# NEW INTERCONENNECTION FOR HIGH TEMPERATURE APPLICATION: HOTPOWCON (HPC)

Steffen Käss, Ph.D., Sebastian Fritzsche, Ph.D., Wolfgang Schmitt, Dipl. Ing., Jörg Trodler, Dipl. Ing.
Heraeus Deutschland GmbH
Hanau, Germany
Steffen.kaess@heraeus.com

Daniel Feil, Timo Herberholz, Ph.D.
Robert Bosch GmbH
Stuttgart, Germany

## ABSTRACT

An innovative interconnection technology developed in the public funded project 'HotPowCon' [7] is capable for resistant joints for SMT components, bigger dies, like MOSFETs or IGBTs and even large area substrates, like baseplate or heat sinks. The presentation showed that the combination of Cu Sn based alloys and Cu powder can increase the melting temperature to over 400 °C by creating intermetallic connections with technologies known from standard SMT reflow soldering. The CuSn intermetallic is grown by a two-paste system wherein the liquid solder paste infiltrates in a dried copper paste. By adjusting the copper particle distribution the presented diffusion soldering process can be used to produce currently large area contact of up to 1000 mm2. First results from power cycling investigations show a significant increase of lifetime compared to a SnAgCu305 solder paste. In addition several mechanical properties of the HotPowCon material were investigated. This allows to design future high temperature stable applications with a significant increase of robustness.

Key words: diffusion soldering, HotPowCon, intermetallic compounds, temperature resistive solder joint, large area contact, CuSn

## INTRODUCTION

The requirements of the joining technology in the field of power electronics gets more and more challenging. The joints varies between small area die connections from 10 to 100 mm² to large area cooler contacts bigger than 100 cm². For die attach the interconnections are exposed to high electrical currents and temperatures. Therefore the semiconductor materials and the substrate materials changes. The materials are developed for higher junction temperatures [1].

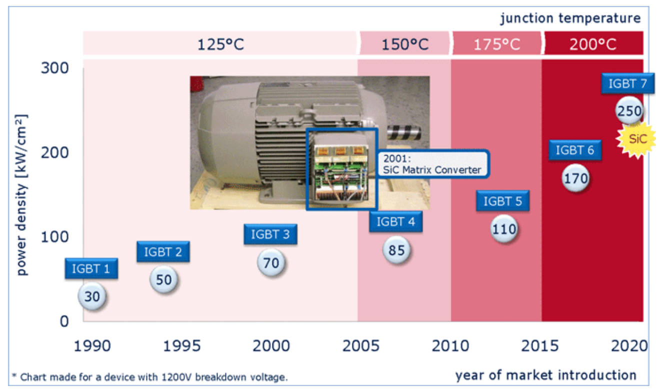



**Figure 1.** Road map of power electronics source Infineon.

This means that there is a need to follow this trends also in the joining technology.

For large area connections like base plate and cooler joints not only temperature stable joining materials are required. The material have to maintain a good thermal conduction. The areas to be soldered are larger than 100 mm2.

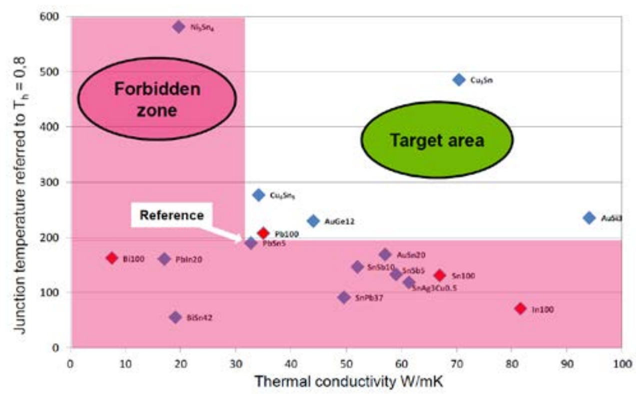



**Figure 2**. Comparison of operating temperature and heat Conductivity [1].

Figure 2 shows some intermetallic compounds (IMC) with a homologous temperature of a factor 0.8, in comparison with the thermal conductivity. The alloys in the reddish colored area are impossible to fulfill the requirements due to low thermal conductivity or low junction temperatures.

A possibility to solve this challenging requirements with manageable costs for die attach and large area connection are $Cu_3Sn$ or $Cu_5Sn_6$ intermetallic compounds. The process developed in the public founded project HotPowCon (HPC) [1] is based on a Cu paste which is infiltrated by a liquid solder. The formed matrix composite of Sn and CuSn and the required intermetallic compounds (IMCs). $Cu_3Sn$, $Cu_6Sn_5$ have a melting temperature of 676°C and 415 °C. With the HPC process it is possible to achieve temperature resistant joints while using state of the art manufacturing processes.

## DIFFUSION SOLDERING

### The HotPowCon Process

For using soft solder alloys based on solder paste there would be a possibility with a combination of thermal solidification and isothermal solidification of the CuSn alloy to achieve the preferred CuSn intermetallic compounds as illustrated in figure 3 with a diffusion soldering process.

In figure 4 the diffusion solder process, developed in the HotPowCon project is described schematically. It is based on a two paste system. The first step is printing the copper paste. The copper paste consists of a suitable copper powder and a vehicle which ensures the printability. The solder is placed adjacent to the copper. After melting the solder, the liquid alloy is able to infiltrate the paste, due to capillary forces inside the Cu paste. As solder material all Sn based and lead free materials which have a melting temperature above 200 °C, are suitable. A quite common alloy for this application is SnAgCu305. The soldering is carried out in an inert atmosphere with standard vacuum or reflow ovens. Formic acid at about 200 °C is used as activation medium. The peak temperature depends on the liquidus of the solder and is typically 240°C for SnAgCu305.

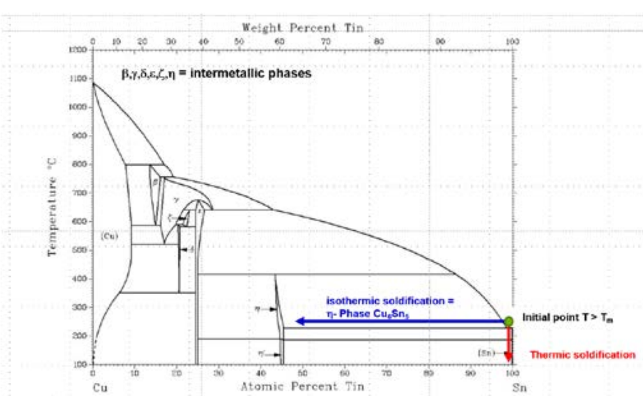



**Figure 3.** Cu/Sn Phase diagram [8].

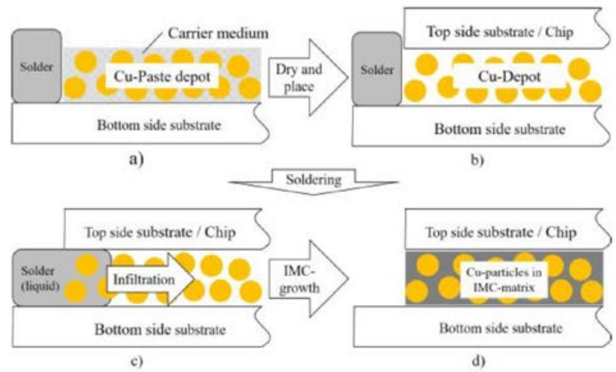



**Figure 4.** Principal of the diffusion solder process [2].

The Sn from the solder then isothermally solidifies to the IMCs $Cu_6Sn_5$ and $Cu_3Sn$. In figure 5 an exemplary micrograph of an infiltrated Cu paste is shown.

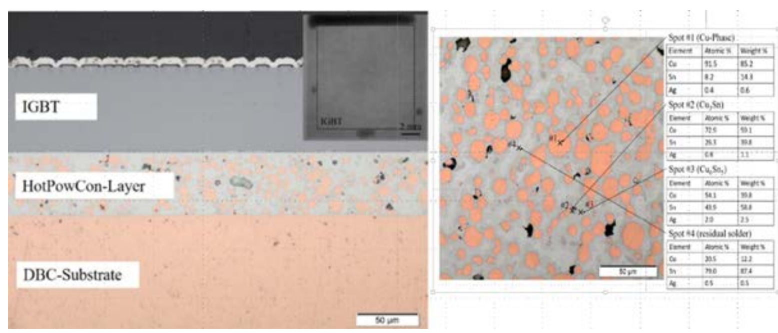



**Figure 5.** Exemplary micrograph of an infiltrated Cu Paste[2].

EDX-Measurements (energy dispersive X-Ray spectroscopy) show that the Cu particles are embedded by a thin layer of $Cu_3Sn$ followed by lager scallops of $Cu_6Sn_5$. The IMC interconnections and Cu particles attach the die with the Cu ceramic substrate. Also small areas of remaining Sn alloy and holes can be found, due to dense packed or not wetted Cu particles [2].

### The challenges of Sn infiltration

For the formation of HotPowCon solder joints especially for large areas, the Sn infiltration of the Cu depots are a limiting factor. The ability of the Sn infiltration is heavily dependent on the Cu powder and the vehicle composition. To get an impression of the influences of the Sn infiltration two kinds of test were developed.

A quick test to evaluate the principle infiltration behavior of the Cu powder [6]. Therefore a Cu paste is printed on a Cu substrate and a conventional available solder paste is printed over the Cu depots. After soldering with a defined profile the wettability of the solder paste is evaluated.

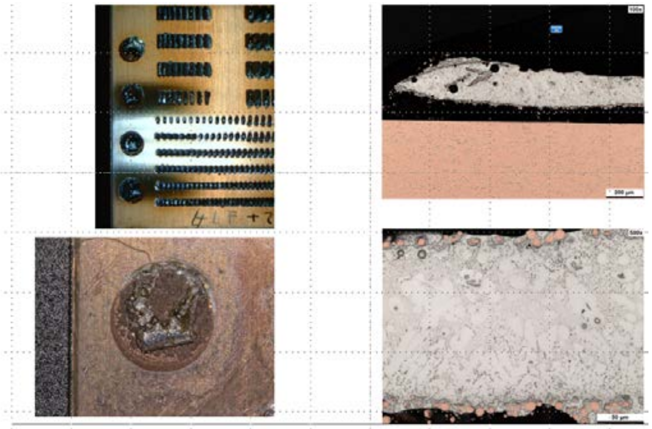


**Figure 6.** Not infiltrated Cu paste: left side: top view of wettability; right side: cross section of the wetted area.

Figure 6 show a bad wettability of the solder paste on top of the copper paste. Cross sections show that this bad wettability correlates to a not infiltrated system. The solder joints consists only on pure solder which can be seen in figure 6's cross section (right side). No intermetallic compounds are formed. The solder joint have no improved thermal resistivity. This copper powder is not suitable for the new joining material.

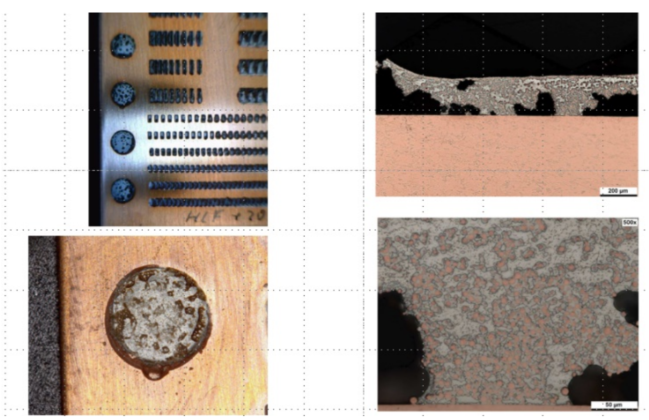


**Figure 7.** Infiltrated Cu Paste: left side top view of wettability, right side cross section of the wetted area

Figure 7 shows a good wettability of the Cu pastes. In the cross section (figure 7 right side) the IMCs around the Cu-particles pointed out that a satisfactory infiltration occurs. Due to the formation of the intermetallic compounds an improvement of the thermal resistivity is expected. This Cu powder is usable for infiltration of Sn alloys.

To measure the infiltration depth of the Sn based solders a test track of a printed copper depot with a length of 100 mm and a width of 10 mm is printed. The layer thickness of the Cu paste is 100 µm. After soldering with a SnAgCu305 solder alloy, with a formic acid activated solder profile, the infiltration range can be evaluated optically. Figure 8 shows an example of different infiltration rates. The left side show an incomplete infiltration meanwhile on the right side the complete test vehicle is infiltrated by the Sn alloy.

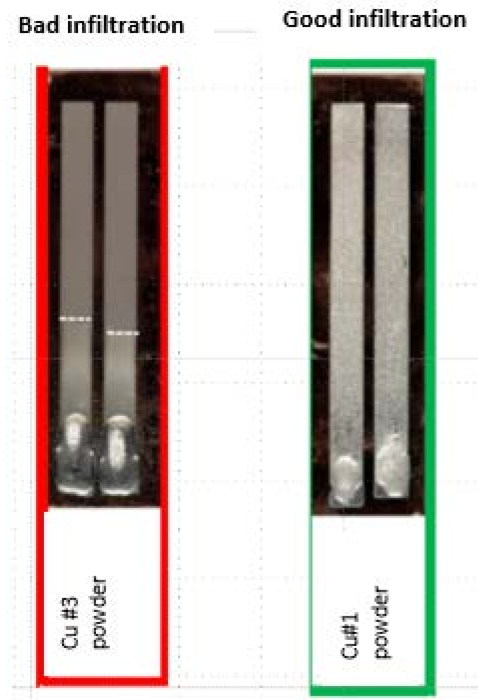



**Figure 8.** Evaluated Infiltration depth: left side: stopped infiltration; right side: full length infiltration.

Experiments with different particle size distribution (PSD), packing density and SSA of Cu powders (table 1) showed a different infiltration behavior (figure 9).

**Table 1.** PSD and SSA of different Cu powders.

| Cu-paste system | Size distribution (µm) | Packing density (%) | SSA ($m^2/m^3$) |
|---|---|---|---|
| #1 | 5 to 15 | 72 | 0.37 |
| #2 | 13 to 25 | 62 | 0.16 |
| #3 | 25 to 45 | 58 | 0.05 |

The infiltration depth is highly dependent on the choice of the respective Cu paste. A Cu paste system with high SSA, finest particle size distribution and high packing density (Cu paste #1) show the lowest infiltration whether Cu paste #3 with a low SSA, a coarse particle size distribution and low packing density show the highest infiltration rate of the Sn alloy. A reason for this is the packaging density of the different Cu powders or rather Cu paste systems. During infiltration the liquid Sn alloy enters the Cu depots. The channels between the Cu particles, in which the liquid solder is entered, are closed by the formation of IMCs. Due to a higher SSA there is more Cu surface provided to form the intermetallic compounds. This results in a retarded infiltration rate of the Sn alloy. For high infiltration rates Cu powders with a low SSA have advantages. However for temperature resistivity higher amounts of IMCs are necessary. As you can see in table 2 a Cu paste system with higher SSA have the biggest amount of IMCs due to the higher Cu surface area. On the one hand, for attachment of large areas a satisfactory infiltration is needed. But on the other hand more IMCs show higher temperature resistivity. To full fill all requirements there is a compromise between Cu powder #3 and #1 needed like Cu powder #2.

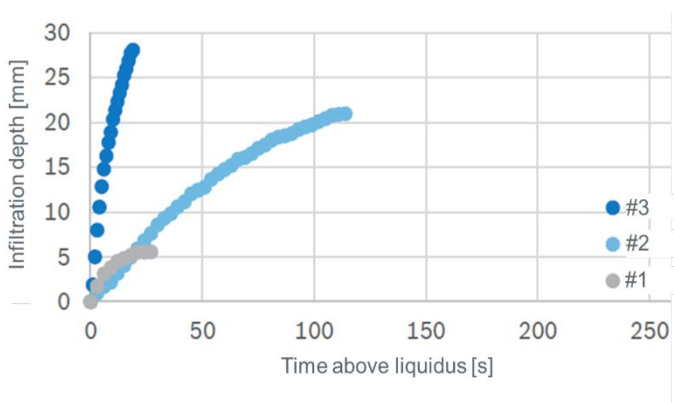



**Figure 9.** Infiltration depth as a function of Cu powder [2].

**Table 2.** Phase proportion of different Cu powders.

| Cu Paste system | Size distribution [µm] | SSA [m²/m³] | Cu-Phase [%Vol] | IMC [%Vol] | Residual solder [Vol%] |
|---|---|---|---|---|---|
| #1 | 5 to 15 | 0,37 | 15 | 63 | 18 |
| #2 | 13 to 25 | 0,16 | 31 | 47 | 16 |
| #3 | 25 to 45 | 0,05 | 41 | 25 | 33 |

Not only Cu powders have an influence on the infiltration depth (figure 10). The use of a resin activated solder paste decrease the infiltration capability of the liquid solder due to the closing of the infiltration channels by the resin. Hence a request of the paste system is to be resin free. The activation of choice, to prevent the SnO formation to ensure the melting of the alloy and to guarantee the wettability of the Cu particles, is gaseous formic acid at about 200 °C. Therefore the paste system doesn't need an activator.

**Paste requirements**

The fact that there is no resin and no activation in the paste system needed, leads to special paste requirements. One important parameter is the tackiness of the paste to avoid die tilt during the pick and place process. For tackiness measurements two different methods were chosen.

A measurement according ICP-TM-650 [5] with a Chatillion tackiness tester wherein printed circles of Cu paste are contacted with a plate and a force of 300 g is applied. The second method is a tackiness measurement with a cone plate viscometer. Therefore a printed Cu paste is contacted and the cone is replaced with a velocity of 25 mm/s. The needed force for the replacement is measured. The results of tackiness are illustrated in table 3. The measurements with the viscometer leads to results with lower standard deviations.

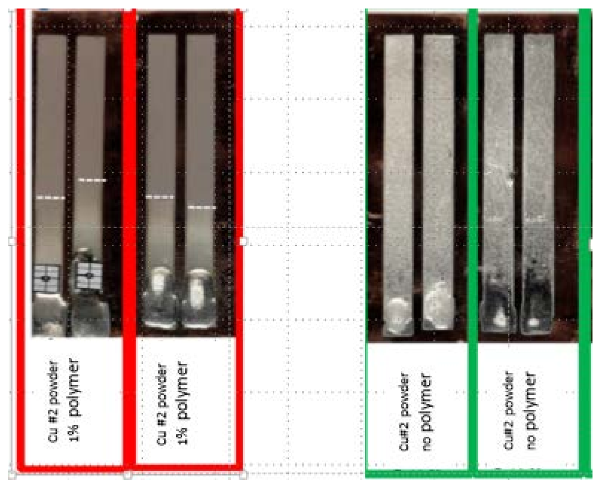



**Figure 10**: infiltration trials: with resins: left side and without resins: right side.

**Table 3.** Tackiness measurements of different solvent systems.

| Solvent system | Cu-Pastes | | | | |
|---|---|---|---|---|---|
| | Tackiness Chatillion (in gf) | SD Chatillion in % | Tackiness Physica (in N) | SD Physica In % | Viskosität (10 1/s; in Pa*s) |
| F645 (ref) | 206 | 33,5 | 38 | 1,2 | 120 |
| polar standard / unpolar standard | 159 | 20,1 | 13 | 1,1 | 116 |
| polar standard | 179 | 11,6 | 43 | 5,3 | 348 |
| polar standard | 179 | 17,4 | 43 | 5,1 | 90 |
| polar high / unpolar standard | 235 | 38,2 | 31 | 0,1 | 198 |
| polar high | 189 | 40,0 | 36 | 2,3 | 185 |

A comparable tackiness to a standard, resin based paste system, can be achieved with polar solvent systems. There is no correlation between viscosity and tackiness.

Samples of these paste system were built up with the HotPowCon diffusion soldering process. First results without drying the Cu paste show the typical HotPowCon solder joint but the resulted drying channels are filled with residual solder which leads to a non-uniform die attachment (figure 11).

Infiltration experiments after dried Cu paste results in improved solder joints (table 4) however the tackiness of the Cu pastes decrease which causes die tilt problems. The preferred solvent system is a polar solvent with a high boiling point compared to the standard system used during the HotPowCon project. The quality of the solder joints is also dependent on the application. A double sided or over etch placed solder pastes leads to a better solder joint with less voids. (Exemplary samples showed in figure 12).

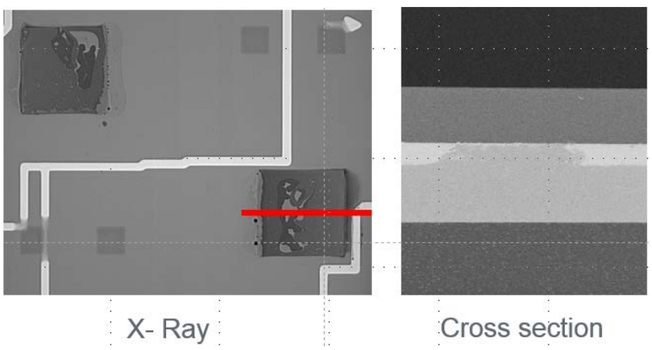



**Figure 11**: Exemplary X-Ray (left side) and cross section (right side) of HotPowCon joint without drying the Cu-Paste.

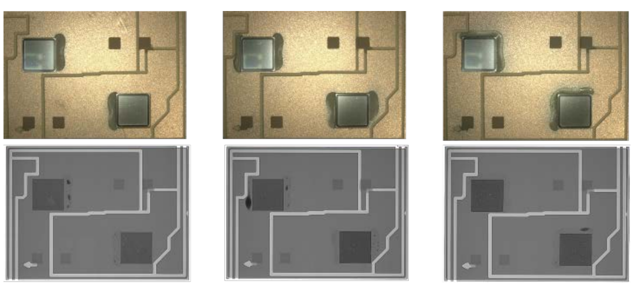


**Figure 12.** Exemplary samples with different solder application. Left: one side application, middle: two sided application, right: over etch application.

**Table 4.** Results of HotPowCon solder joints with dried Cu-Paste.

| Solvent systems | Cu-Pastes | | | |
|---|---|---|---|---|
| | X-Ray Evaluation Solder paste placed one side | X-Ray Evaluation Solder paste placed double sided | X-Ray Evaluation Solder paste placed over etch | Die tilt |
| polar (HotPowCon ref )/ none polar standard HotPowCon ref) | 😐 | 😐 | 🙂 | 😐 |
| Polar (HotPowCon ref ) | 😐 | 😐 | 🙂 | ☹️ |
| polar high bp/ none polar (HotPowCon ref ) | 😐 | 🙂 | 🙂 | 😐 |
| polar high bp | 😐 | 🙂 | 🙂 | 😐 |

However the dried Cu paste are less tacky than the wet pastes, which results in problems with a die tilt in x-y direction. With the current 2 paste systems good HotPowCon like joints can be formed. Nevertheless some improvements like tackiness of dried Cu-Paste have to be applied. Another possibility could be an improvement of the drying procedure after the die or base plate is placed on the Cu paste.

**Mechanical properties**

The above mentioned solder joint leads, as already explained, to a composite of Cu particles, intermetallic compounds and residual solder. Therefore the influence of the different paste systems with their varying phase compositions on the bulk mechanical properties are investigated [2]. Tensile strength of HPC samples were measured. The bulk material were prepared by filling a two component mold by Cu powder. The infiltration was done with molten SnAgCu305 and the above mentioned solder profile. The samples were unmolded and residual solder were grinded.

First tensile tests at room temperature with a share rate of 3 x $10^{-3}$ $s^{-1}$ shows different stress stain curves. Exemplary curves are illustrated in figure 13. The plastic behavior of this three system is quite different. For the System #1 there is measured a more brittle behavior than for system #3. This can be explained by the higher amount of intermetallic compounds in #1 (see table 2). The higher ductility of #3 is a consequence of the higher amount of residual solder and Cu particles. Powder system #2 is laying between #1 and #3 and is a good compromise having a residual amount of ductility to overcome mechanical stress peaks and high stiffness to bear overloads [3].

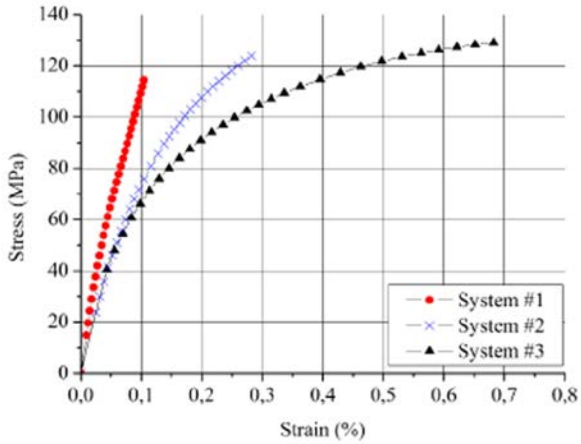



**Figure 13.** Stress strain curves of different Cu powder systems [2], [3]

**Reliability of HotPowCon joints**

For first investigations of the reliability of HotPowCon joints the following test vehicles were built. An IGBT with 16 AlCu Ribbons and a Cu-DCB substrate was soldered respectively sintered with different die attach materials. As solder alloys SnAgCu305 and SnSb5 was used. Additional IGBTs were attached with silver sintering. Last but not least the die attach was done with the HotPowCon process. For testing the reliability temperature, controlled power cycling with a $\Delta T$ of 130 K and a $T_{max}$ of 175 °C was preferred. The on time of the current was 3 s and the off time 4 s. For the evaluation the $Z_{th}$ and Bond drift was measured (see table 5).

**Table 5:** Measuring and failure mode of Power cycling test [4].

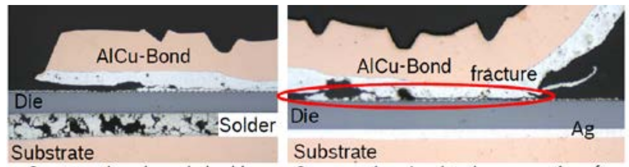
| Measurement | Failure condition | Expected failure mode |
|---|---|---|
| Zth / Rth | 20% drift in die area | Die-attach failure |
| Rbond | 5% drift | Bond-failure |

The results of this reliability tests were illustrated in table 6. The reliability of the power cycled substrates with HotPow-Con joining material show comparable results to silver sintering. For both materials a bond lift off was detected.

**Table 6:** Power Cycling results of different die attach material [2].

| Die-attach | avg. cycles till failure | Failure mode |
|---|---|---|
| SnAgCu305 | 25 k | Die-attach failure |
| SnSb5 | 26 k | Die-attach failure |
| Sinter-Ag | 364 k | Bond failure |
| HotPowCon | 273 k | Bond failure |

The life time with sintered and HotPowCon soldered die attach material increase about 10 fold towards the solder materials. The die attach material was not degraded after the life time of the test vehicles which means the wire bond is the weakest connection of this system. For the SnAgCu305 and the SnSb5 solder alloys the failure mode is a degraded solder connection. Thermal shock tests are currently under work.




Cross-section: degraded solder connection after power cycling

Cross-section: Ag-sintering connection after power cycling with bond failure.

**Figure 14**. Failure modes after power cycling.

With the HotPowCon die attach material a high reliable solder joint comparable to silver sintering can be achieved.

**CONCLUSION AND OUTLOOK**

It has been demonstrated that with the HotPowCon process a new innovative joining technology was developed. The die attach is realized by a defined process based on a 2 paste system with state of the art manufacturing equipment. The innovative material is a composite of Cu particles as well as intermetallic compounds especially $Cu_3Sn$ and $Cu_6Sn_5$, formed by isothermal solidification after a commercial available Sn based solder alloy is infiltrated in a Cu depot.

Not all Cu powders are able to form the composite material. This can be tested with a quick wettability test. The infiltration rate of liquid solder, which is the key parameter to attach areas bigger than 1000 $mm^2$ depends on the particle size distribution or the Cu powders. Smaller particle sizes leads to a decreasing infiltration depth. To get a satisfactory amount of intermetallic compounds (high temperature resistivity) and a good infiltration depth a middle particle size distribution will be the Cu paste system of choice.

The resins also decrease the infiltration rate. Despite a lack of resins in the organic vehicle systems, the Cu pastes needs to fulfill special requirements like tackiness. A polar solvent system with higher boiling point, as in the HotPowCon project used, looks promising. Currently the Cu paste have to be dried to avoid drying channels. This leads to die tilt problems during the process due to the lack of tackiness of the dried Cu paste.

Investigations in the tensile strength show that a middle powder size distribution should be preferred to have a residual amount of ductility overcome mechanical stress peaks and high stiffness to bear overloads. First power cycling tests of the new material show that the HotPowCon joints have comparable life times as silver sintering.

In the HotPowCon project a new high temperature stable material is developed. The high infiltration rates allow to join big areas. To check the full possibilities of this material further investigation have to be done. Interesting is the behavior of this composite material in thermal shock tests. Improvements of the Cu paste especially in terms of tackiness have to be realized. Further intensive work is ongoing to get a better understanding of joining big areas like base plates.

## REFERENCES


[1] A. Fix et al, “HotPowCon”, Hot-Power-Connection, Fügewerkstoff-, Verfahrens- und Anlagenentwicklung zum Aufbau neuer elektronischer Leistungsbaugruppen für elektrische Antriebs- und Energiemanagementkonzepte mit Betriebstemperaturen bis 300°C für Elektrofahrzeuge, für das BMBF Ausschreibung vom 1.4.10 HPC

[2] D. Feil, et al. Highly variable Sn-Cu diffusion soldering process for high performance power electronics, Microelectronics Reliability (2017)

[3] D.Feil et al EBL 2018

[4] LV 324, qualification of power electronics modules for use in automotive components, general requirements, test conditions and tests, 6.2.2014

[5] IPC-TM-650

[6] Trodler et al; Method for producing a soldered Connection; patent WO2016030287A1

[7] Fix A., Herberholz T. Method for creating a soldered connection and circuit component. European Patent EP2713685. 2014.

[8] A. Fix et al EBL 2014.