Novel Conductive Paste Using Hybrid Silver Sintering Technology for High Reliability Power Semiconductor Packaging

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Abstract

A number of industries are developing new product-lines with innovative electronics packages that require low thermal resistance and high temperature stability, including hybrid electric vehicles, concentrator photovoltaic and wide bandgap RF amplifiers. One of the largest obstacles in the design and manufacture is the thermal management of the devices. Localized heat generation is the characteristic of the semiconductor chips used in these devices. For high power applications the thermal impedance of the die attach layer can play significant role in the thermal management and the operating temperature. Therefore, one would like to use the highest thermal conductivity and lowest thermal resistance die attach material that is capable for high volume manufacturing.

In a typical electronic packaging process, chips are attached to substrates and electrically connected before they are encapsulated or sealed for protection. The attachment and electrical interconnections provide the chip with an infrastructure for the flow of electrical signals, mechanical support and heat removal. The die attach materials[1] used in the packaging of high performance power semiconductors are required to have high thermal conductivity. Lead solders, eutectic gold-tin, transient liquid phase sintering (TLPS) pastes[2] and nano-silver sintering technology[3] are typical materials used for the die attachment of power semiconductor. This paper will introduce a new die attach material using Hybrid Silver Sintering Technology (HSST).

Introduction

Power semiconductor packaging engineers are looking for Pb-free alternative to traditional high Pb solder die attach paste and wire . Lead solders have respectable thermal conductivity of 30-50W/mk, but have known process difficulties in high volume mass production such as voiding, bond line control, and the requirement inert gas(Nitrogen or Forming gas) environment. Lead is now categorized as hazardous substance to human body and environment and products containing are scheduled to be banned. Silver epoxy paste used in standard semiconductor packaging is another die attach technology but its thermal conductivity is not high enough for Power devices. Silver sintering materials have became an attractive alternative for power devices because they possess high thermal conductivity (150~200W/MK) achieved through solid state diffusion or "silver sintering". But most often high bonding temperature and pressure are required to achieve a high reliability joint when silver sintering technology is employed. Similar to soldering, silver sintering technology requires backside metallization due to slow diffusion into bare silicon. HSST is composed of micron size silver powder and an organic phase. This technology overcomes the limitations of conventional silver epoxy and silver sintering products by using the unique design of polymer composition. The unique organic and polymer composition facilitates silver sintering at relatively low temperature compared with sintering silver and enables up to 150W/MK thermal conductivity without pressure during cure. The polymer enables adhesion to a variety of surfaces, bare silicon, gold and silver metalized die and silver and copper metal surfaces.. The viscosity of hybrid silver sintering product is similar to standard epoxy paste and its application process is as easy as conventional silver epoxy die attach paste. HSST paste can easily drop into existing commercial die bonders and serve as a replacement for soft solder die attach.

Experimental Procedure

A. Sample Preparation

Five silver paste samples were prepared. Sample A-1, A-2, A-3, C-1 have 7 wt% thermoset resin and B-1 and D-1 have 13wt% organic resin. The thermoset resin has more than one reaction group in a molecule and reacts above 150°C. All the samples have organic enhancers except C-1 and D-1. E-1 has silver, diluents and organic enhancers but doesn't have any thermoset resin. Three different diluents are used for the sample preparation of A-1, A-2 and A-3 and the property of each diluent is in Table2. A-1 has the highest boiling temperature diluent and A-3 has the lowest boiling temperature diluent. The detail compositions are listed in Table 1. The silver used in the formulation is micron size flake and the average size is 5um. The SEM image of the silver flake is in Figure 1.

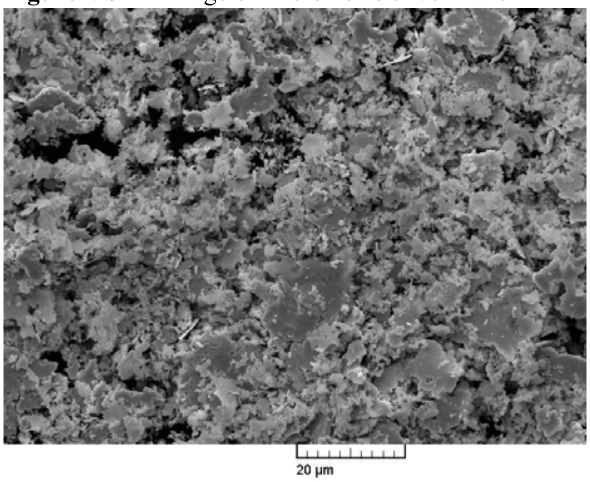
Table 1. Silver paste composition

	Silver wt%	Thermoset resin	Diluent	Organic Enhancer
A-1	80%	7%	Type1, 13%	Yes
A-2	80%	7%	Type2, 13%	Yes
A-3	80%	7%	Type3, 13%	Yes
B-1	80%	13%	Type1, 7%	Yes
C-1	80%	7%	Type1,13%	No
D-1	80%	13%	Type1, 7%	No
E-1	80%	0%	Type1, 20%	Yes

Table 2. Diluents

	Type 1	Type 2	Type 3
Boiling temperature	230 °C	190 °C	171 °C
Vapor pressure at 20°C	0.04 mmHg	0.3 mmHg	0.85 mmHg

Figure1. SEM image of micron size silver flake

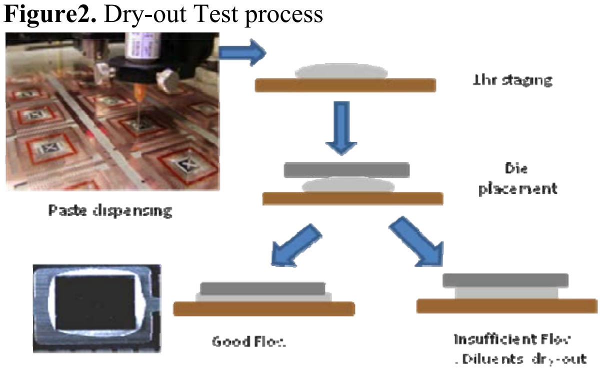


B. Measurement and evaluation result

B-1. Dry-out and void

A-1, A-2 and A-3 were tested on dry-out and void. The dry-out test is to test if paste can achieve uniform bond line thickness up to one hour staging time. Each paste was dispensed on lead frame by needle using an automated dispenser and die was placed on the paste immediately after dispensing and then subsequently after one hour staging. The samples were cured by box oven following the curing profile of Figure 3. The adhesive thicknesses of 0 minute and 60 minutes staged samples were measured using a micrometer. Less than 25% change in thickness after the one hour staging is considered a pass for the dry-out test.

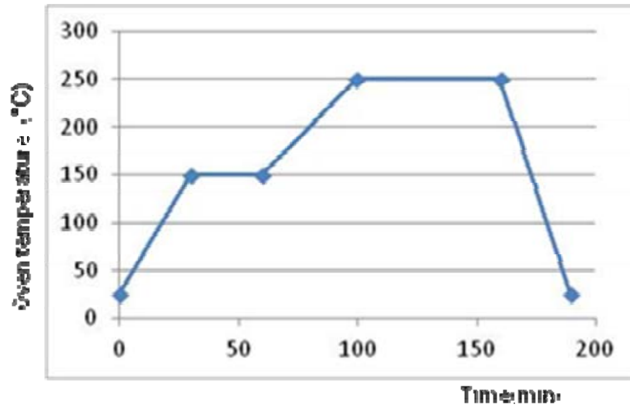
Figure2. Dry-out Test process



To determine the level of voiding in the bond line, the cured sample of A-1, A-2 and A-3 were tested by X-ray. A 3mm x 3mm gold plated silicon die was used along with a silver plated copper lead frame. The die attached samples were prepared without staging and cured in box oven with Nitrogen environment used during the curing process.

1. Ramp 30 min from 23°C to 150°C
2. Hold 30 min at 150°C
3. Ramp 40 min from 150C to 250°C
4. Hold 60 min at 250°C
5. Cool down from 250°C to room temperature

Figure3. Curing profile with box oven



B-2.Die shear strength

The die shear strength of A-1, B-1 and C-1 were tested using a Dage 4000 bondtester equipped with heat block was used for the evaluation. Figure 4 showed the measurement set up. The paste was first dispensed on a lead frame and die was placed on the dispensed paste with appropriate bonding force to achieve ~300 micron filet around the die. Silver plated copper lead frames and gold plated or bare silicon dies were used for this experiment. The die size is 3mm x 3mm and the thickness is 250 microns. The die attached samples were cured in box oven and the final dry thickness is 25 microns +/- 3 microns. The curing profile is shown in Figure 3 and the die shear strength was measured on heated block as shown in Figure 4.

Figure4. Schematic illustration of die shear test

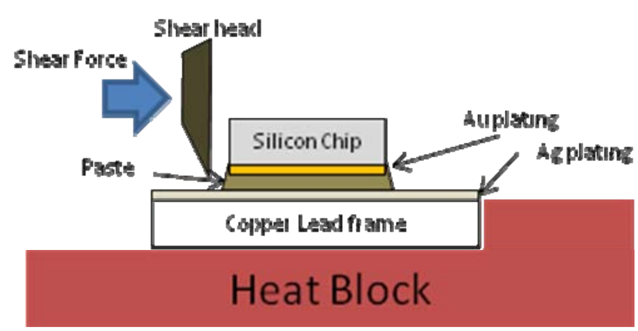


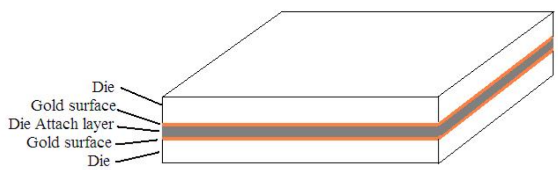
Figure 4 shows the die shear strength of A-1, B-1, C-1 and D-1 without heating the heat block. Figure 5 shows the die shear strength with 260°C heat block temperature.

B-3.Thermal conductivity measurement: Bulk & K_{eff}

The bulk thermal conductivity of A-1, B-1, C-1 and D-1 were measured by Netzsch LFA 447N Nanoflash instrument. The samples were cured with the same cure profile as the die shear sample preparation of Figure 3. The sample size is 8mm by 8 mm with 1.5mm thickness.

In many cases, the bulk thermal conductivity data of die attach paste doesn't have correlation with the thermal resistance in the package level because it only represents bulk conductivity and doesn't consider interfacial resistance between die and adhesive layer. To obtain more information about the contact or interfacial resistance, we developed a test method in which we determine the "effective" conductivity, termed K_{eff}, which accounts for the loss of thermal conductivity due to die attach layer to substrate and die attach to die resistance. The K_{eff} sample is prepared by making sandwich with die attach paste and two gold metalized silicon die as shown in Figure 5. The thickness of the adhesive layer is 23-27 micron thickness.

Figure5. K_{eff} sample

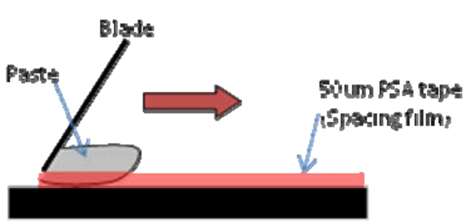


Netzch LFA 447 Nanoflash instrument was used to measure K_eff .

B-4.Adhesive bond line thickness measurement during cure

A 50 micron thick samples of A-1, B-1 and E-1 were prepared by printing on glass slide. In order to print 50 micron thickness of die attach paste, 50 micron PSA (pressure sensitive adhesive) tapes were used as a spacer and taped on the left and right sides of glass slide.

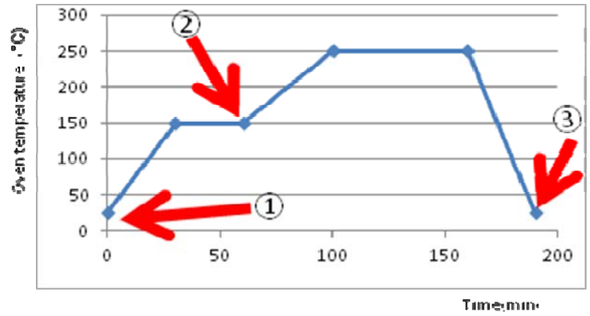
Figure 6. 50 micron thickness sample preparation of A-1, B-1 and E-1.



The curing profile of the printed samples is shown in Figure 3 and the thickness was measured during the curing process. The measurement was conducted at three points of below.

①Before cure
②After 150°C for 30min
③After full cure

Figure7. Bond line thickness measurement during cure



B-5. Viscosity measurement and needle dispensing

Viscosity and thixotropic index are the material properties to indicate the dispensing performance of die attach material. The viscosity of A-1 and B-1 were measured by Brookfield HBDVIII+ viscometer and compared with a silver epoxy, which has good dispensing performance with needle.

Thixotropic index was calculated from the viscosity numbers with 0.5rpm and 5rpm spindle speed.

Thixotropic index = (0.5rpm viscosity)/(5rpm viscosity)

Result and Discussion

A. Diluents test

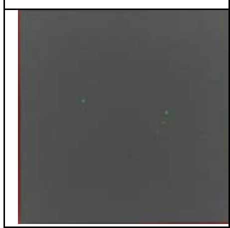
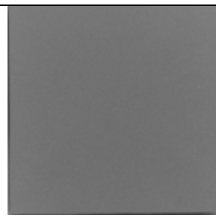
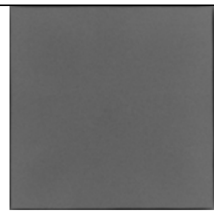
The properties of the diluent are very critical for making consistent bond line thickness, controlling flow and being void free after the curing process. If the diluent in die attach paste dries prematurely at room environment, the die attach adhesive will thicken in short time period after dispensing and not be able to flow well enough to cover the die. The result is a thicker bond line than targeted and insufficient die coverage. Die attach paste needs to flow consistently and uniformly to achieve good die coverage at least one hr after dispensing. Thus, the diluents in die attach paste should not evaporate for at least one hour under ambient conditions. The results are summarized in Table 3. A-2 and A-3 dried too quickly and failed the one hour staging test and resulted in too thick of a bond line. Thus, we concluded that the diluents type 2 and type 3 in the formulations are not appropriate diluents for die attach application.

On the other hand, if the diluents do not evaporate during oven cure process, they will be captured inside of die attach layer. The capture diluents would become voids and negatively affect thermal conductivity, adhesion strength and reliability performance. The void test results were shown in Table 4 and the three samples showed no void or minimal voids. Thus, we concluded the diluents of three formulations were adequately removed during the curing profile described in Figure3. Type 1 diluent was found to be the best diluent with acceptable staging time and minimal voiding.

Table 3. Dry-out result

	A-1	A-2	A-3
Bond line thickness: No staging	35um	37um	38um
Bond line thickness after 1hr staging	38um	49um	73um
Bond line thickness change	7.9%	32.4%	92.1%
Dry-out test result	Pass	Fail	Fail

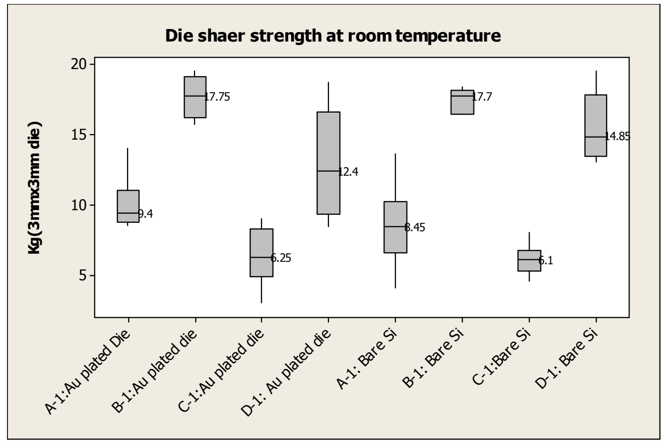
Table4. X-ray image of void after cure. Die size is 3mm x 3mm

A-1	A-2	A-3
		
Void: 0.04%	Void:0.00%	Void: 0.00%

B. Die shear strength

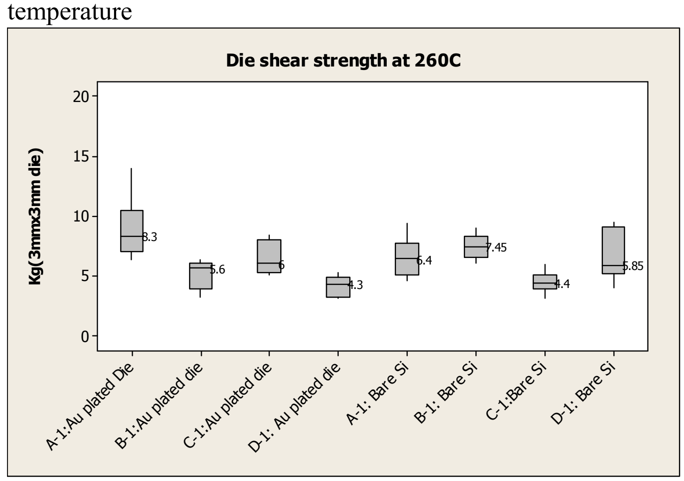
The die shear strength of A-1, B-1, C-1 and D-1 were measured at room temperature and 260°C(heat block temperature) and the results are shown in Figure 8 and 9. A-1 and B-1have organic enhancers and higher die shear strength than C-1and D-1, which don't have organic enhancers in the formulation. We believe the organic enhancers play a role in the die shear strength because they seem to enhance the sintering of silver particles. The silver sintering can increase cohesive strength of die attach layer and also adhesion strength to metal substrate and metalized die. If comparing the die shear strength of A-1 and B-1 to gold plated and bare silicon dies, the die shear strength to bare silicon die is as good as to gold plated die. Other die attach materials such as solder, gold-tin and nano-silver sintering products requires metal plated surface to have respectable adhesion strength. They cannot have good adhesion to bare silicon die because they cannot diffuse into silicon surface. But HSST die attach paste shows good adhesion with bare silicon die because it has polymer component to enable the paste to bond to the silicon surface.

Figure8. Box plot of the die shear strength at room temperature



If comparing the die shear strength of A-1 and B-1, A-1 has lower adhesion at room temperature than B-1 but higher adhesion at 260°C shown in Figure9. A-1 has the higher silver loading and can have more sintering than B-1. The die shear strength of A-1 at 260°C is good and not much different from the room temperature because the cohesive strength of the sintered silver is maintained through 260°C as long as it is below the melting temperature of silver. Formulation B-1 has relatively low silver and high resin ratio, so the adhesion is affected by die shear temperature. The die shear strength at room temperature is relatively high due to the thermoset resin but drops dramatically at 260°C because the thermoset resin has the glass transition temperature at 150°C and becomes soft at the 260°C die shear test condition.

Figure9. Box plot of die shear test with 260°C heat block temperature



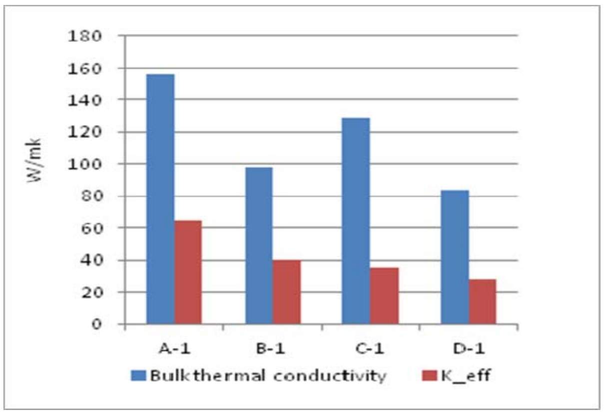
C. Bulk thermal conductivity and K_eff

Figure10 showed the bulk thermal conductivity and K_{eff} of A-1, B-1, C-1 and D-1 after cured by the curing profile of Figure3. A-1 has the highest thermal conductivity and K_{eff} among them. B-1 has higher thermal conductivity than D-1. The organic enhancer is doing significant role for bulk thermal conductivity and K_{eff}. A-1 has higher thermal conductivity than B-1 because it has higher silver ratio than the other after curing.

K_{eff} is measured of the sandwiched sample by two dies(Figure 5) and represents bulk and interface conductivity. K_{eff} number is more relevant than bulk thermal conductivity to the die attach thermal resistance in package level.

Pb solder has the bulk conductivity in the range of 30 to 50 W/MK and tin-gold has 58 W/MK. A-1 and B-1have comparable thermal conductivity with tin-gold and Pb-solder.

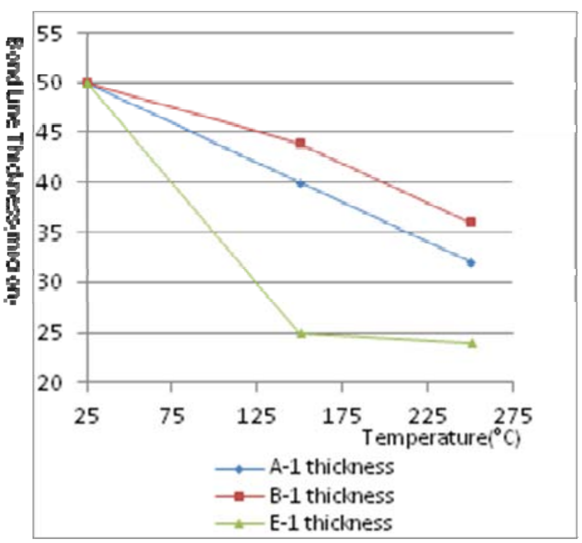
Figure10. Bulk thermal conductivity and K_{eff} of A-1, B-1, C-1 and D-1



D. **Bond line thickness change during cure**

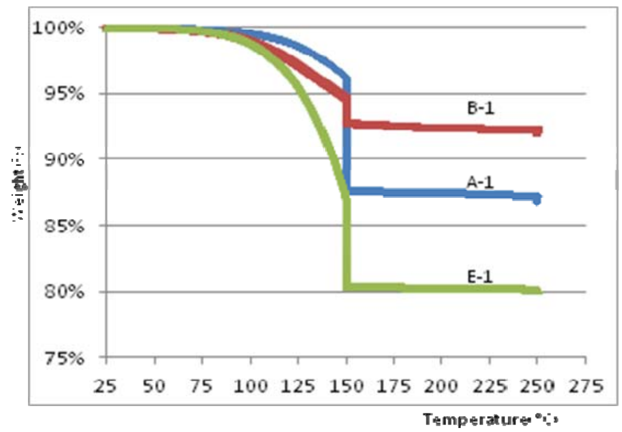
The wet paste thickness shrinks during cure due to the evaporation of the diluents and the shrinkage from the thermoset resin cross linking. The paste samples of A-1, B-1 and E-1 were cured by the curing profile shown in Figure 3 and the bond line thickness was measured before and after cure and during cure.

Figure11. Bond line thickness change during cure : A-1, B-1 and E-1



E-1, which has no thermoset resin and 20 wt% of diluent in the formulation, showed significant shrinkage from room temperature to 150°C but little shrinkage from 150°C to 250°C. However, A-1 and B-1 showed significant shrinkage from 150°C to 250°C as well as room temperature to 150°C. The weight loss of A-1, B-1 and E-1 measured by TGA(thermal gravimetric analysis). The temperature profile is the same as the curing profile of Figure 3. According to the TGA graph shown in Figure 12, the diluent of E-1 was fully removed by the end of 150°C. The diluents of A-1 and B-1 were also removed more than 98% from room temperature to 150°C. But A-1 and B-1 shrank 20% and 18% respectively from 150°C to 250°C. The shrinkage of E-1 is mostly driven by the diluent evaporation. However, the shrinkage of A-1 and B-1 were induced not only by diluent removal but also by resin shrinkage. It is known that the epoxy cure reaction can induce the resin shrinkage more than 6% by volume[(4),(5)].

Figure12. TGA(thermal gravimetric analysis) weight loss of A-1, B-1 and C-1 by the temperature profile of Figure3.



E. Viscosity and needle dispensing

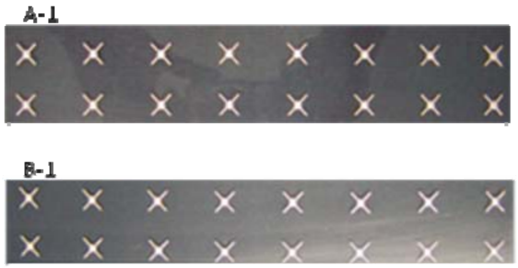
Viscosity and thixotropic index are important material properties related to dispensing performance. The viscosity and thixotropic index of A-1 and B-1 are not much different from silver epoxy used in mass production today as shown in Table 5. If viscosity is higher than 25K cps, the paste cannot flow through small needle such as 23gage needle which will result in poor dispensing. If thixotropic index would be lower than 3.5, the dispensed pattern will not be uniform.

Table5. Viscosity of A-1 and B-1 comparing with Ag Epoxy

	A-1	B-1	Ag Epoxy **Atrox^{TM} 5582A**)
Viscosity	10500 cps	13800 cps	9000 cps
Thixotropic Index	4.9	5.7	4.2

The dispensing test was conducted to validate the performance of A-1 and B-1. **A** Camalot 1818 time pressure dispenser was used for the evaluation. The needle used for the test was 23 gage size and the pressure was 20 psi. Both A-1 and B-1 showed uniform dispensed patterns without tailing.

Figure13. Dispensed pattern of A-1 and B-1

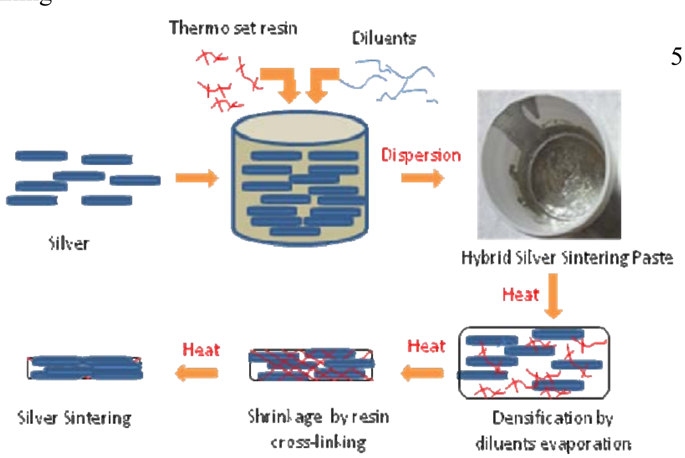


Paste Manufacturing and Application

Figure 14 illustrates the basic procedure of making hybrid silver paste and processing it.

Silver flakes are dispersed in the mixture of thermoset resin and diluents. The mixed paste samples are cured in box oven following the two step curing profile shown in figure 3. The diluents evaporate in the 1st step cure temperature (150°C). The thermoset resin starts cross-linkage from 150°C to 250°C. The resin shrinks by the cross-linking reactions and the resin shrinkage forces silver flakes get closer each other. The silver flakes eventually sinter at or below 250°C due to their close proximity

Figure14. Process diagram for making hybrid silver sintering formulation and silver sintering by resin cross-linking



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Summary and Conclusion

Hybrid silver sintering technology (HSST) is the mixture of micron silver flakes, thermoset resin and diluents. HSST described in this paper takes advantage of the shrinkage force of the selected thermoset resin to bring particles closer together. We have demonstrated that with the correct formulation approach micron silver can effectively sinter at reasonable process temperatures without pressure during the curing process.

The formulation approach to use thermosetting resin enables hybrid silver sintering products to have excellent adhesion to bare silicon die. This is a primary advantage over Pb solder, eutectic gold-tin, transient liquid phase sintering (TLPS) and nano-silver sintering materials that require back side metallization

The formulations presented in this paper are capable of achieving very high bulk, high effective conductivities, low thermal resistance and can serve as a solder replacement. The HSST formulations presented also have the correct rheology and dispense characteristics for high volume manufacturing on commercial available die bonders

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