanical compliance cost [18]. Compliant metal nano-springs [20] and nanowires [21] can be quickly deformed and soldered onto a rough surface in a conformal manner. These micro and nano-structured TIMs provide feasible solutions that greatly improve the thermal interfacial conductance of surfaces with microscopic roughness, but these TIMs bind surfaces permanently or plastically deform to achieve conformal contact with the mating surfaces, which are intended for applications where the mating surfaces are not moving through [22]. Thermal interface materials, such as thermal conductive gap filling materials are commonly used in electronic packaging to minimize the thermal contact resistance of interfacial air, the volume and thermal conductivity (k) of which can be as high as 99% and as low as 0.026 W/mK, respectively [23]. To rising the overall thermal resistance, high performance TIMs should possess high k, low thickness and high conformability (low hardness and low modulus). Therefore, in the present study on the TIM is hardened by Al@Al2O3 particles (filler) with different weight percentage has been made. The influence of Al@Al2O3 particles on the thermal conductivity, mixture homogeneity and hardness have been considered. The aim of this works is to obtain the relationship between hardness and thermal conductivity of the hardened TIM for better electronic device heat dissipation applications.

2. EXPERIMENTAL SET-UP
As shown in Figure 1, a bar heater (1) is used as a heat source in the right and the cooling water flow in (2) and flow out (3) is used as a heat sink in the left to ensure a steady state heat flow along longitude axis of the test specimen (4). Several TIM hardness values are made and tested varied from 45 to 70 shore for the heat rate of 3W and 7W. A set of thermocouples (5) is mounted at the brass bar together with temperature and power measurement systems. Heat sink compound is applied to reduce the contact resistance between heater and chiller. Hollow cylindrical brass block acted as a chiller (7). The cooling water tank (2) and water circulation pump has been used to obtain a steady state condition during experimental measurement. The experimental rig setup and specimen are shown in Figure 2. The experimental rig is developed for ambient environment experiment. The apparatus consists of two brass bars and specimen (TIM) at the middle. Four different specimens insulated with insulation material in the experiment, i.e. TIM is hardened with different weight percentage of Al@Al2O3 particles. The dimension of specimen as shown in Figure 3 with diameter of 25mm and length of 10mm. The specimen hardness is measured by a shore-hardness durometer.
3. RESULTS AND DISCUSSION

The result of temperature for different hardness is taken at steady state condition where it took about 30 minutes to reach steady state after the experimental rig is switched ‘on’. Six locations are measured on the experimental rig using thermocouples and have been used to obtained thermal coefficient of TIM with different hardness. The thermal conductivity coefficient of TIM is measured at different heat rate. Figures 4 and 5 show the typical temperature measurements across the heat conduction apparatus and specimens for 3W and 7W respectively. The thermal conductivity coefficient can be obtained from the Fourier equation of heat transfer as given by:

\[
k = \frac{Q}{AdT/dx}
\]  

where \(k\) is the conductivity coefficient, \(Q\) is the heat rate used, \(A\) is the cross section area of specimen, \(dT/dx\) is the temperature gradient across specimen. The value of \(dT/dx\) for different hardness of the specimens are found to be in the range of 622.99-735.02K/m for \(Q=3W\) (Figure 4), and 1402.9-1765.78k/m for \(Q=7W\) (Figure 5). The results show that the lower temperature gradient obtained at higher TIM hardness has increased the thermal conductivity coefficient as expected from the Fourier equation (1).
In the present study all the specimens (total of 16) have been group for the hardness ranges of 45-52 shore (Category I), 54-60 shore (Category II), 61-66 shore (Category III) and 67-70 shore (Category IV) as illustrated in Table 1. The results obtained show that the thermal conductivity increased significantly with the hardness up to nearly 26%. The Al@Al₂O₃ particles increased the hardness, thermal conductivity of the TIM and could improve heat dissipation of the electronic device. Moreover, the TIM hardened with Al@Al₂O₃ particles has increased about 10 times compare to the TIM without filler.

### Table 1: Average thermal conductivity of TIM specimens

<table>
<thead>
<tr>
<th>No.</th>
<th>Specimen Category</th>
<th>Hardness Range</th>
<th>Thermal Conductivity Q= 3W (Average)</th>
<th>Thermal Conductivity Q= 7W (Average)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>I</td>
<td>45-52 shore</td>
<td>8.319 W/mK</td>
<td>8.080 W/mK</td>
</tr>
<tr>
<td>2.</td>
<td>II</td>
<td>54-60 shore</td>
<td>8.512 W/mK</td>
<td>8.140 W/mK</td>
</tr>
<tr>
<td>4.</td>
<td>IV</td>
<td>67-70 shore</td>
<td>9.815 W/mK</td>
<td>10.170 W/mK</td>
</tr>
</tbody>
</table>

Figures 6(a)-(d) is the SEM images of TIM with different hardness to observe the homogeneity of fillers. As overall, the homogeneity of Al@Al₂O₃ particles distributions are improved with the increase of percentage filler. Figure 6(d) shows the particles are well distributed inside silicone and provide higher hardness of the TIM as shown in Table 1. Moreover, Figures 7(a)-(d) show the EDX results of different hardness. The figures clearly show the elements consists of silicone, aluminum and oxygen. The increase of specimen’s hardness is expected as the aluminum percentage increases and the grain size of aluminum are smaller and compactly formed as shown in Figures 6(d) and 7(d). The produced microstructure improves conductivity of heat in the specimen which eventually increases the thermal conductivity.
Figure 6: SEM images of (a) Specimen I with hardness 45 shore (b) Specimen II with hardness 54 shore (c) Specimen III with hardness 65 shore and (d) Specimen IV with hardness 70 shore
Figure 7: SEM images and EDX results of (a) Specimen I with hardness 45 shore (b) Specimen II with hardness 54 shore (c) Specimen III with hardness 65 shore and (d) Specimen IV with hardness 70 shore

Figure 8 shows the overall results obtained from the study. The thermal conductivity of hardened TIM for different heat rate also show similar trend. Both heat rates of 3W and 7W are almost linearly increased with the hardness and the maximum variation of the thermal conductivity is about 3.5%. The results also show that the TIM is dense with Al@Al₂O₃ particles for the higher hardness value.

Figure 8: Thermal Conductivity at different heat rate and hardness for specimen categories I-IV
4. CONCLUSION
TIM reinforced with Al@Al$_2$O$_3$ particles was successfully hardened the TIM and has increased the thermal conductivity coefficient up to almost 10 times compared to the pure silicone. Whereas the hardness has increased up to 27%. Thus, additional of Al@Al$_2$O$_3$ particles are significantly improved the hardness and thermal conductivity of TIM. The thermal coefficient is varied almost linearly up to 10.17W/mK for the hardness of 70 Shore. The Al@Al$_2$O$_3$ particles used as filler are found good homogeneity at higher hardness. The results also can be a guideline to the semiconductor industries especially for the usage of TIM in product development. Moreover, with successful development of experimental set-up, various TIM and filler materials could be investigated and analysed further on the thermal resistance via experiment in future study.

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