A Comparison of Bulk and In Situ Ag Epoxy Die Attach Thermal Performance
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Abstract:
In this paper, we compare the bulk thermal conductivity of Ag epoxy die attach materials with the same material’s thermal conductivity in an actual in situ die attach configuration. We find that the effective in situ thermal conductivity, which includes contact resistance at the pad metallization/epoxy interface, is significantly lower than bulk values for epoxies ranging from 11 to 77 W/m-K. We model the bulk conductivity using a percolation model which shows a percolation threshold of 18 volume percent Ag, in good agreement with theoretic percolation models.

Introduction
Ag filled epoxy die attach is extensively used in the electronics industry in a wide range of applications that require die attach with both electrical and thermal conductivity. This technology offers both thermal and electrical performance at a much lower cost than solder alternatives due to the very high manufacturing throughputs that can be achieved with epoxy.

The Ag epoxy interface that bonds to both the package pad and the die pad contains two phases: an epoxy phase, which provides adhesion, and a Ag conductor phase, which is the heat and electrical conduction path. Due to this heterogeneous structure, one critical question is how the measured bulk thermal conductivity of Ag epoxy compares to the actual performance of the die attach bonded to the die and package?

In this paper, we address this question. We evaluate commercial Ag epoxy die attach materials utilizing laser flash thermal conductivity measurements. The bulk thermal conductivity of the epoxies included in this study ranged from 2.5 W/m-K to 77 W/m-K. Utilizing laser flash, we measured both the bulk thermal conductivity and the in situ die attach layer thermal conductivity (“interfacial thermal conductivity”) for samples prepared by bonding Ag epoxy between two Cu foils plated with electrolytic Ni and Au. These Cu foils simulated the pads on the die and package. Au was chosen as the top metallization since this is a common plated top metal on both die and package pad.

Our study shows a significant difference between bulk thermal conductivity and the actual layer thermal conductivity which includes the interfacial thermal impedance of the Ag epoxy bond to the metallization layers. We explain the difference between the bulk and layer thermal conductivity by utilizing models which account for the difference between 3-dimensional bulk conduction and 2-dimensional heat transfer dominated by surface contact resistance.

For high thermal conduction epoxies (> 18% Ag by volume, the significance of 18% will be discussed later), the experimental results and model indicate that the difference in thermal performance between the bulk material and the Ag epoxy in an interface is a fundamental consequence of the restricting effect of contact resistance and is consistent across a range of epoxies.

Laser Flash Thermal Conduction Measurements – Applied to Layered Structures
In this measurement, a short laser pulse illuminates the front surface of the sample creating a heat pulse. The subsequent temperature rise is measured on the back surface of the sample using a sensitive infra-red detector. The overall temperature rise is typically only a few degrees centigrade. The temperature rise on the back surface as a function of time is fitted to a one-dimensional heat flow model and the thermal diffusivity of the sample is determined. Thermal conductivity is the product of the sample density, heat capacity and the measured thermal diffusivity\(^1\). A typical temperature rise profile measured on the sample backside as a function of time is shown in the Figure 1 below:

\(^1\) ASTM E1461-07
The time = 0 for this profile begins when the laser pulse is incident on the sample.

A schematic of the laser flash system used for these measurements is shown in Figure 2.

In our laser flash system, a pulsed CO2 laser with a wavelength of 10.6 µm and 5 micro-second pulse duration was used to illuminate the front side of the sample, and a liquid nitrogen cooled HgCdTe IR detector was used to measure the temperature on the backside of the sample.

For a monolithic sample ("bulk sample"), this temperature rise is fitted to a 1D heat flow model and the thermal diffusivity of the sample is determined from this fit. The time dependent temperature of the backside of the sample $T(t)$ in the 1D heat from model is described by:

$$T(t) - T(0) = T_m - T(0) = 1 + 2 \sum_{n=1}^{\infty} (-1)^n \exp \left(-n^2 \pi^2 \alpha t / L^2 \right),$$

where $t$ is time after the laser pulse, $T(0)$ is the initial backside temperature at $t=0$, $T_m$ is the maximum backside temperature after the laser pulse, $L$ is the sample thickness and $\alpha$ is the thermal diffusivity.

If we input the experimentally measured time required for the sample backside to reach 0.5$T_m$, $t_{1/2}$, then from the equation above calculate the thermal diffusivity

$$\alpha = 0.138 \frac{L^2}{t_{1/2}}.$$
The thermal conductivity is the product of the thermal diffusivity $\alpha$, sample density ($\rho$) and heat capacity $c_p$.

The discussion above is relevant for monolithic samples. However, the laser flash technique can also be applied to layered structures. In this case, a model is utilized which considers one dimensional heat flow through a layered structure. Application of the diffusion equation to layered structures is discussed in Taylor et. al and references therein\(^2\).

The input requirements for a three-layer model are shown in the table below.

<table>
<thead>
<tr>
<th>Structure</th>
<th>Model Input Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Known layer (Cu pad)</td>
<td>Heat capacity, thermal diffusivity, density, thickness</td>
</tr>
<tr>
<td>Unknown layer (Epoxy)</td>
<td>Heat capacity, density, thickness. Model solves for the thermal diffusivity calculates thermal conductivity</td>
</tr>
<tr>
<td>Unknown layer (Cu pad)</td>
<td>Heat capacity, thermal diffusivity, density, thickness</td>
</tr>
<tr>
<td>Three-layer structure</td>
<td>$t_{1/2}$ as defined above for whole stack</td>
</tr>
</tbody>
</table>

For our Cu/die attach/Cu structure, the two Cu layers represent the “known layer” and the die attach represents the “unknown” layer.

**Experimental Details**

The Ag filled epoxies used in this study were commercial products. Each sample was dispensed on a Ni and Au plated Cu foil approximately 1 cm\(^2\) and then cured using a curing cycle recommended by the manufacturer. Each sample was x-rayed to ensure that there was no die attach voids which would have significantly impacted the thermal measurements. Samples were also cross sectioned after the laser flash measurements to get an accurate die attach layer thickness and to ensure that there was no delamination at the metal pad interfaces. Die attach thicknesses were about 20 µm.

For all epoxy samples in this study, we also measured the heat capacity using a TA Differential Scanning Calorimeter (DSC) and density using the Archimedes principle approach. The heat capacity value was used in combination with the thermal diffusivity result and density measurement to determine thermal conductivity for each sample.

**Results**

Figures 3 and 4 below shows SEM micrographs of one of the Ag epoxy samples at 200 and 5000x respectively. The bright phase in this SEM micrographs is the Ag and the dark areas are the epoxy phase.

Figure 3: Cross section of Ag Die Attach Epoxy SEM Micrograph at a magnification of 200x.

Figure 4: Cross section of Ag Die Attach Epoxy SEM Micrograph at a magnification of 5000x.

Figure 5 below shows a plot of the bulk thermal conductivity vs. the interfacial thermal conductivity for a range of samples with bulk thermal conductivity between 2.5 and 77 W/m-K.

The fit shown in the graph is linear with a slope of 0.26 indicating that the interfacial thermal resistance is significantly lower than the bulk values. For example, a sample with a bulk thermal conductivity of 77 W/m-K had interfacial thermal conductivity of 22 W/m-K.

To get physical insight into these thermal conductivity results, we determined for each sample the volume percent of Ag (from the density measurement) and then plotted the bulk and interfacial thermal resistance vs. the Ag content. This is shown in Figure 6 below.
Let’s first consider the bulk thermal conductivity of a Ag filled conducting epoxy. Since this epoxy is a combination of a very poor heat conducting phase (epoxy) and a very good heat conducting phase (Ag), the conductivity as a function of Ag content must be described by a percolation model\(^3\). An example of conduction as a function of conducting filler content $\phi$ in a percolation model is shown below.

The basic idea is that at very low Ag content, the conduction will be very low since there is no conducting path through the material. In this case, a “rule of mixture” approach which considers the thermal conductivity and volume percent of each phase will give a good approximation of the overall thermal conductivity of the composite structure.

At a certain critical Ag concentration, called the percolation threshold $\phi_c$, there will be enough Ag to form a continuous Ag pathway and the conduction will increase rapidly. As more Ag is added, conduction will increase further due to an increased volume of conductor, but the rate of increase will be much lower than at the percolation threshold. This is shown in the figure below.

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\(^3\) See, for example: Harry Kesten, *What is ... Percolation?*, Notices of the American Mathematical Society, 53 (5), May 2006. 572-573.
We can describe conduction above the percolation threshold $\phi_c$ with the expression:
\[
\sigma = A(\phi - \phi_c)^\alpha
\]
Where $\sigma$ is conductivity, $A$ is a constant, $\phi$ is the filler volume percent, $\phi_c$ is the filler volume percent at the percolation threshold and $\alpha$ is the percolation exponent which is equal to 1.9.

If we fit Equation 1 to the bulk thermal conductivity curve in Figure 6, using $A$ and $\phi_c$ as fitting parameters and $\alpha = 1.9$, we get the best fit curve shown in the figure for $A = 0.13$ and $\phi_c = 18$. This indicates that the percolation threshold for the Ag epoxies analyzed here is at 18% volume percent Ag. This value is the same as the theoretical percolation threshold for randomly packed conducting spheres discussed in Reference 4. So, for Ag contents above 18%, this data and the percolation model fit would indicate that the thermal conductivity (as well as the electrical conductivity) will start to rapidly increase as a three-dimensional conducting network begins to form.

Now let’s consider the Ag epoxy that is confined between two Cu pads, also shown in Figure 6. In this case, conduction through the epoxy layer itself would also be described by the percolation model of Equation 1, but now the heat transfer between the Ag epoxy and the pad can only occur in areas where the Ag particles directly contact the pad metallization. This constriction of heat transfer at the two interfaces reduces the “effective” thermal conductivity of the Ag epoxy die attach to the values shown in Figure 6, much lower than the bulk conductivity results.

This interfacial thermal conductivity data can be best analyzed by converting the thermal conductivity to thermal resistance, and plotting this versus Ag volume percent as shown in Figure 8 below:

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4 M.J. Powell, Phys. Rev. B20, 4194 November 15, 1979 “Site Percolation in Randomly Packed Spheres”
We model the total interfacial thermal resistance $R_T$ as the sum of the bulk resistance $R_B$ and the contact resistance $R_C$. The bulk resistance is calculated from the bulk thermal conductivity measurements. We model the contact resistance using the expression:

$$R_C = A/(x - B)$$

where A and B are fitting parameters and x is the volume % Ag. We expect the contact resistance to scale inversely with the Ag contact area (which is the same as the volume percent Ag). What is interesting is that in order to fit the data, we need to utilize the parameter B which is 30% in this model. This result indicates that the contact resistance goes up rapidly as the Ag volume percent goes below 30%. Physically, this may mean that for the higher epoxy volume percent, some epoxy segregation will occur which results in poor thermal contact between the Ag phase and the metallization pad.

**Summary and Conclusions**

In this investigation, we have analyzed the bulk thermal conductivity and the interfacial thermal conductivity of a number of Ag epoxy die attach materials. This study has shown:

- There is a significant difference between the effective thermal conductivity of the die attach material bonded to Cu pads vs. the bulk thermal conductivity. We attribute this difference to the impact of contact resistance between the Ag epoxy and the pad metallization.
- We can model the bulk thermal conductivity of the epoxy using a percolation model. A fit to this percolation model shows a percolation threshold of 18% Ag. This is very close to the predicted percolation threshold for a random conducting sphere model.
- Physically, this mean that below 18% volume percent Ag, conducting Ag pathways vanish rapidly and the thermal conduction will drop abruptly. In this region, a rule of mixtures model should predict the thermal performance. At 18% Ag, the conductivity will increase rapidly as 3 dimension connected conducting paths develop. Above this percolation region, the density of Ag conducting paths will increase but the conductivity will increase more slowly than near the percolation threshold.