ABSTRACT

The continued desire to utilize an alternative to lead-based solder materials for electrical interconnections has led to significant research interest in Anisotropic Conductive Adhesives (ACAs). The use of ACAs in electrical connections creates bonds using a combination of metal particles and epoxies to replace solder. The novel ACA discussed in this paper allows for bonds to be created through aligning columns of conductive particles along the Z-axis. These columns are formed by the application of a magnetic field, during the curing process. The benefit of this novel ACA is that it does not require precise printing of the adhesive on pads and also enables the mass curing without creating shorts in the circuitry.

This paper will present the findings of the thermal conductivity performance tests using the novel ACA and its applicability as a thermal interface material and for assembling bottom termination components, power devices, etc. The columns that act as electrical conduction paths also contribute towards the thermal conductivity. The thermal conductivity of the novel ACA was measured utilizing a system that is similar to that in ASTM (American Society of Testing Materials) D5470 standard. The goal was to examine the influence of Bond Line Thickness (BLT), particle loading densities, particle diameters and adhesive matrix curing conditions on the electrical and thermal performance of the novel ACA. This paper will also present a numerical model to describe the thermal behavior of the novel ACA.

The novel ACA’s applicability for PCB-level assembly has also been successfully demonstrated by RIT, including base material characterization, effect of process parameters, failures, and long-term reliability. Reliability testing included the investigation of the assembly performance in temperature and humidity aging, thermal aging, air-to-air thermal cycling, and drop testing.

INTRODUCTION

The use of conductive adhesives as a thermal interface material has been in existence for many years in electronics packaging. Generally speaking most conductive adhesive solutions use some sort of conductive filler particles that are then cured to create the electrical and thermal bonds. The most common type of adhesive is the Isotropic Conductive Adhesive (ICA) [1]. This type of adhesive has become quite popular due to improvements in the reliability of bonds and a refined understanding of its curing process [2]. The general concern with ICAs is its conductivity in all directions, requiring it to be precisely printed, especially for fine pitch applications. Anisotropic Conductive Adhesives (ACA), on the other hand, offers the ability to conduct in one direction, which is crucial for electrical and thermal conductivity. Therefore, ACAs become more useful when dealing with fine pitches [3].

In this paper, the performance of a novel ACA will be examined as a possible thermal interface material. This ACA is unique, as it uses no pressure during assembly, to capture the monolayer of particles and create the bonds, as with traditional ACAs. Instead, the fillers for this ACA are silver coated ferromagnetic materials, which allow for the magnetic alignment of the fillers into conductive z-axis columns, during cure, and provide the anisotropy (Figure 1.). A complete cure schedule and assembly methodology is provided in a previously published paper [4]. The three ACA formulations investigated as part of this experiment include silver coated ferrite particles, which are 3µm, 8µm and a combination of 3 and 8µm diameters, in an epoxy matrix.
attacked samples were assembled using the appropriate solder paste and reflow profile.

![Figure 1. Magnetically Aligned Ferromagnetic Particles](image1)

The primary aspect of this novel ACA that will be examined in this paper is its thermal resistance as compared to tin-lead and lead free solder. The initial analysis will be based upon experimentation conducted to measure the thermal resistance of the novel ACA joint. The experimental analysis will be utilized to develop a model to analytically calculate the thermal resistance of the novel ACA. The thermal model will be based upon the electrical model proposed in a prior publication by one of the lead authors of this paper for the novel ACA [4].

**EXPERIMENT**

A Design of Experiment (DOE) was conducted in order to investigate the thermal resistance of the novel ACA. Experimental factors that have proven to be significant during previous testing have been the cured bond line thickness and the particle size. These factors proved to have bearing on the electrical resistance of the novel ACA [4]. Additionally, the magnetic field strength, applied to the novel ACA during the bonding process was also varied (1000 and 1600 Gauss) as a part of this DOE.

In order to test these factors and its influence on the thermal resistance (Units: K/W – Kelvin per Watt) of the novel ACA assembly, uniform copper blanks were used as test vehicles. These blanks had holes drilled directly in the center in order for thermocouples to be attached, for temperature measurement. After being cut to size (approximately 9.6mm x 9.6mm x 4.7mm), one surface of each copper blank was polished to a uniform finish. The test samples were created by attaching the two polished surfaces of the copper blanks as shown in Figure 2, using the novel ACA or solder.

The particle size that was used in the experiment included 3µm, 8µm and a mixture of the two (denoted as 38 in the graphs). The novel ACA was applied to approximately 83% of surface of the copper blanks by using screens cut to the 8mm by 8mm dimensions and placed directly over the blanks. The reduced print area is to accommodate for the spread of the ACA when the blanks are bonded to each other. The ACA was found to spread to the entire area of the copper blanks. The thickness of the screens determines the bond line thickness (1, 2, 4 and 5 mils). The mating blank was placed by a pick and place machine to ensure uniformity of placement. The blanks were then cured at a temperature of 160°C for 15 minutes in an oven that was capable of providing a constant magnetic field, in the Z-axis, to align the particles. The magnetic field within this oven could be varied to provide different magnetic flux densities for the experiment. Solder

![Figure 2. Assemblies for Experimentation](image2)

After the curing process, the samples were measured for their thermal resistivity. The methodology used for measuring the thermal resistivity was similar to that outlined in ASTM D5470. The measurement setup consisted of a heat source on one side of the sample and a heat sinking material on the opposite side. The thermocouples in the holes of the copper blocks measured the temperature difference between the two copper blanks [5]. The blocks were heated to approximately 50°C to determine the general thermal resistivity at this temperature.

**RESULTS**

The results of the DOE analysis reflected similar results seen in other studies with this novel ACA. The particle size and the bond line thickness were identified as the significant main effects in this study. These two main effects were also measured as significant factors during the measurement of electrical resistance [4]. The magnetic field strength during the cure process was not a significant factor in measuring thermal resistivity of the samples.

![Figure 3. Main Effects Plot for Bond Line Thickness and Particle Size](image3)

Figure 3 reveals the distinct advantage of mixing the 3µm and the 8µm particles in providing the lowest thermal resistivity. The 3µm formulation provides lower resistance than the 8µm formulation primarily due to the number of parallel columns formed, for a given printed area and bond line thickness of the novel ACA. In addition, as one would expect, lower bond line thickness provides the lowest thermal resistance, because of lesser number of particles per column.
and hence considerably reduced interfacial resistance between particles.

**THERMAL MODEL**

The proposed thermal model will take a similar electrical model [4] and modify it for the thermal domain. This model basically analyzes the significant factors that affect the columns within the epoxy. Overall, this model begins at the particle level resistance and builds up to the entire material including multiple parallel chains for calculating the overall thermal resistance of the assembly. In building this model, first the columnar resistance is determined and then applied to the entire system of columns within the epoxy matrix.

The model is built around determining the thermal resistance of a single chain of aligned particles (R\textsubscript{Chain}) as shown in equation 1. In determining the R\textsubscript{Chain}, constriction (R\textsubscript{C}), particle(R\textsubscript{p}) and interfacial(R\textsubscript{i}) resistances must be determined. Additionally, the number of particles (M) that form the column based on the particle size and bond line thickness must be calculated.

\[
R\textsubscript{Chain} = R\textsubscript{C}(M + 1) + R\textsubscript{p}(M) + R\textsubscript{i}(M + 1)
\]  

The initial step is to model the resistance of the individual particles. Particle resistance is determined by treating the particles as individual spheres that come into contact with other spheres providing a contact area for thermal conductivity. This model ignores the possible agglomeration of particles during the formation of conductive chains. The particle resistance is described as:

\[
R\textsubscript{p} = \frac{\rho \pi}{4d} \tan^{-1}\left(1 - \frac{d^2}{D^2}\right)
\]  

Where:
- \(\rho\) = Thermal resistivity of the material
- \(D\) = Particle diameter
- \(d\) = Diameter of the contact area

Figure 4 shows the influence of the ratio of particle diameter to the contact diameter on the particle thermal resistance, for both the 3µm and 8µm formulations. As the contact diameter decreases, the resistance increases. The only way to increase the contact diameter is by ensuring adequate compression of particles against each other. This will not be possible with the novel ACA, as no pressure is applied during component assembly. The column formation (automatic stacking of particles one on top of each other) controls the contact diameter. Figure 4 purely provides an empirical relationship that can be used to approximate the particle resistance for a given particle diameter, assuming a contact diameter.

The next step in putting together the thermal model is to determine the resistance that occurs between the particles. This specific resistance is referred to as the constriction resistance. It manifests as a resistance due to the deformities that occur as the particles are pressed together. The constriction resistance is mainly determined as a relationship between the size of the particle and contact area of the particles as shown in equation 3.

\[
R\textsubscript{C} = \left(\frac{\rho \pi}{\rho_p}\right)\left(\frac{1}{d} - \frac{1}{D}\right)
\]  

Where:
- \(\rho\) = Resistivity of the particle material
- \(\rho_p\) = Resistivity of the particle material
- \(d\) = Diameter of the contact area
- \(D\) = Particle diameter

Since it is difficult to determine the constriction resistance experimentally, between particles, for the 3µm and 8µm formulations, it must be determined mathematically, based upon the diameter of the contact area. Figure 5 shows the relationship between the constriction resistance and the ratio of particle diameter to the contact diameter. The core material resistivity was considered to be that of iron as the particles were silver coated iron particles in both formulations. As the contact diameter decreases, the resistance increases linearly. As with the particle resistance, the only way to increase the contact diameter and thereby reduce constriction resistance is by ensuring adequate compression of particles against each other. This will not be possible with the novel ACA, as no pressure is applied during component assembly. The column formation (automatic stacking of particles one on top of each other) controls the contact diameter. Figure 5 purely provides the relationship that can be used to approximate the constriction resistance for a given particle diameter, assuming a contact diameter.
The final aspect of modeling the column’s thermal resistance is determining the interfacial resistance. This resistance is contributed by the insulating film that may be present between particles. The interfacial resistance is determined only by empirical means using the resistance offered by each particle chain, formed during the assembly of the copper blanks, for varying particle diameters and bond line thicknesses (Equation 4).

\[ R_I = \frac{R_{\text{chain}} - (M)R_p - (M+1)R_C}{M+1} \]  (4)

The number of particles (M) that would theoretically be present in each column is determined by:

\[ M = \frac{BLT}{D} \]  (5)

Where:

- \( BLT = \) Bond Line Thickness
- \( D = \) Particle Diameter

In order to calculate \( R_{\text{chain}} \), from the experimentally measured thermal resistance, the theoretical approximate number of columns formed within the epoxy must be calculated. Initially, the number of columns per unit area must be determined and then this value applied to the surface area that contacts the epoxy [6].

\[ N_{UA} = \frac{6V_F}{\pi D^2} \]  (6)

Where:

- \( N_{UA} = \) number of columns per unit area
- \( V_F = \) Volume fraction of particles
- \( D = \) Particle Diameter

Once this value is determined, \( R_{\text{chain}} \) can be calculated,

\[ R_{\text{chain}} = (N_{UA})(SA) \]  (7)

Where:

- \( SA = \) Surface Area

**Thermal Resistance of the Particle Chain**

The total thermal resistance of the assemblies was determined from the experiment. The thermal resistance provided by the individual particle chains, for the two material formulations, is derived using the approximations described in the previous section and the total thermal resistance of the assemblies. The number of columns per unit area was first determined as shown in Table 1.

\[
\begin{align*}
3\mu m & \quad N_{UA} = \frac{6(0.061)}{\pi(0.003)^2} = 12945 \text{ columns/mm}^2 \\
8\mu m & \quad N_{UA} = \frac{6(0.061)}{\pi(0.008)^2} = 1820 \text{ columns/mm}^2
\end{align*}
\]

**Table 1. Column Density per Unit Area**

The theoretical number of particles in each chain (M) is shown in Table 2, for each particle diameters and bond line thickness.

<table>
<thead>
<tr>
<th>BLT (mils)</th>
<th>3µm</th>
<th>8µm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>17</td>
<td>6</td>
</tr>
<tr>
<td>4</td>
<td>34</td>
<td>13</td>
</tr>
<tr>
<td>5</td>
<td>42</td>
<td>16</td>
</tr>
</tbody>
</table>

**Table 2. Theoretical Number of Particles per Column**

Using the mean values for the surface area for the copper block assemblies the theoretical total number of columns was determined to be as shown in Table 3.

\[
\begin{align*}
3\mu m & \quad \text{Columns} = (92\text{mm}^2) \left( \frac{12945 \text{ columns}}{\text{mm}^2} \right) = 1,190,940 \text{ Columns} \\
8\mu m & \quad \text{Columns} = (92\text{mm}^2) \left( \frac{1820 \text{ columns}}{\text{mm}^2} \right) = 167,440 \text{ Columns}
\end{align*}
\]

**Table 3. Total Number of Columns per Assembly**

Using the experimentally obtained mean values for the thermal resistance of the assemblies, and the theoretical values for the constriction and particle resistances, and the number of particles in the chain, the \( R_{\text{chain}} \) was determined for each bond line thickness, as provided in Table 4. In calculating the appropriate values for both \( R_C \) and \( R_P \), a small contact area was selected, to have a ratio of less than 10 for the particle diameter to contact diameter. The calculation for interfacial resistances is shown in Table 5 and a plot of \( R_c \) versus the bond line thickness is shown in Figure 6. This provides a model to determine \( R_c \).

\[
\begin{align*}
3\mu m & \quad R_{\text{Chain}} \quad (\text{K/W}) & \quad \text{Mean} \quad (\text{K/W}) \quad R_{\text{Chain}} \quad (\text{K/W}) \\
1 & \quad 1176685 & \quad 1.0945 & \quad 183266 \\
2 & \quad 1089981 & \quad 0.7832 & \quad 131136 \\
4 & \quad 1098506 & \quad 0.9434 & \quad 157957 \\
5 & \quad 1038382 & \quad 1.0940 & \quad 183184
\end{align*}
\]

**Table 4. Measured Assembly Mean Thermal Resistance and Calculated Resistance per Chain**

\[
\begin{align*}
3\mu m & \quad R_C \\
1 & \quad 2.65 \\
2 & \quad 2.65 \\
4 & \quad 2.65 \\
5 & \quad 2.65 \\
8\mu m & \quad R_P \\
1 & \quad 5.105 \\
2 & \quad 5.105 \\
4 & \quad 5.105 \\
5 & \quad 5.105
\end{align*}
\]

**Table 5. Calculated Interfacial Resistance between Particles**
are eliminated. The authors are investigating the void volume to identify possible correlation between the void volume and thermal conductivity.

**Table 6. Predicted Thermal Resistances**

<table>
<thead>
<tr>
<th>BLT</th>
<th>RColumn</th>
<th>R</th>
<th>RColumn</th>
<th>R</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1176665</td>
<td>0.988014</td>
<td>183264.1</td>
<td>1.094506</td>
</tr>
<tr>
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<td>1089939</td>
<td>0.915192</td>
<td>131132.3</td>
<td>0.78316</td>
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<tr>
<td>4</td>
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<td>0.922316</td>
<td>157948.9</td>
<td>0.943316</td>
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<tr>
<td>5</td>
<td>1038279</td>
<td>0.871815</td>
<td>183174</td>
<td>1.093968</td>
</tr>
</tbody>
</table>

**CONCLUSION**

After observing the thermal resistivity of the novel ACA, it appears to have comparable properties to other thermal epoxies but not as effective as solder or metal attach or nano-particle filled materials. Overall, a viable model was provided to explain the thermal conductivity of the novel ACA. Although, the current formulations of the novel ACA may not be suitable for all thermal conductivity applications, it can serve as one, in applications that do not require high power dissipation while providing electrical conductivity.
References


