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A Comparison of Pressure-less Silver Sintering Materials with Conventional Electronic Die Attach Practices

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A Comparison of Pressure-less Silver Sintering Materials with Conventional Electronic Die Attach Practices

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ABSTRACT

This thesis contains information on an experiment which validates silver sintering paste manufacturer's die attach processes and examines feasibility for use in commercial products. Four silver pastes were used in constructing die attach samples, which were then void and shear tested. The silver sintering materials that are investigated in this work are compared with manufacturer data and also with data from conventional attaches such as conductive epoxy and solder. In addition, materials demonstrating the highest shear strength were down-selected and processed to compare thermal characteristics with solder and conductive epoxy. Under theoretical analysis, the characteristics of silver provide the most optimal solution as a die attach material for extreme conditions. Additionally, silver sintering paste technology has been significantly increasing over the last decade, leading to the potential for silver sintering pastes to be the next standard in power electronic die attaches, specifically in high temperature and rugged designs [1].

I. INTRODUCTION

Silver sintering paste holds much promise in improving the electrical, thermal, and mechanical characteristics of die to substrate attaches. Possessing the key characteristics of silver, silver sintering pastes include a high thermal conductivity, which is the material's ability to conduct heat and is determined by the rate of heat flow; a high electrical conductivity, which is the material's ability to conduct electricity with low impedance; a relatively high strength, which in this case is the ability to form solid mechanical bonds between die and substrate; and an extremely high melting temperature, which is the temperature at which the material transitions to its liquidus state. As such, it has the potential to outperform traditional solders using low temperature (< 200 °C) assembly processes [2,3]. The theoretical qualities exhibited could prove invaluable for high temperature and high power density applications.

This thesis explores the heat transfer potential using three-dimensional finite-element modeling in SolidWorks® by sweeping device size, baseplate thickness, and die attach methods. Data from these simulations demonstrate the validity of the theoretical performance and give reason to move forward with void and shear testing mechanical devices. Silver sintering pastes from four different companies are used in assembling mechanical test devices and are compared with four other standard die attach materials. Manufacturer process instructions were followed and are specified in the report. Data from shear and void tests of silver sintering attach material is compared to the manufacturer performance claims and with traditional solder performances as a control. Process optimization for die attach strength is considered. Finally, if shear strength for the silver die attach materials is comparable to conventional solders, experimentation validating the thermal conductivity of the pastes will ensue to find the best alternative to solder. These final results can be compared with the initial SolidWorks® simulations, experimentally validating the theoretical performance.

The theoretical qualities exhibited by silver sintering pastes could prove invaluable for high temperature and high power density applications. This, along with the fact that silver sintering paste technology has significantly increased over the last decade points toward silver sintering pastes to be the next standard in power electronic die attaches, specifically in high temperature and rugged designs.

II. THEORETICAL BACKGROUND

A. SHEAR STRENGTH

One important characteristic for a die attach material to possess for high temperature applications is a high shear strength. This thesis uses United States measurements of shear strength which correlate to units in kg/in^2 rather than N/m^2 (1 kg/in^2 is equal to 15.2 kN/m^2). Notice that both standard units measure the force applied over the area of the attach. The procedure for gathering die attach strength data is by shearing the electronic device from the substrate. Special equipment is needed for this test, which applies increasing pressure to the side of the device and records the pressure data at the point at which the device breaks free from the substrate. A United States military standard [4] has been defined for electronic die attaches to ensure the integrity of the attach material under stressful conditions. This military standard plateaus at 2.5 kg once the area of the attach reaches 0.0065 in^2 or about 4.2 mm^2. Furthermore, this thesis includes data on only 3 mm x 3 mm devices and so only considers the plateau region defined in MIL-STD-883G.

A factor to consider is the shear strength at temperature. Many new power devices have the capability of operating past conventional solder melting points. While still electrically conductive as a liquid, the solder loses all mechanical strength and therefore is unable to meet military strength specifications at temperatures exceeding its melting point. Silver sintering paste, having a melting point greater than 600°C, can theoretically withstand device operating temperatures far greater than solder can withstand, and continue to meet the shear strength military specifications. By removing the melting point of the die attach limit from operating requirements, device characterization and operating conditions at high temperatures may be added to data sheets to provide more comprehensive models for pushing the limits of semiconductor devices.

B. THERMAL CONDUCTIVITY

Thermal conductivity is also an extremely important factor in power-dense, high temperature applications. Understanding heat spreading through materials and interfaces is necessary in the design of multichip power modules (MCPMs) [5,6]. In power modules, interfaces between materials contribute to the rate of heat dissipation through the module and away from the power die. Interfaces with high thermal conductivity coefficients increase the rate of heat dissipation and are preferred in high temperature applications. The equations (1) and (2) below relate the thermal conductivity of two materials, showing the effect they have on the dissipation of heat through the materials. This relation can be translated to interfaces between materials as well. Figure 1 gives a graphical representation of the application of these equations.

$$\alpha_a = \tan^{-1}\left(\frac{k_a}{k_b}\right) \tag{1}$$

$$L_2 = 2 \cdot t_a \cdot \tan(\alpha_a) + L_1 \tag{2}$$

Where α_a is the angle of thermal spreading through material a (° angle), k_a and k_b are the thermal conductivities of the materials in (W/m·°C), and L_1 and L_2 are the lengths of thermal effect at interface one and two respectively (m).

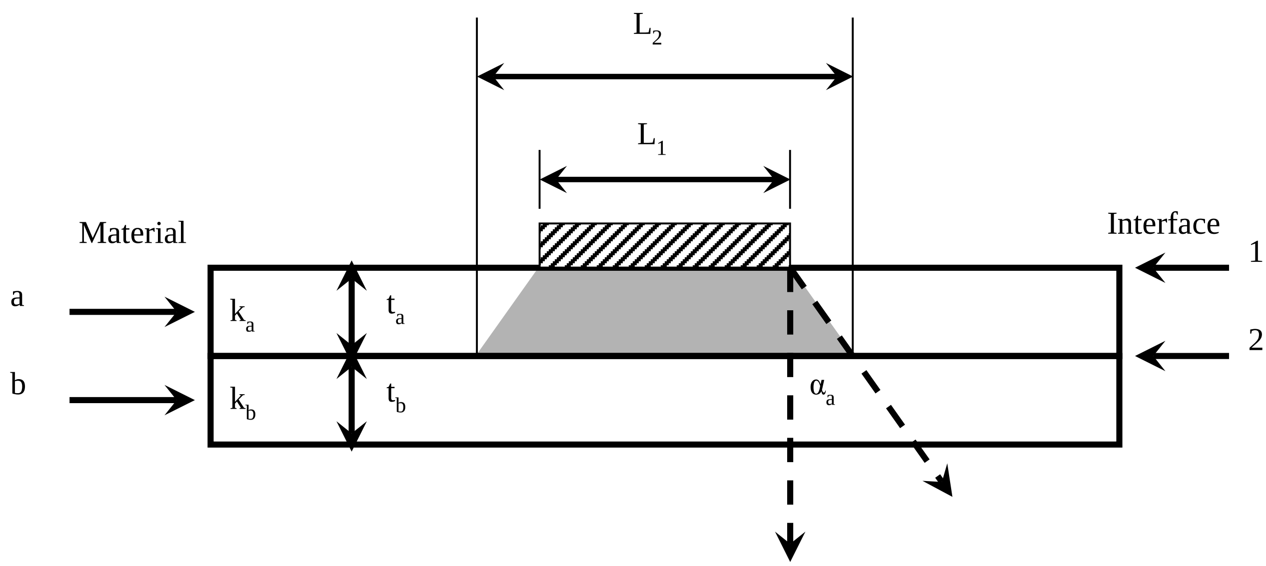


Figure 1. Representation of heat spreading [7]

After performing analysis by hand of the potential improvements in heat dissipation over traditional solder interfaces, SolidWorks® was used to verify the calculations and give more accurate data. A three-dimensional model with similar layers to the schematic shown in Figure 1 was constructed in SolidWorks®. Conduction coefficients, matching the materials used, were assigned to each layer. Variables in the simulation were the die size (2x2mm or 3x3mm), die attach thickness, baseplate thickness, and conductivity coefficient of the die attach layer. Results demonstrated, by sweeping all variables, that a higher thermal conductivity of the die attach layer promises great potential at increasing heat dissipation, thus lowering the device temperature significantly. Figures 2 and 3 show the representation model and thermal analysis used in SolidWorks® for investigating the effect of sweeping the thermal conductivity.

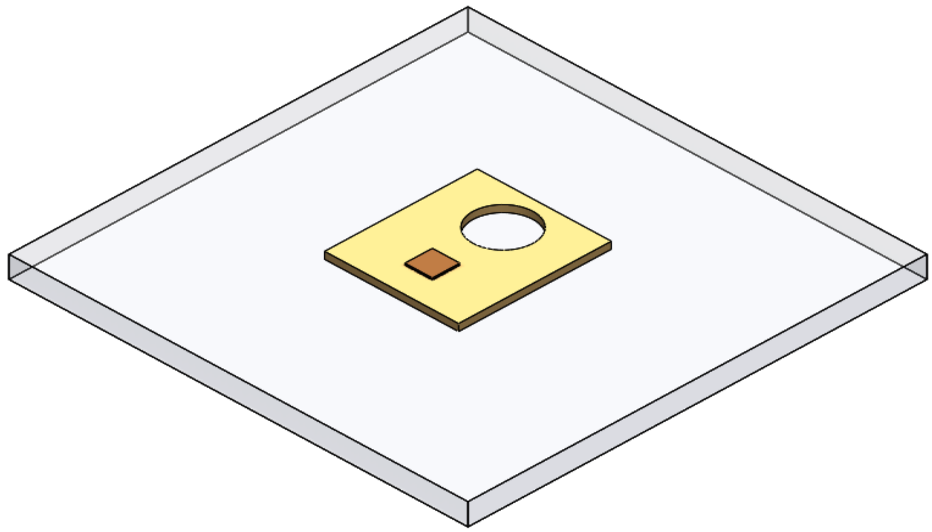


Figure 2. Isometric view of SolidWorks® model.

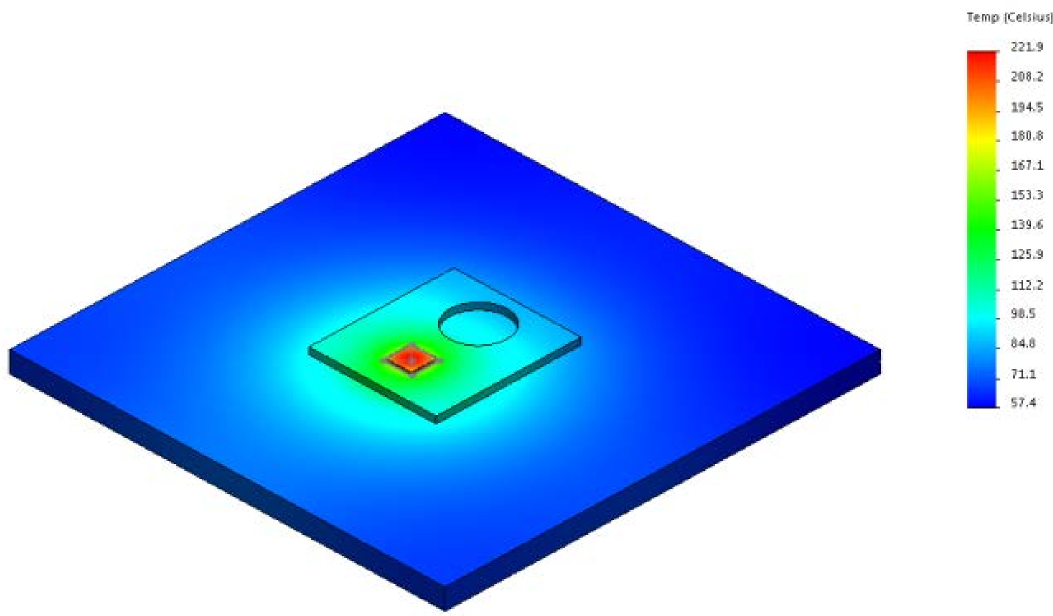


Figure 3 Thermal simulation of SolidWorks® model.

From the data in Figure 4, much lower junction to case resistances occur with higher die attach thermal conductivities, all other variables being the same. By sweeping the thermal conductivity of the die attach material and running simulations at each interval, a curve relating the junction to case thermal resistance may be recorded to provide the data given in Figure 4. This lower resistance allows heat to spread efficiently through the surface for transfer to a heat sink, thus drawing the heat away from the device quicker than a lower thermal conductivity, which would translate to a higher resistance. The thickness of the die attach layer was also varied between 1 mil and 2 mils, represented by “tda”, to further show the range of variables which affect the thermal conductivity. As the thermal conductivity increases, the effect that the thickness has on the thermal resistance is greatly reduced.

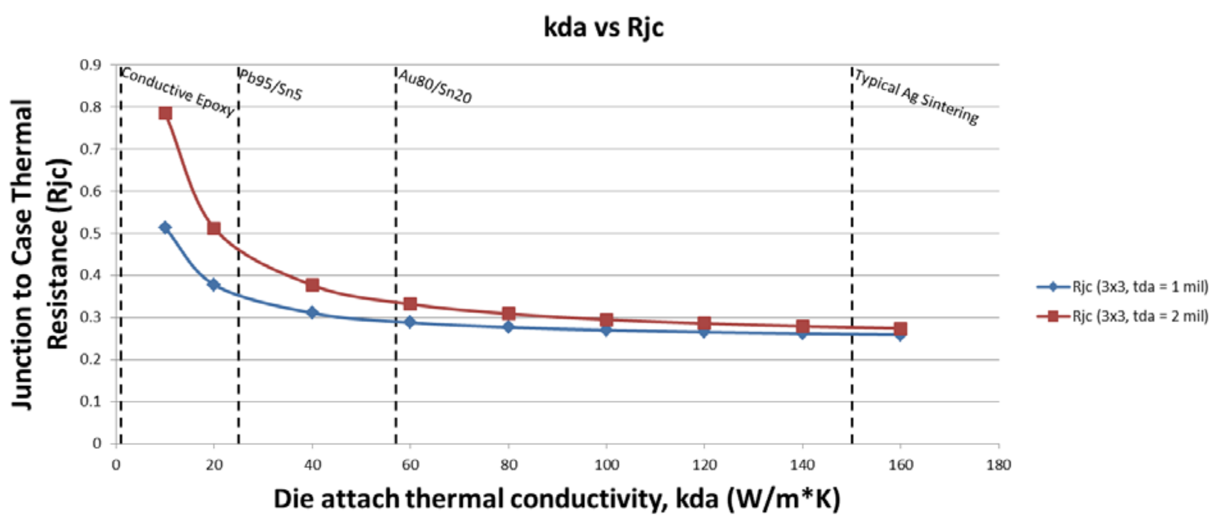


Figure 4. The junction to case thermal resistance as a function of die attach thermal conductivity. The junction to case thermal resistance is significantly reduced when the die attach thermal conductivity is > 100 W/m K. In addition, the thickness of the attach layer has a much lower effect on the junction to case thermal resistance at higher thermal conductivities.

III. EXPERIMENTAL PROCEDURE

After choosing the materials to be compared in the experiment, process plans matching material manufacturing plans were created to validate manufacturer claims on die attach shear strength. Process techniques for each material are provided in Table 1. Comparison of die attach strength among materials at varying temperature levels provide data on which material has the best overall mechanical performance for integration into high temperature applications needing high reliability.

Twelve samples of each material were processed for experimental testing of mechanical strength. Note that no materials requiring a pressured process were tested due to a lack of in-house, high temperature, pressured processing equipment. Before shear testing the die, x-ray

Table 1. Materials to be void and shear tested.

Material	Process
Ag Sinter A	Ramp up 30 min to 200 °C, dwell 90 min at 200 °C, in conventional oven
Ag Sinter B	Ramp up 60 min to 200 °C, dwell 60 min at 200 °C, on Hotplate
Ag Sinter C	N/A
Ag Sinter D	Ramp up 30 min to 200 °C, dwell 60 min at 200 °C, in conventional oven
Au80Sn20 Solder Preform in SST	Use APEI, Inc. SST recipe
Pb95Sn5 Solder Preform in SST	Use APEI, Inc. SST recipe
Conductive Epoxy	Use APEI, Inc. standard oven recipe

analysis of the die attach layer was performed to provide insight into potential strength performance from voiding [8,9]. After void analysis, shear testing was performed at temperatures of 25 °C, 125 °C, 225 °C, and 325 °C. This allows for three samples of each material to be sheared at each temperature. Results of x-ray images and shear tests are displayed below. The use of conventional solders is for comparison to demonstrate whether or not silver sintering paste exceeds current die attach methods. Figure 5 and 6 display the typical voids in a sintered material versus a conventional solder attach respectively.

Notice the voids in the sintered attach are extremely small and very few as compared with the solder sample. These results were common across all materials tested. Voiding in the attach increases the thermal resistance of the die attach layer because heat dissipation is impeded by the voids present. With less voids, a material would have much lower thermal resistance than it would with many voids. Voiding can also contribute to decreased mechanical strength as well because of the reduced contact area of the material with each surface.

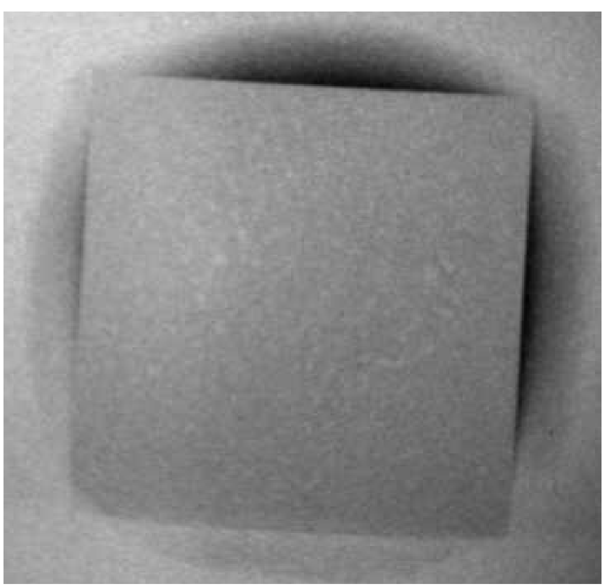


Figure 5. Typical sintered attach taken from Ag sinter batch.

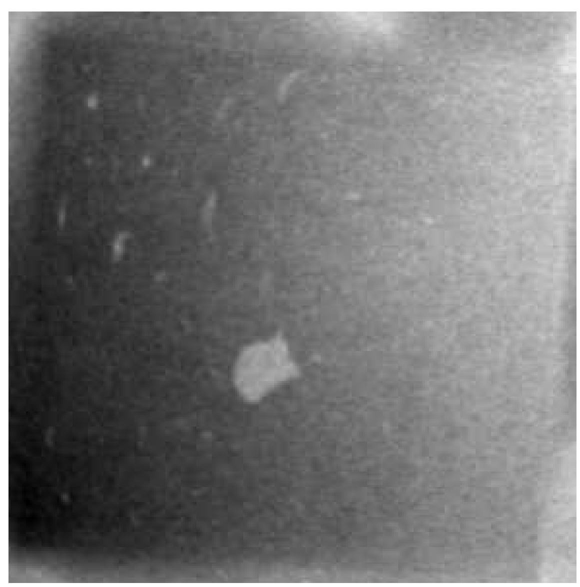


Figure 6. Typical solder attach taken from Au80/Sn20 solder batch.

A. SHEAR TESTING

After x-rays for void testing, each die was shear tested at temperatures ranging from 25 °C to 325 °C. This is to ensure a stable mechanical attach at extreme temperatures. All shear strength values are normalized to a 3mm x 3mm area. Figure 7 displays the data of shear strength in grams versus temperature. Note that the clusters around 25 °C, for example, were actually performed at exactly 25 °C but are spread out for better data visibility. Also, the high and low for each material is marked with the main point being the average. Three samples of the same material per temperature were tested. At 325 °C the solder materials returned to their liquidus states.

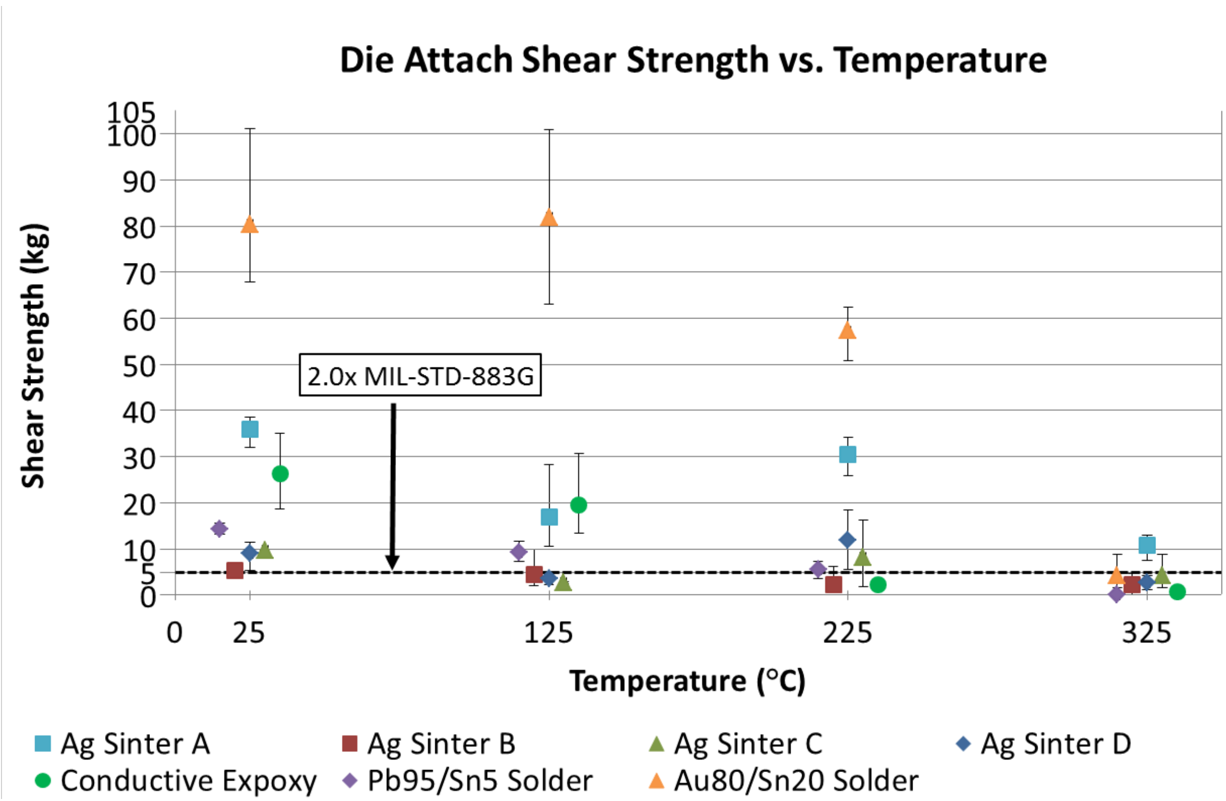


Figure 7. Shear strength vs. temperature of different die attach materials for a 3 mm × 3 mm SiC die (Au backside).

Of all the materials tested, Figure 7 shows that the Ag Sinter A material was the only one to remain above the 2.0× specification for shear strength in MIL-STD-883G [4] in the range from 25 to 325 °C for every device tested. Recall that MIL-STD-883 defines 2.0x specification at 5kg once the area of the attach has increased beyond $4.2mm^2$. This result that Ag Sinter A material remained above this specification at all temperatures tested is significant for pushing the temperature limits of devices with a strong attach at extreme temperatures which is not only important for power devices but also high temperature die that are used to control the power die. Table 2 goes on to compare the experimental results of shear testing over temperature with the paste manufacturer claims. These results demonstrate how untested and potentially unreliable silver sintering pastes currently are in terms of mechanical bond strength. The Ag Sinter A paste seemed to be the clear winner in terms of best manufacturer accuracy in determining bond strength as well as shear strength in general.

Table 2. Comparison of manufacturer strength claims with experimental results. The average results include the tests at 325 °C due to the theoretical operating temperature range of silver sintering pastes being around 600 °C.

Material	Manufacturer Claimed Shear Strength (3x3mm die)	Tested strength (3x3mm die)
Ag Sinter A	~ 26 kg on Ag plated Cu	~ 23.5 kg on average (Ni/Au plated Cu)
Ag Sinter B	~ 41 kg at 25 °C ~ 23 kg at 260 °C	~ 3.5 kg on average
Ag Sinter C	~ 23 kg	~ 5.4 kg on average (results very scattered)
Ag Sinter D	~ 18 – 27 kg	~ 7 kg on average

Table 3. Comparison of the Au80/Sn20 solder and Ag Sinter A paste characteristics [10].

Material	Processing Temperature	Working Temperature	Electrical Resistivity	Thermal Conductivity	Shear Strength (experimental)
Au80/Sn20	≥ 300 °C	≤ 280 °C	16.4×10^{-8} Ω·m	57 W/(m·K)	≤ 225°C → 73.2kg At 325°C → 4 kg
Ag Sinter A	200 °C	≤ 600 °C	~ 5×10^{-8} Ω·m	>120 W/(m·K)	≤ 225°C → 27.7kg At 325°C → 10kg

Some major reasons to continue research on silver sintering pastes include lower processing temperatures, much higher thermal and electrical conductivities, as well as higher operating temperatures. Table 3 gives numbers to these claims proving sintering pastes are at least twice as thermally conductive and over three times more electrically conductive than the best performing traditional solder.

Now that the shear strength of the materials have been characterized through a range of temperatures, further experimentation to validate an improved thermal conductivity of silver sintered material over conventional solders must occur to demonstrate the feasibility of integrating silver sintering pastes into commercial products. This test will induce a power loss in the devices and monitor the heat dissipation through the material to the cold plate by measuring the die temperature with an infrared camera. Power losses are calculated during testing by passing a known voltage and current through the device. Adjusting the gate voltage determines the resistance of the device and may effectively be used to dissipate more or less power in the form of heat.

B. THERMAL TESTING

To accurately measure heat transfer in an experiment, an infrared camera must be used with the device under test (DUT) coated with a paint having a known emissivity. This setup used a matte black paint with emissivity of 0.96 to measure the maximum temperature of the die, the temperature of the top of the baseplate, along with the temperature of the top of the heat sink. Measurements at these points allow for data to be easily compared, determining the best performance.

Defining the power dissipated in the device is also important for thermal measurements. For this experiment, the voltage across the device and the current through the device were measured at each recorded temperature, leaving the power from conduction losses to be calculated. Once several temperature and power measurements have been taken for each device, die temperature as a function of power loss curves can be generated from the data. Figure 8 shows an example of the thermal images taken for measurements. The maximum temperature on the scale is the max temperature of the device, while the temperatures listed on the left measure the temperature of the two areas; area one represents the copper baseplate and area two represents the heat sink. Since the device dissipates the most heat, the high value of the scale on the right represents the device temperature.

With all of the data for two samples of each material recorded, several graphs were created to compare the performance of the materials with each other.

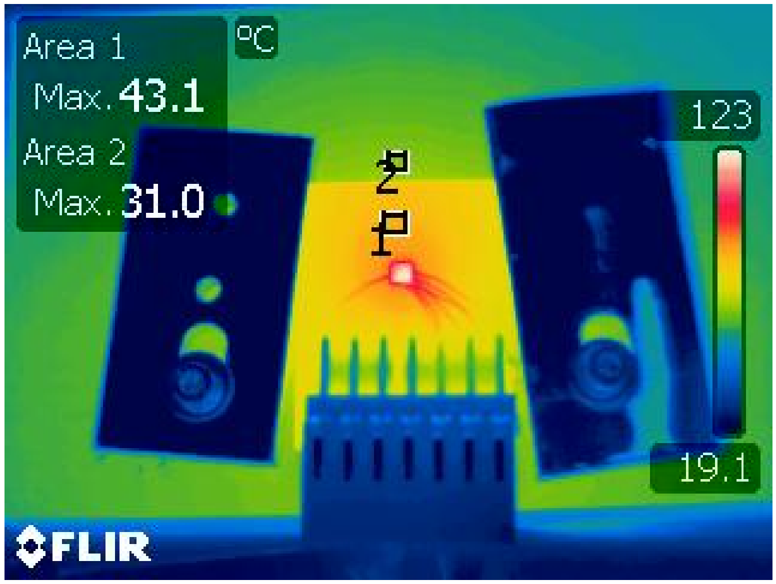


Figure 8. An infrared picture of a sample being tested.

Using the measurements of the maximum die and baseplate temperatures, the relationship between temperature and effective power dissipation may be graphed as shown in Figures 9 and 10 for each material. It can be seen that for the Ag Sinter B and D materials, the curves seem to diverge from each other. Because of this, a linear trend line for every sample was created and the two equations for each material were averaged together. It should be noted that the curves for the Au80/Sn20 samples correlated closely to each other which implies consistent characteristics if additional samples were made. The same can be said for the Ag Sinter A material. Additionally, the conductive epoxy produced a strange discontinuity in Figure 9, most likely as a result of an inherent increase of thermal resistance past a certain temperature, which is normal for this material.

Finally, with all of the data extrapolated and analyzed, the theoretical temperatures of the die and baseplate may be calculated at specific power dissipations. This is done by extrapolating the conduction coefficient from the line equations of each material given by Figures 9 and 10. Using these coefficients and applying 50 W of dissipation, Figure 11 gives a theoretical model based on the results of the experiment. From Figure 11 it is can be seen that along with having the lowest device temperature at 50 W of heat dissipation, the Ag Sinter A material has a higher thermal conductivity than any other samples tested. The temperature difference between the die and the bottom of the baseplate is a function of the thermal conductivity and the die attach material, and since the temperature

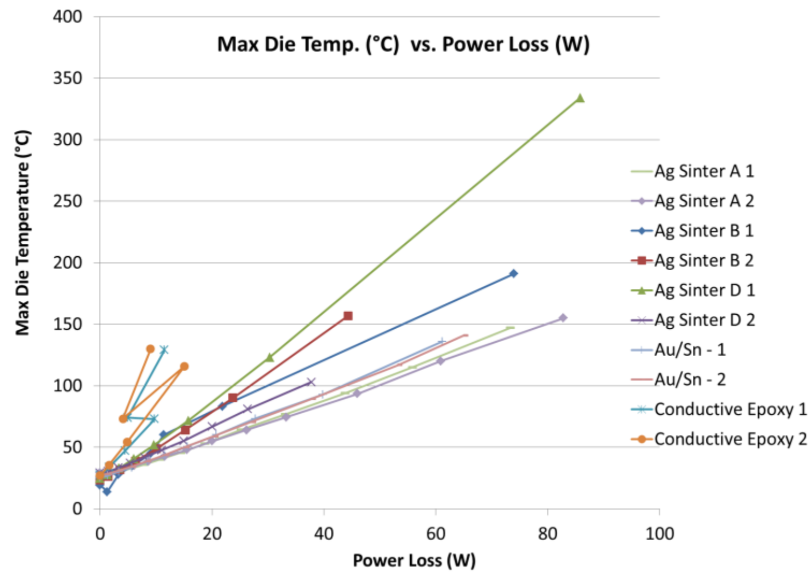


Figure 9. Compiled data for max die temperature vs. power loss.

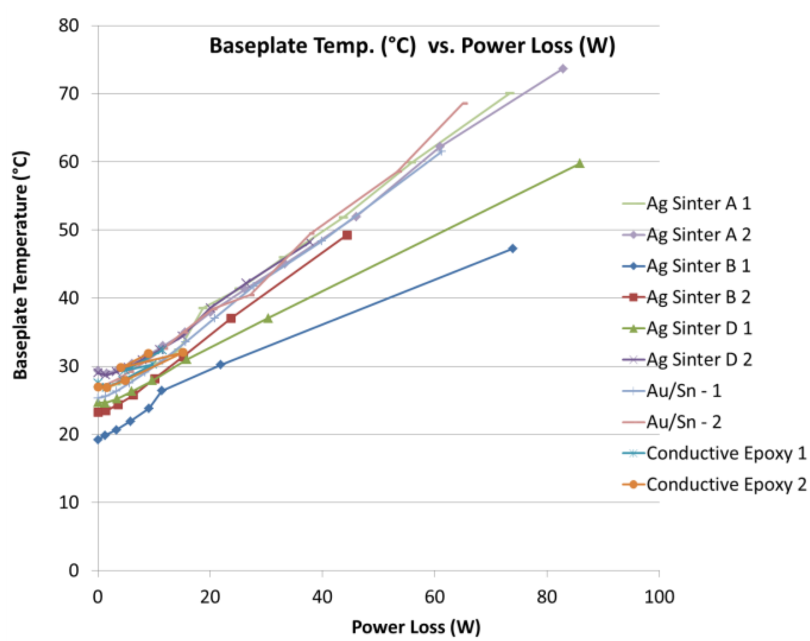
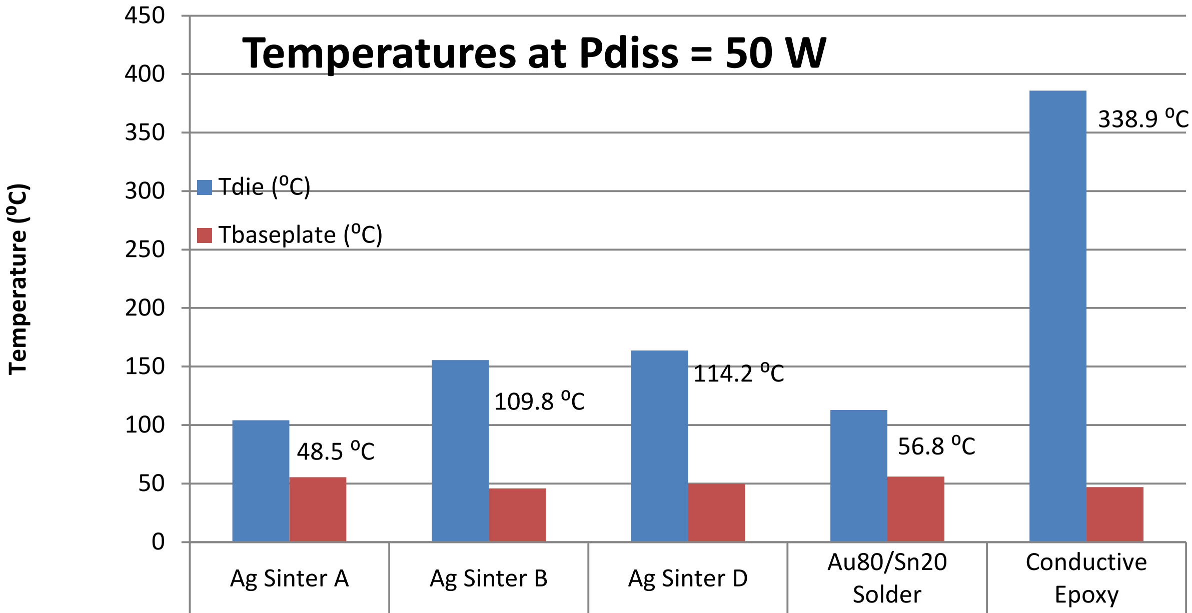


Figure 10. Compiled data for baseplate temperature vs. power loss.



	Ag Sinter A	Ag Sinter B	Ag Sinter D	Au80/Sn20 Solder	Conductive Epoxy
Tdie (°C)	103.956	155.57	163.857	112.759	385.886
Tbaseplate (°C)	55.467	45.798	49.6765	55.9315	46.9725

Material

Figure 11. Temperature of device at specified power dissipation. Temperature difference between die and baseplate is also shown.

difference is the lowest for the Ag Sinter A paste, it has the highest thermal conductivity. The conductive epoxy on the other hand, does not dissipate heat efficiently at 50 W, which causes the device to overheat while the baseplate stays relatively cool, translating to the lowest thermal conductivity of the group.

IV. DISCUSSION OF RESULTS

Employing experimental validation to confirm manufacturer die attach data showed much discrepancy between manufacturer claims and experimental results. Materials used were processed per the manufacturer data sheet guidelines to theoretically match manufacturer strength and thermal conductivity claims. Only Ag Sinter A met manufacturer specifications and achieved an average shear strength of four times MIL-STD-883G. Along with the advertised shear strength, Ag Sinter A exceeded the standard high temperature solder, Au80/Sn20, in terms of thermal conductivity. No other silver sinter came close to the standards set by Ag Sinter A.

Other than Ag Sinter A, process optimization for the other materials may not have been provided by manufacturers, leading to the large discrepancy between their claims and experimental results. Improved pressure-less processes could lead to much more competitive results [11].

Pressured processes were not in the scope of this experiment due to the limitation of equipment, however these results open the door to continued exploration of process optimization, such as pressurized processes or increased temperature processes. Low process temperature and pressure requirements are optimal to reduce device stresses while attaching them to substrates, though previous experimentation has proven that devices can withstand significant increases in temperature and/or pressure. This headroom could potentially optimize silver sintered attaches in terms of strength and thermal conductivity, the limits of these characteristics being those of solid silver [12].

V. CONCLUSION

Through theoretical analysis and model simulation, the merits of utilizing the key characteristics of silver in silver sintering pastes were proven for high temperature and high power density applications. Continuing with experimental validation demonstrated that indeed, silver sintering paste can exceed the thermal conductivity of Au80/Sn20 solder and can sustain shear stresses exceeding military standards over 325°C (Ag Sinter A).

As semiconductor device technology continues increasing, device packaging technology must also increase to provide as few limits to device operating conditions as possible. As shown through these experiments, specific silver sintering pastes provide exceptional characteristics beneficial to devices operating in high temperature and high power density applications.

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