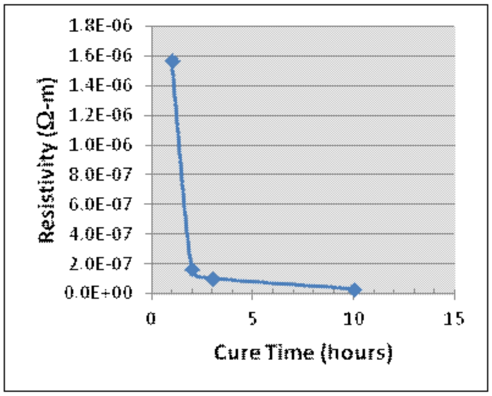

Figure 6: Resistivity as a function of cure time at 150 °C. Resistivity continues to decrease over several hours approaching an asymptotic value 2x of bulk silver. SEM analysis shows that after an initial cure the silver flakes sinter and form an interconnected metallic network.

Figure 7 shows cross section SEM micrographs of uncured and cured silver epoxy. The uncured micrograph shows distinct, overlapping silver flakes. However, the micrograph of cured material clearly shows that the flakes are merging to form a connected metallic network. Consequently the increased conductivity observed with longer cure times may be a result of continued merging and densification of the silver flake. The high silver content in the epoxy then suggests that the primary conduction occurs through the metal network rather than by tunneling from particle to particle.

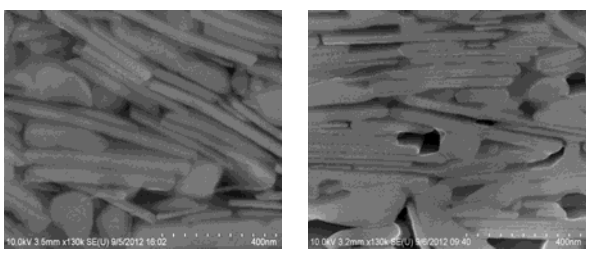

Figure 7. Cross section SEM of uncured silver epoxy (left) and silver epoxy cured for 2 hrs at 150 °C (right). The individual plates merge over extended cure times.

Laser Curing

Since extended curing schedules may not be acceptable for some applications, we have also examined laser assisted curing. Figure 8 show a schematic of the laser curing technique used in the Optomec system as well as resistivity data. As mentioned above, the focused CW laser beam acts as a point source of heat to rapidly cure material under the impinging spot. In this case, a 200 mW, 832 nm laser is focused to a spot size of 20 µm to give a peak intensity of $2x10^5$ W/cm^2. The laser spot is scanned at a rate of 10 mm/s. Based on color changes observed while scanning the laser over a silver epoxy film, the heat affected zone is estimated to extend to 50 µm. In other words, even though the laser is focused to 20 µm, the lateral heat spread is sufficient to process a 50 µm spot. Printed features larger than 50 µm can be cured by scanning the laser in a raster pattern with a 50 µm pitch. A larger pitch and larger spot size would be possible with a more powerful laser.

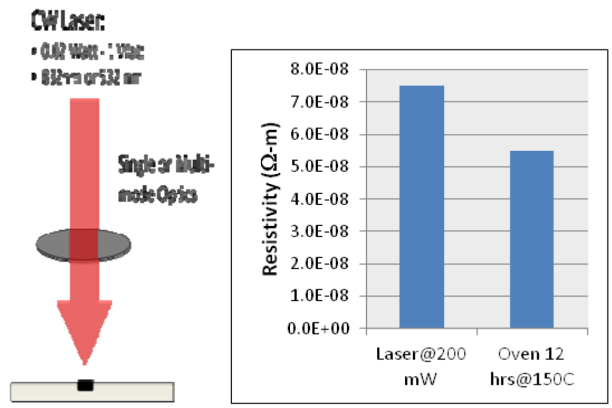

Figure 8. Schematic diagram of laser sintering configuration (left). Resistivity of laser sintered silver epoxy compared to oven cured epoxy (right). While similar resistivity values are obtained, the laser process greatly reduces the overall cure time and can be performed without removing the substrate from the system for oven processing.

The resistivity data in Figure 8 compares the resistivity of laser cured silver epoxy to the resistivity of epoxy that was cured in an oven at 150 °C for 12 hrs. The values are similar to within 30%. The advantage of the laser cure process is that high conductivity can be achieved within minutes of printing the ink, whereas the oven curing requires hours for the lowest values. The laser curing can also be performed without removing the substrate from the system, so it can reduce the number of steps required for printing multiple layers of dissimilar materials. On the other hand, the laser requires a line of sight to the substrate, which is not always possible, especially if the epoxy is used to bond between a chip and PCB.

Adhesive Properties

One of the primary applications for dispensing nanosilver epoxy is for attaching chips to PCBs. Figure 9 shows images of 15 mil (375 µm) Kovar tabs attached to gold coated alumina. The epoxy pads are printed with a 20 mil (500 µm) width and 1 mil (25 µm) thickness. When the tabs are placed, the epoxy clearly wets the vertical edge and forms a fillet. Die shear measurements indicate that the highest shear strength is obtained when the epoxy wets the sidewall in this way. The measured die shear strength is 2000 PSI which is comparable to standard die attach epoxies and meets the MIL-STD-883, method 2019 minimum requirement of 882 PSI. Cohesive failure is seen in all cases. The glass transition temperature is approximately 100°C.

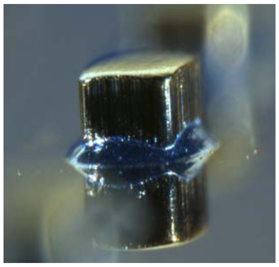

Figure 9. 15 mil (375 μm) Kovar tab bonded to gold coated alumina substrate using silver epoxy.

Applications

Multiple bond pads can be printed at high density for attaching multiple I/O chips. Figure 10 shows the attachment of 0402 SMT resistors to ceramic substrate and QFN devices to glass plates. As described above, the substrates are heated to 60 °C when jetting the silver epoxy pads. This temperature is sufficient to evaporate residual solvents in the epoxy, but low enough that the epoxy does not cure. The printed epoxy remains uncured until subjected to elevated temperatures of 100 °C or higher. Consequently, it is possible to print a large number of bond pads sequentially and then attached the chips later. The chips shown in Figure 10 were manually placed with assistance of an optical microscope. The QFN sample also shows that the chips are physically connected to printed conductor lines.

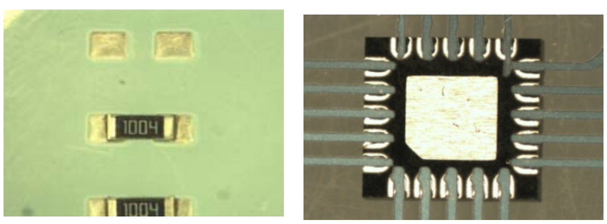

Figure 10. Images of attached SMT devices using printed silver epoxy. The 0402 resistor (left) is attached to ceramic using 8 mil (200 μm) pads with an 8 mil (200 μm) gap between pads. The QFN chip (right) is attached to printed silver lines on glass substrate. Dots of epoxy have been printed on the ends of the lines and then the chip was placed manually with the assistance of a microscope.

Compared to conventional nanoparticle silver inks, the silver epoxy exhibits far less shrinkage during curing. After solvent evaporation, the measured volumetric shrinkage during curing is less than 2.5%. Consequently, the silver epoxy may be more effective at producing solid conductive fills in confined geometries. One application where low shrinkage is required is in producing conductive via plugs in Through Silicon Via (TSV) die. Figure 11 shows an SEM cross section of a 50 μm diameter by 300 μm tall TSV, which contains jetted and cured silver epoxy. The fill process consists of several steps. The silver epoxy can be jetted into an open via, but there is substantial leakage from the bottom side. Consequently, the amount of time required to fill the open via becomes variable, depending on the amount of leakage. In this work, an adhesive tape is applied to the back side of the die to convert from an open via to a blind geometry. The next step is to fill the via completely by dispensing liquid, silver epoxy down the center of the via. The epoxy flows to the bottom of the via and fills from the bottom upward. When full, the liquid epoxy is flush with the top surface. The platen is heated to 60 °C to evaporate the solvent and in this drying process the top level of the epoxy recesses into the via. If needed, the filling step is repeated at least once more to return the liquid level to the top surface. Repeated partial fills can bring the dried epoxy level flush to the surface, but at the expense of additional process time. After filling and allowing the solvents to evaporate, the samples are fully cured at 150 °C. Since the dried epoxy has low shrinkage, highly dense metal plugs are achieved.

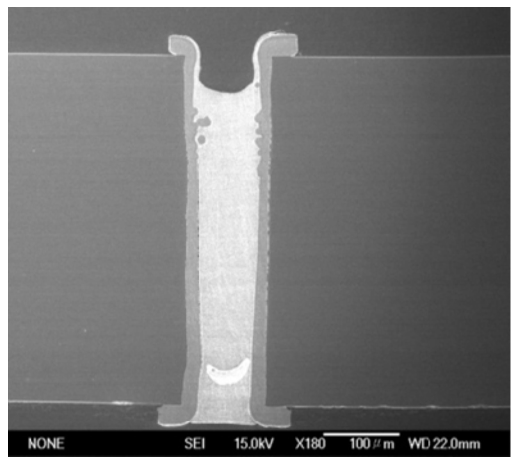

Figure 11. SEM cross section of silicon via filled with silver epoxy. The cured silver epoxy appears bright white and a sidewall coating of plated copper is also evident.

FUTURE WORK

Future development work is planned for measuring thermal conductivity of the silver epoxy. High thermal conductivity is important for attaching power devices and heat generating chips. Given the high metal loading, the silver epoxy is expected to have an excellent thermal conductivity. Additional work is needed to determine contact resistance between the silver epoxy and various chip and board metallizations. Finally, a full characterization die shear strength as a function of bond line thickness is under way.

CONCLUSIONS

A new nanoflake silver epoxy has been developed for small feature, die attach applications. Using the Aerosol Jet tool, uniform dot sizes as small as 1 mil (25 μm) can be dispensed. The epoxy is curable at 150 °C and at that temperature the die shear strength exceeds MIL-STD-883, method 2019. The electrical resistivity is 100 times greater than bulk silver with a 1 hour cure, but can go down to 2 times greater with extended curing. Laser assisted curing results in similar resistance values but with dramatically shorter processing time. The Aerosol Jet dispensing system is capable of non-contact printing at high standoff heights. Consequently, the silver epoxy can be printed into recesses and over steps. This capability should enable various TSV and chip-on-chip configurations and support high density I/O packages.

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