A Breakthrough in Power Electronics Reliability – New Die Attach and Wire Bonding Materials

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Abstract

Power Electronics on DCB are used for high power devices. There is a wide field of applications for such power electronic devices like converters or inverters for wind mills, solar parks or for electric and hybrid vehicles. High efficiency, long life time and increased power density are the major technical requirements for those devices. Especially the life time, but also the power density are limited by die attach and wire bond materials.

New material solutions to overcome these limitations in life time will be discussed in this paper. Results of an active power cycling test of DCB devices supported by the failure analysis and material data will be used to demonstrate and explain the novel materials advantages versus conventional solutions.

Introduction

Conventional Solder can be used at operation temperatures up to 125°C. However, solder fatigue during operation will increase the thermal resistance of the device and increase the die temperature. Because of the increasing operation temperature conventional Al wires will usually be a limiting factor in such a system and fail first, even if the root cause for the failure could be die attach weakening. Knowing about this interaction of die attach and wire bond material determining the life time of power modules, Heraeus utilizes its in-house know-how of both material technologies to improve the life time of DCB modules using a multi-material approach.

A breakthrough in life time and power density is provided by the usage of silver sintering material for the die attach. Silver provides a high specific thermal conductivity (430 W/m·K) at the bulk material. This will allow an improved heat transfer through the die attach material out of the package. Furthermore the melting point of this material is compared to soft solder quite high (961°C cf. 220°C tin-silver or tin-silver-copper solders). As a result the sinter layer will not show measureable thermal fatigue during the device life time.

The stable thermal properties of the die attach material result in a longer life time of the Al wire bond and, consequently, in a longer life time of the power electronic devices. A further increase of the device life time can be achieved by the usage of the novel AlCu clad wires. These wires are characterized by their improved mechanical and electrical properties. Furthermore, the AlCu clad wires are suitable for the wire bond connection on the standard chip technology. The combination of AlCu clad wires and silver sintering die attach results in even better reliability of the package compared to a single application of one of the new technologies.

In this paper the authors describe the enhanced life time and the failure modes resulting out of the new interconnection methods after power cycling, as well as an analysis of potential root cause.

Die Attach Material

As most commonly used material for the die attach of DCB modules SnAg3.5 solder is selected today. This material is well established in the industry. Knowledge for material and process, as well as the required equipment is available. As mentioned, solders are one of the major materials limiting the life time of power electronic devices due to solder fatigue.

In order to reduce the fatigue of the die attach material a joining material providing a significant higher melting point compared to solder would be a possible solution. Additionally, the process temperature of this material should be in the same temperature range as solder to minimize a possible additional thermal impact to the substrate and semiconductor. Silver as a potential candidate has a melting point of 961°C. One approach to utilize silver as joining material is the use of nano silver. However, nano silver is not easy to handle in terms of health protection and equipment cleaning. Furthermore, it is limited by the maximum bond line thickness and easily agglomerates during storage.

To overcome this limits of nano silver special silver sinter formulations like the Heraeus mAgic ASP043 are developed. This material is based on micro scaled silver particles. In combination with special additives this paste allows a processing at temperatures of 230°C. The mAgic ASP043 sintering paste creates a pure silver layer after processing. During die attach curing this material transforms from a paste to a porous Ag layer. The die attach benefits from the properties of silver like e.g. its high melting point and excellent thermal conductivity (Table 1). This material requires a noble interface for reliable bonding, as e.g. Ag, NiAu or Pd.

Property	SnAg solder [1]	mAgic sinter paste
Liquidus temperature	221°C	961°C
Process temperature	250°C	230°C
Bulk electrical resistivity	0.01 mΩ·cm	≤ 0.008 mΩ·cm[1]
Bulk thermal conductivity	30 - 50 W/m·K	>> 100 W/m·K[1]
Shear strength	40 N/mm^2 @ 25°C	>10 N/mm^2[1] @25°C & 260°C
E-modulus at 25°C[1]	30 GPa	> 35 GPa[1]

Table 1: Comparison of material Properties of SnAg-Solder and Ag-sinter joint

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[1] depending on adjusted porosity

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Compared to soldering the processing of silver sintering pastes for DCB application requires some different steps. The material will be printed by stencil printing using conventional printing equipment. Before die placement solvent contained in the paste have to be evaporated in a box oven. The die placement will be performed at a temperature of 100-130°C using industrial die attach equipment. The sintering step is done using a heated press. A pressure of 10-20 MPa has to be applied for two minutes at a process temperature of 230°C. Process flow and description is summarized in Figure 1.

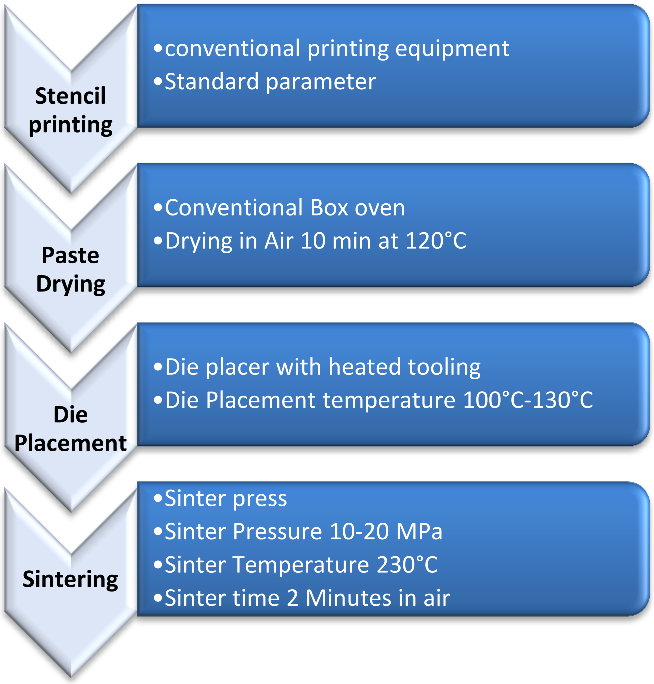

Figure 1: Sinter Process for DCB Application

Wire Bond Material

Two bonding wire materials were considered at a thickness of 300 µm, i.e. a conventional high purity Al wire (Al-H11 from Heraeus) and a new Al/Cu cladded wire (CucorAl from Heraeus). The latter consists of a Cu core and an Al coating. The area fraction of Cu/Al is approximately 70/30.

The electrical conductivity of the wires was measured by using a four point measuring set-up. A current of 10 mA was applied and the voltage drop along a 1 m piece of the wire was measured.

The fusing current as a measure for the current carrying capability was measured at a 20 mm piece of wire which is clamped between two connectors. The current was ramped at a rate of 0.2 A/s until the wire fused. The test was done under ambient condition, i.e. approx. 45%-r.H. and 22°C.

The stress in the wedge was estimated using a two dimensional finite element (FE) simulation using the software LISA [6]. Due to the two dimensional approach a plane strain situation is simulated. The model was copied from a cross-section shown in Figure 2a. A chip with a thickness of 120 µm consisting of pure Si was used for the simulation. On top of the Si chip an Aluminum bond pad of 5 µm thickness was modeled. The wire was simulated with a diameter of 300 µm. The resulting model is shown in Figure 2b.

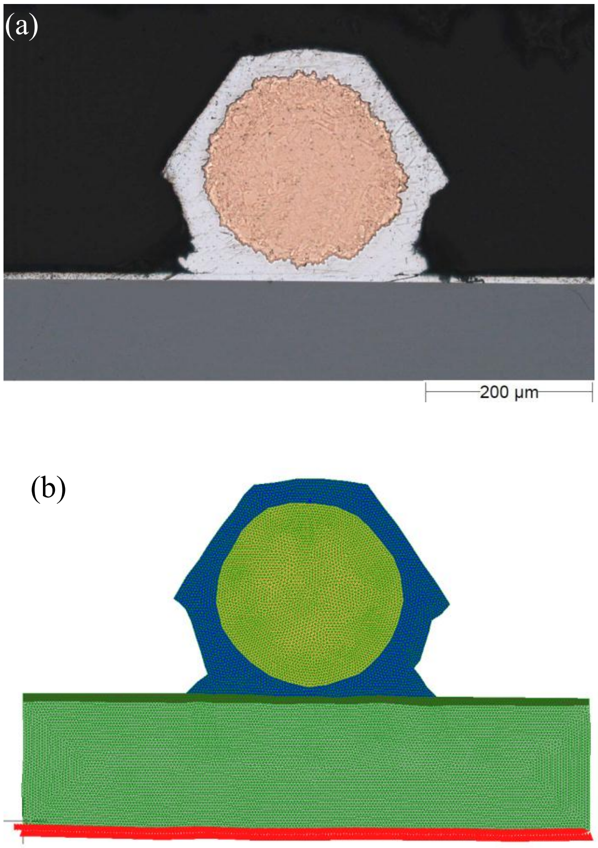

Figure 2: (a) Cross-section of the bonded wedge
(b) FE model of the wedge

The meshing was done using triangular elements and was not changed while going from CucorAl wire to Al-H11. Only the material parameters of the core were changed. The material parameters are shown in table Table 2. Only linear elastic stress was considered. As boundary condition of the model the lower side of the chip was fixed and the rest could deform freely. The set-up was assumed initially stress free. A quasistatic simulation to evaluate the stress was done by homogeneously increasing the temperature of the system by 100 K.

	CTE [10^{-6} K^{-1}]	E [GPa]	Poisson ratio []	El. Cond. [m/(Ω.mm²)]
Si	2.6	150	0.17	1
Al	23.1	70	0.34	37
Cu	16.5	110	0.34	56

Table 2: Material parameters for FE simulation

Results and discussion

In order to assess the material properties of the new CucorAl wire the fusing current, the coefficient of thermal expansion (CTE) and the electrical conductivity was measured.

The CTE, measured using Thermo Mechanical Analysis (TMA) was measured to be 19.5 ± 0.5 10^{-6} K^{-1} in the range from -50°C to 250°C.

The fusing current is shown in Figure 3, where the current for wires of different diameters for bare Cu, bare Al and CucorAl wires were measured.

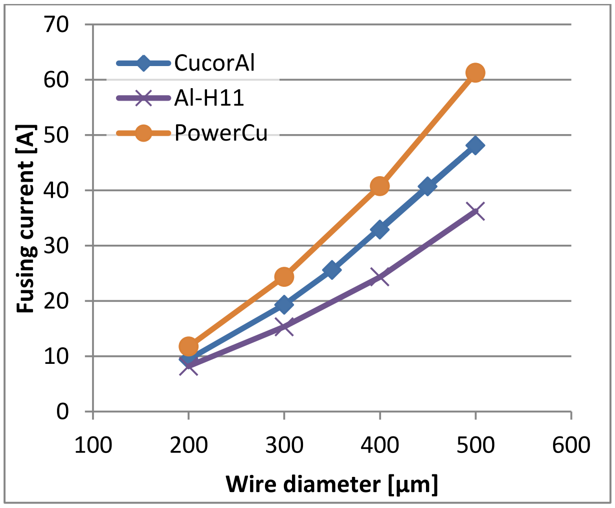

Figure 3: Fusing current for Al, Cu and CucorAl wires of different diameter

It shows the advantage of CucorAl over bare Al wire. It corresponds to the good electrical conductivity which was measured to be 51 m/(Ω.mm²). This fits well to the area fraction of Al and Cu, which is 30% and 70% respectively. Using the area fraction and conductivities in Figure 2 one would calculate 50 m/(Ω.mm²).

Reliability Evaluation in active Power Cycling Test

To evaluate the improvement of the silver sintering compared to conventional solder and the CucorAl wire compared to conventional Al wire DCB devices (see Figure 4) were built and tested. An diode used in standard DCB modules by today in the size of 8.15 mm x 9.00 mm and a thickness of 120 µm was mounted on a conventional DCB. The thickness of Al_2O_3 ceramic of the DCB was 0.635 mm, the thickness of the Cu layer was 0.3 mm (usage of DCB layout by courtesy of IISB, Nuremberg). For the die attach by solder bare Cu DCBs were used. Solder was applied by stencil printing in a thickness of 150 µm. The parts were reflowed using a vacuum reflow oven.

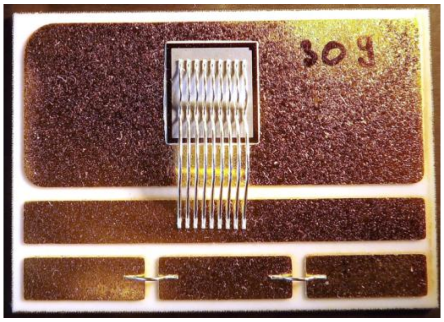

Figure 4: Test Device for active power cycling tests

For the die attach using the ASP043 sintering paste DCBs providing an Ag-finish were used. The sintering paste was applied by stencil printing using a 75 µm thick stencil. For the sintering the process as described in Figure 1 was used.

Some of the soldered samples were wire bonded by using a conventional Al wire, others using the CucorAl wire. Wire diameter used for all trials and all wires was 300 µm. The sintered devices were wire bonded using the CucorAl Wire, also in a diameter of 300 µm. For all devices bonded with Al- or CucorAl-wires nine wires were used. For the test matrix see Table 3.

	SnAg3.5 Solder	ASP 043-Series
Die Attach Process	Vacuum reflow	10 MPa
Al-Wire, ∅ = 300µm	X	
AlCu-Wire, ∅ = 300µm	X	X

Table 3: Test Matrix active Power Cycling Test

All devices were tested in a symmetric active power cycling test. The time the diodes were heated (t_{on}), applying a constant current and the time the diodes cool down (t_{off}) was set equally to 15 s. The devices were mounted to a cooler. The temperature of the cooler was set to 40°C. At the beginning of the power cycling test the current was adjusted to get a ΔT=110 K. Heating current and temperature swing of the devices were monitored during the testing. An increase of more than 20% of these values was considered as failure of the device. The result of the test is shown as graph of the change of ΔT in Figure 5.

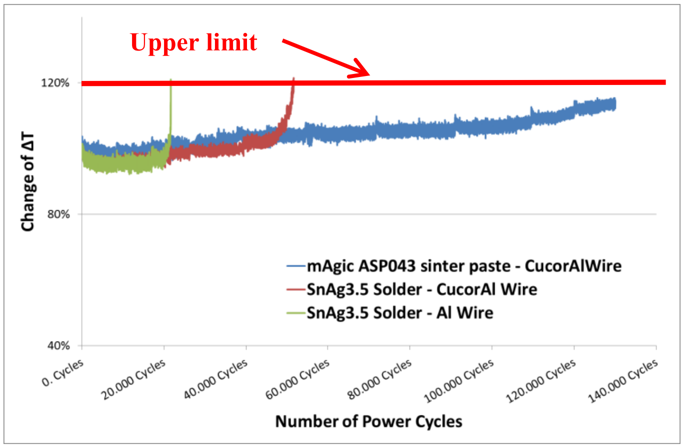

Figure 5: Change of ΔT during power cycling test in [%]

The test of soldered devices ended because these parts failed during testing. The test of the sintered devices was stopped because of the long test duration and because the end of life based on the temperature measurement was not foreseeable even after more than 130,000 power cycles.

Sample	No of power cycles till failure	life time compared to soldered device with Al-wires
SnAg3.5 solder – Al-wire	21,800	1 times
SnAg3.5 solder – CucorAl-wire	56,300	2.6 times
mAgic ASP043 sinter paste - CucorAlWire	n/a >130,000	>6 times

Table 4: Overview of test results of the active Power Cycling Test

After submission to Power Cycling Test (PCT) the samples were cross-sectioned to assess the interface wedge to bond pad, as well as the die attach layer. Figure 6 shows an optical image of the cross section of an Aluminum wire using conventional solder. The solder does not show an obvious fatigue while a wire lift of the Al-bond wire was observed, already.

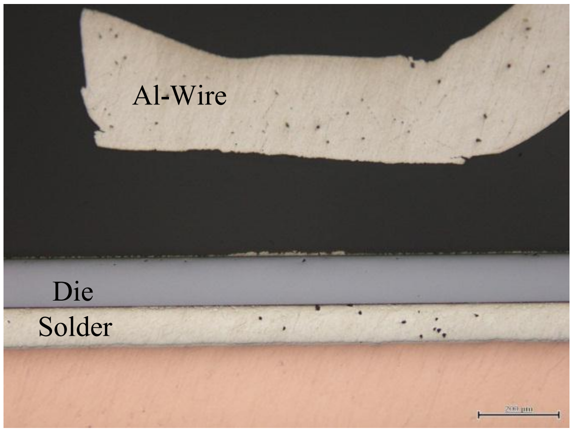

Figure 6: Optical image of the crack using Aluminum wire with solder die attach after 21,800 PCT

Figure 7 shows the SEM picture of a cross section of the soldered device after 21,800 PCT. The cross section picture at the center (Figure 7a) does not show an obvious solder fatigue whereas a beginning damaging is visible at the corner of the die (Figure 7b). The die attach layer is still intact and has not triggered the lift off of the wire bond. The limiting factor for this built was obviously the Al-wire.

The fracture on the wire bond connection occurs near the interface bond pad to wire, while remains of the wire on the bond pad indicate that the actual fracture is within the wire.

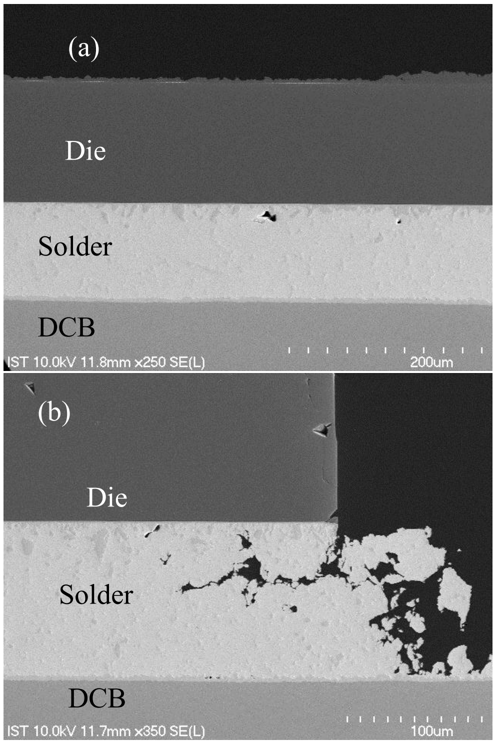

Figure 7: (a) SEM picture solder device after 21,800 PCT – center
(b) SEM picture solder device after 21,800 PCT – corner

A similar cross-section was done for the soldered device bonded using CucorAl wire (Figure 8 and Figure 9). For the device bonded with the CucorAl wire a wire bond lift is also visible. However, a total disruption of the solder can be observed, too (Figure 8). The wire lift off is caused by an increase of the die temperature because of the disrupted solder layer. This die attach layer cannot dissipate the heat generated by the power loss of the die as an intact solder layer. As a consequence the temperature of the die increases and the wire bond will lift which result in a malfunction of the device.

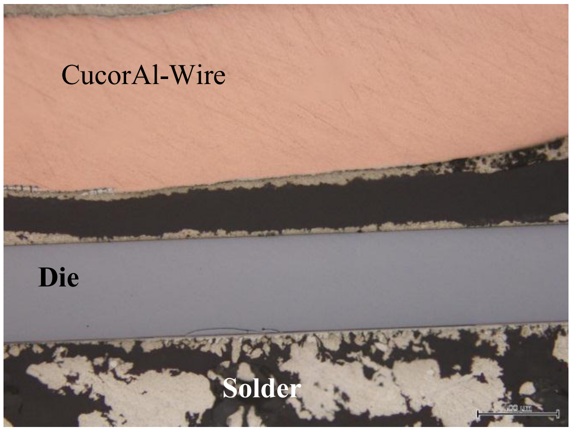

Figure 8: Optical image of the crack using Aluminum wire with solder die attach

Figure 9 shows a SEM image of the soldered device after 56,300 PCT at the center of the die. It was found that there is a crack through the intermetallic compound (IMC) of the solder at the substrate side of the device. Similar cracks are observed also at the corners of the device and in the IMC at the die side. It was found that these cracks also cause a crack of the die (Figure 9b).

This crack in the IMC is an unexpected phenomenon. Based on the experience of the authors out of passive temperature cycle test crack propagation at the interface between the IMC and the solder would be expected. A crack in the IMC is unexpected due to its mechanical stability. The cause of this behavior has to be further investigated.

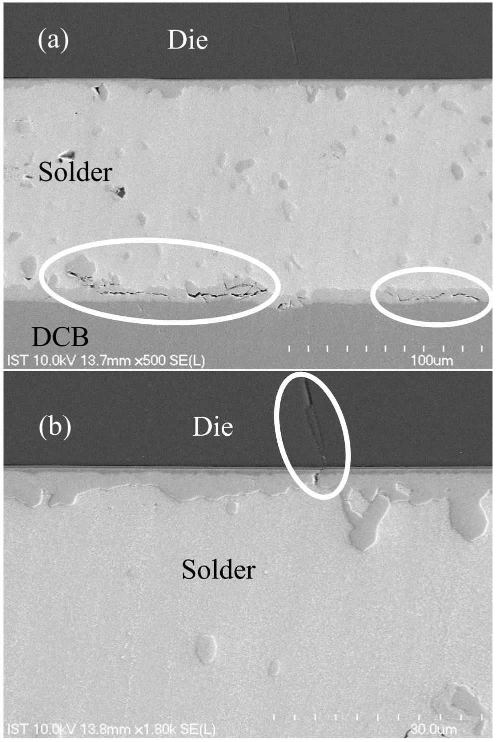

Figure 9: (a) SEM picture solder device after 56,300 PCT – center
(b) SEM picture solder device after 56,300 PCT – center detail

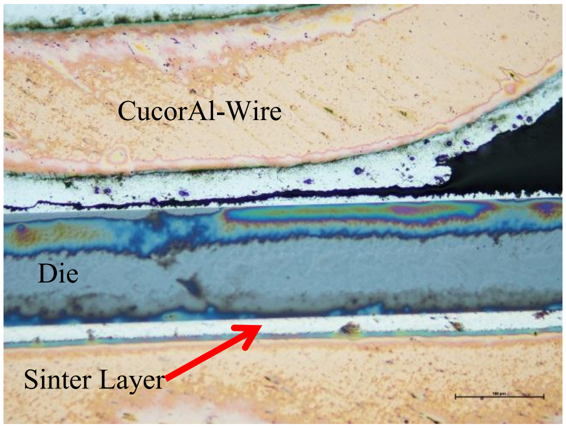

Figure 10: Optical image of the crack in the bond wire connection using CucorAl wire with Ag sinter paste die attach after 130,000 PCT

In Figure 10 the optical image of the x-section of the sintered device connected by the CucorAl wire is shown. Even at the SEM image (Figure 11), no delamination or fatigue at the sinter layer can be observed. The SEM picture shows the typical porous structure of a pressure sintered layer.

A crack in the wire bond connection can be seen. The connection is still intact but expected to fail soon. The improved CucorAl wire will be the factor limiting the life time of the sintered device.

In Figure 8 and Figure 10 a similar fracture mode of the bonding wire as in the case of the Aluminum wire (Figure 6) can be seen. Aluminum of the wire remains partially on the bond pad. However, some regions can be found where the crack goes along the Cu to Al interface of the CucorAl wire, which would indicate a different fracture mode. But it cannot be made certain if this Al/Cu fracture is due to the brittle AlCu intermetallic phases or if the crack path was anyway going deeper into the wire and is just stopped by the rigid Cu core. Profilometer results of Al wire showed remains on the bond pad up to 25 µm on the bond pad which corresponds to the thickness of the Al coating of the CucorAl wire.

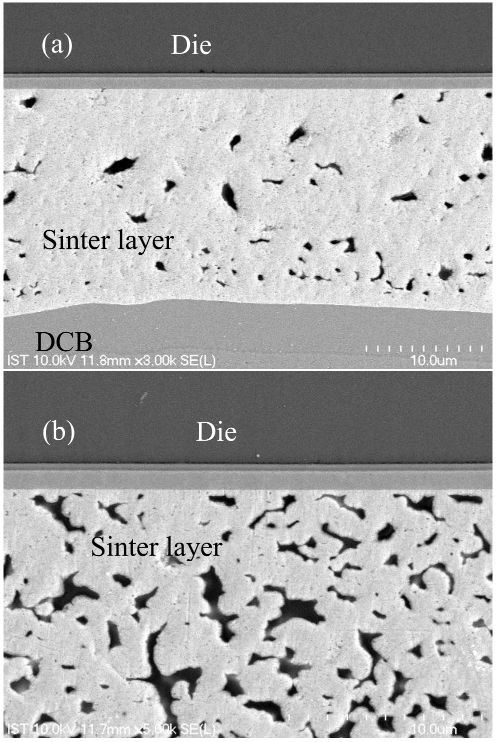

Figure 11: (a) SEM picture sintered device after 130,000 PCT – center
(b) SEM picture sintered device after 130,000 PCT – corner

In order to examine differences in failure mode between Al and CucorAl wire Focused Ion Beam (FIB) and Backscatter Electron (BE) mode images were taken to examine the grain structure. Since the BE mode showed a better contrast, we will focus on those results here. Figure 12 shows the crack interface for the Aluminum and CucorAl wire on solder die attach. In the case of bare Al wire (Figure 12a) a larger Al grain size in the order of 50 µm can be observed for the material still being attached to the wire. On the other hand, the remains on the die side or bond pad show a smaller grain size in the order of less than 10 µm. It seems that the fracture occurs at the interface between larger to smaller Al grains. The small grain size can origin from the bond process, as reported earlier in literature [7].

The detailed cross section in BE mode of CucorAl wire is shown in Figure 12b. Due to the limited Al thickness of approx. 20-30 µm such large grain size, as in the case of pure Al wire is a priori not possible. Overall a more homogeneous grain size distribution of less than 10 µm above and below the crack is found. This may favour a more homogeneous stress distribution and, therefore, promote an extended life time than in the case of bare Al wire.

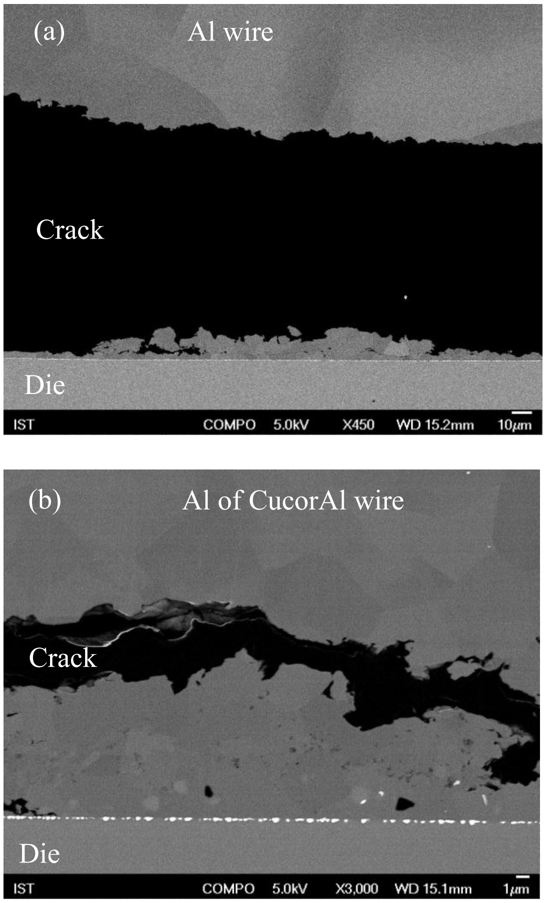

Figure 12: EBSD images of the Aluminum of (a) Al wire and (b) CucorAl at the bond pad interface.

Since the failure mode of Al and CucorAl wire seems still to be quite similar, FE simulations were done to estimate the stress distribution in the wedge. As a first approach a two dimensional wedge was taken as model (Figure 2a) and the internal stresses during a temperature increase of 100 K were simulated. The resulting von Mises stress is shown in Figure 13a for the Al wire and in Figure 13b for the CucorAl wire.

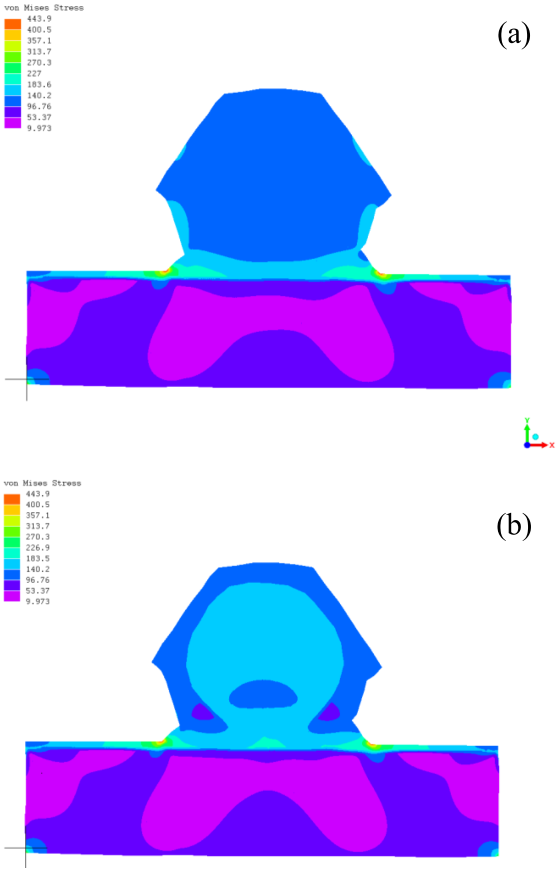

Figure 13: Von Mises stress for (a) Al wire and (b) CucorAl wire

Since the failure occurs at the interface from the bond pad to the wire, the von Mises stress of the element along the interface bond pad to bonding wire was extracted and plotted in Figure 14. Near the outer edge of the bonding wedge the stressess increases due to edge effects in the simulation. Neglecting these outer approximately 100 µm there is still a significant difference between the stress distribution of the Al core compared to the Cu core. Pure Al wire has high stress at the outside of the wedge. On the other hand, the CucorAl wire shows approximately the same peak stress, but in the middle of the bond. It is known [7], that cracks start from outside and grow towards the inner wedge. From this, the Al wire can be considered as more critical than the CucorAl wire. The model can be assumed as free, so that the stress calculated are generated purely by miss-match of the thermal coefficient of expansion. The effective CTE of the CucorAl wire was measured to be less than pure Al, which creates less miss-match compared to the silicon chip.

In order to get more information a full simulation would be needed. The authors believe, that the temperature distribution of the CucorAl should be benefitial for the reliability, as the heat, which is generated in the chip, will be better dissipiated towards the second bond on the DCB, which is also at cooler temperature. This should result in lower temperatures directly under the wire.

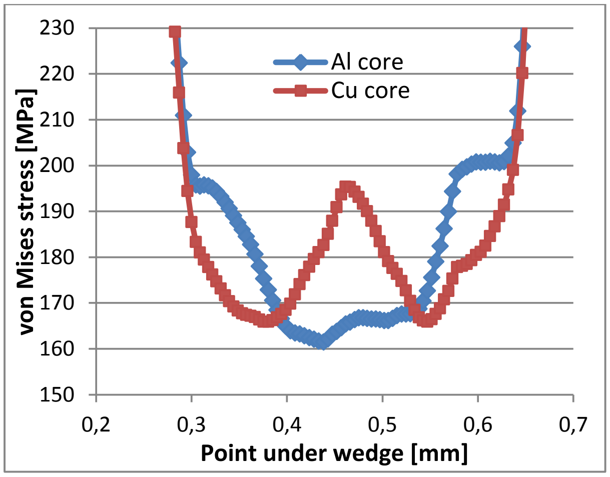

Figure 14: Von Mises stress for Al and CucorAl wire at the interface bond-pad to bonding wire

Summary and Conclusions

The trials showed a significant improvement in the life time of soldered DCB modules by replacing the conventional Al-wire by the novel CucorAl-wire by 2.6 times. During analysis of the x-sections of the devices with the improved life time an unexpected crack in the IMC was observed. The mechanism of this failure mode is not understood and has to be investigated further.

A further improvement of more than 6 times compared to a soldered and Al-wire bonded module was archived by the combination of a die attach using mAgic sintering materials and the CucorAl wire. It was shown that the sintered joint did not show a visible aging during the active power cycling test.

The stability of the sintered joint combined with the improved life time of the CucorAl wire compared to Al wire will allow a markable extension of the life time of DCB modules compared to modules build using conventional interconnect materials.

A further advantage of these novel interconnect materials is their processability on the majority of available dies. The CucorAl wire is bondable on Al surfaces as this finish is the standard finish for bond pads on dies used in DCB modules. The mAgic silver sintering paste provides stable bonding on Ag, NiAu or Pd interfaces, as these are standard finishes for dies and DCBs. Consequently, the material availability for semiconductors or DCB substrate would not be an issue, because the introduced mAgic sintering paste and the CucorAl wire are suited for a processing on standard interfaces.

Acknowledgments

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