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Thermal Stability of Intermetallic Cu–Sn Interconnections for High Temperature Applications

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Abstract—**New technology based on mixing of standard alloy SnCu in form of solder paste with copper paste was presented. This technology allows the production of solder joints with higher stand-off consisting of intermetallic compounds. Such solder joints were qualified for high temperature applications by investigation of thermal stability of overlapped solder joints. For this purpose a special test bench for the investigation of remelting temperature up to 300°C was developed.**

Keywords—**Intermetallic phase, composite solder material, remelting temperature**

INTRODUCTION

The trend for power electronics based on direct copper bonding applications with mounted insulated-gate bipolar transistor components will result in increasing of temperature more than 200°C for the next 10 y. For soldering technology there are no suitable alloys in the form of solder pastes for an operation temperature of more than 250°C (Fig. 1). There are some alternative alloys available on market with melting temperatures higher than 250°C but they have significant disadvantages such as high cost (Au-based), toxicity (Pb-based), or insufficient wetting properties (Zn-based). The operation temperature based on the homolog temperature should have a factor to the melting temperature not more than 0.8 [1].

For using solder alloys based on a solder paste there would be a possibility with a combination of thermal solidification and isothermal solidification (Fig. 2). Such technologies are known under the names solid–liquid interdiffusion (SLID) and transient liquid phase soldering (TLPS) [2]. Both of them are limited by the stand-off height of solder joints which has to be very small (under 10 μm) for the realization of such an intermetallic connection. Because of this limitation, the electroplated solder layer or a thin solder preform is normally used. Smaller stand-offs result in higher thermomechanical stress and can be a reason for earlier failure of the connection due to solder creeping and crack growing.

In this article, the investigation of new technology based on the mixing of standard alloy SnCu in the form of a solder paste with copper paste is presented. This technology allows the production of solder joints with higher stand-offs consisting of intermetallic compounds to increase the thermomechanical stability of the solder joints. Such solder joints were qualified for the high temperature applications by investigation of thermal stability by measuring the remelting temperature.

SOLDER MATERIALS

As part of German founded project for new technology in the automotive market together with high power modules for e-mobility (HotPowCon [HPC]), a new technology based on the mixing of standard alloy SnCu in the form of a solder paste with copper powder or rather copper paste was developed [3, 4]. This technology enables the production of intermetallic interconnections with standard parameters of soldering of SnCu solder paste. The produced solder joints consist of homogenously distributed copper particles surrounded by grown together SnCu intermetallic phases (IMPs). This enables higher stand-offs in contrast to SLID and TLPS technologies.

There are two binary Sn–Cu IMPs that can be produced during standard soldering process, namely, copper rich ε-phase Cu_3Sn and tin rich η-phase Cu_6Sn_5. The melting temperatures of these are 676°C and 415°C, respectively. The eutectic solder alloy SnCu has a melting point of 227°C (Fig. 3).

PRODUCTION OF INTERMETALLIC CONNECTIONS

Solder material can be produced by mixing of standard SnCu solder paste with copper powder and then applying it on the board by stencil printing. Such composite material system will work with usual single stencil printing process but is limited by the amount of copper particles inside. It was possible to add up to 20 wt% of copper but this amount was not enough to create the intermetallic connection bridging over the whole stand-off of the solder joint [4]. However, higher amounts of copper can lead to imperfections in the solder joint such as large voids (Fig. 4).

To increase the proportion of copper it was decided to apply copper and solder paste in two separate stencil printing processes. Practically, it was realized by using stepped stencils. In the first step, the copper paste (mixture of pure copper particles with the size 5-15 μm and solvent) was printed on the contact pads with the thickness of 100 μm, and in the second step, the standard solder paste SnCu1 (particle size 20-38 μm) was printed with the thickness of 200 μm and close proximity to the copper prints. By varying the area and volume of the prints, the required proportion can be reached. The main process steps are

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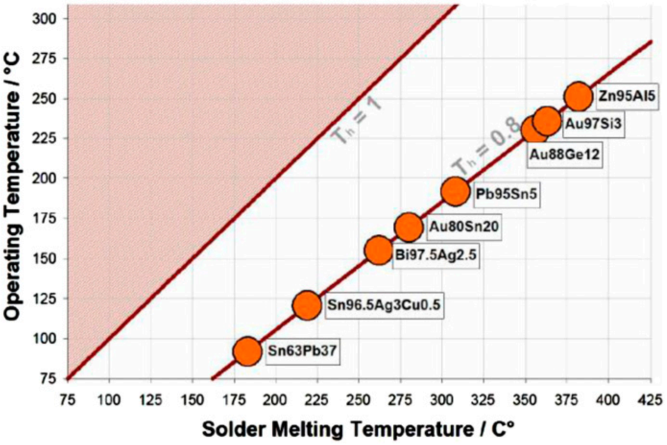

Fig. 1. Melting temperature of soft solder alloy vs. operation temperature in consideration of the homolog temperature 0.8 [1].

demonstrated in Fig. 5. In this simplified technology demonstrator, two pieces of PCB, one as substrate and one for chip (10 × 10 mm), were connected. The stand-off of the final solder joint is at least defined by the thickness of printed copper paste.

The advantage of this technology is that the reflow soldering can be realized in the convection oven with standard lead-free reflow profile (Fig. 6) without additional postheating at higher temperature.

During reflow process infiltrates solder at liquid state almost completely the printed matrix of copper particles driving by capillary forces and wetting them. During peak soldering zone the IMPs grow on the surface of copper particles so that the connection solidifies on the isothermal way (Fig. 7). The requirements for this are the sufficient amount of copper and as a result relatively short distance between copper particles.

In an ideal case, the whole solder material penetrates into the copper matrix during melting and builds at the end composite solder interconnection consisting of homogenously distributed copper, copper-rich and tin-rich IMPs, and remaining solder alloy (SnCu) with a relatively low amount of imperfections such as voids.

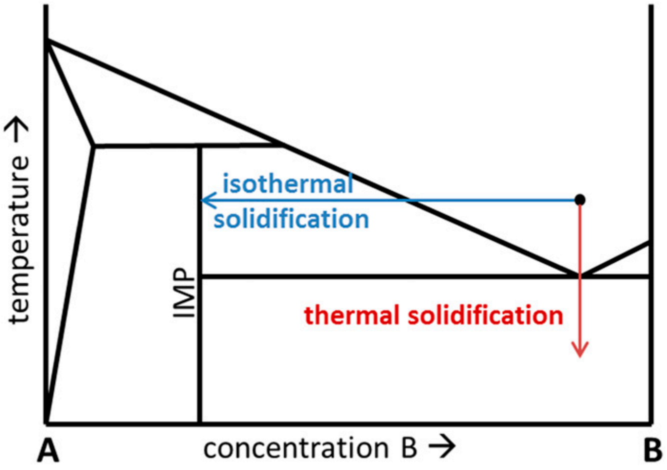

Fig. 2. Solidification of eutectic binary alloy with the formation of IMP [3].

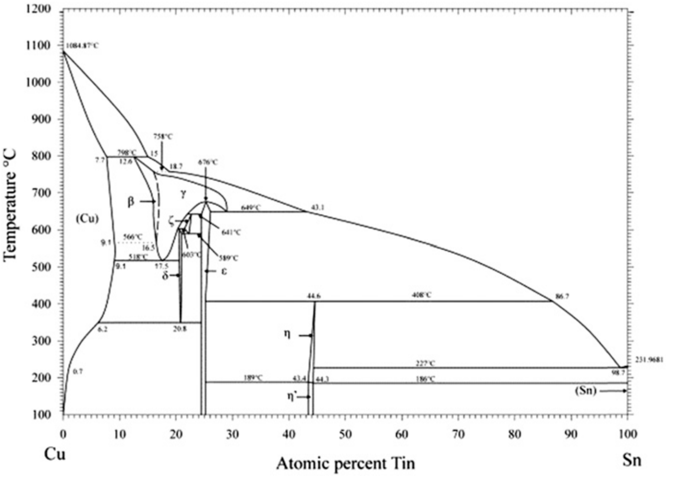

Fig. 3. Phase diagram of binary Sn–Cu alloy.

The thermal stability of the solder joint that can be defined by remelting temperature will be reached by the growing together of intermetallic compounds (Fig. 8, middle grey color) surrounding the copper particles (Fig. 8, dark grey color) and the IMP of the surface of contact pads so that a complete stand-off will be bridged by intermetallic compounds at different positions. There are still some areas that are filled with the original alloy, e.g., SnCu1 (Fig. 8, light grey color), but they do not influence the remelting temperature of the whole solder joint.

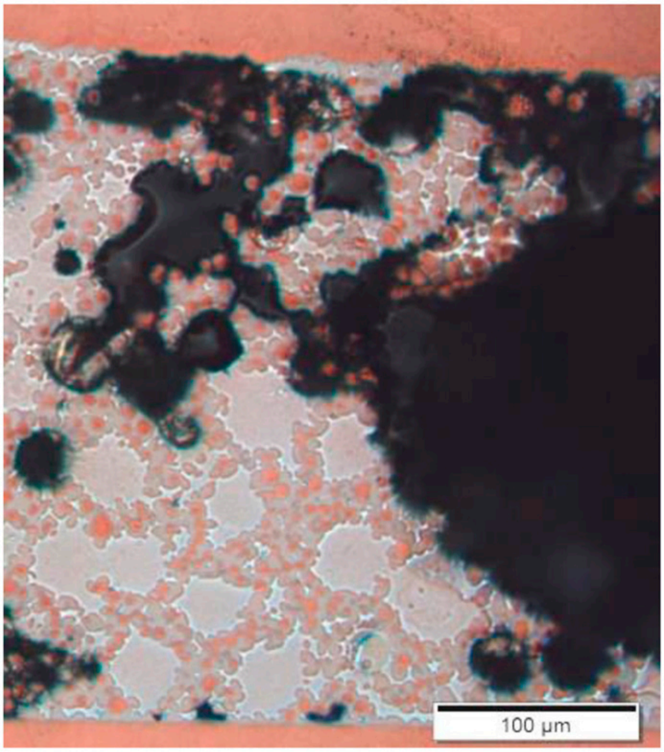

Fig. 4. Cross section of solder joints with more than 20 wt% of copper [4].

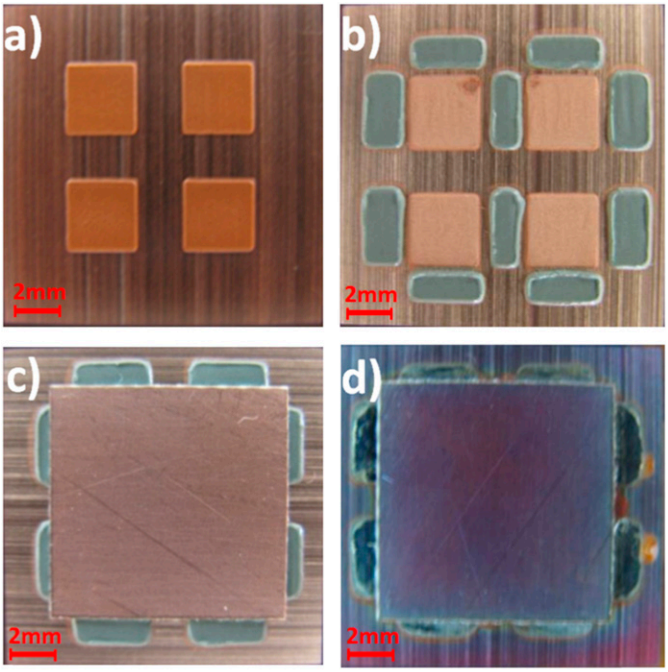

Fig. 5. Production of intermetallic connections: (a) printing of copper paste, (b) printing of solder paste, (c) placing the chip, and (d) after soldering.

THERMOMECHANICAL TEST AND REMELTING TEMPERATURE

For the thermomechanical investigation of intermetallic solder connections, a test method was developed in [5] to determine the remelting temperature of samples.

The remelting temperature of the composite soldering material is generally defined by a low-melting phase. For homogeneous soldering materials the remelting temperature is defined by melting of the grain boundaries that can be lower than the solidus temperature of the solder alloy [6]. Such behavior is based on the different chemical compositions of the grain boundary in comparison with the grain volumes. When the remelting temperature is reached, the grain boundary film is melted, and the soldered joint is destroyed as a result of an intercrystalline brittle fracture when a mechanical load is applied [6].

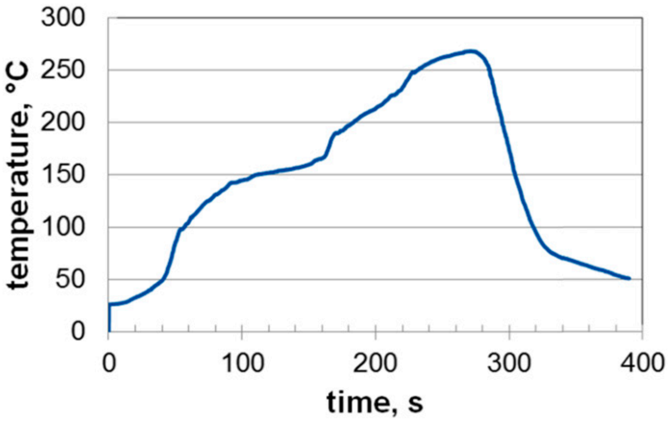

Fig. 6. Reflow soldering profile.

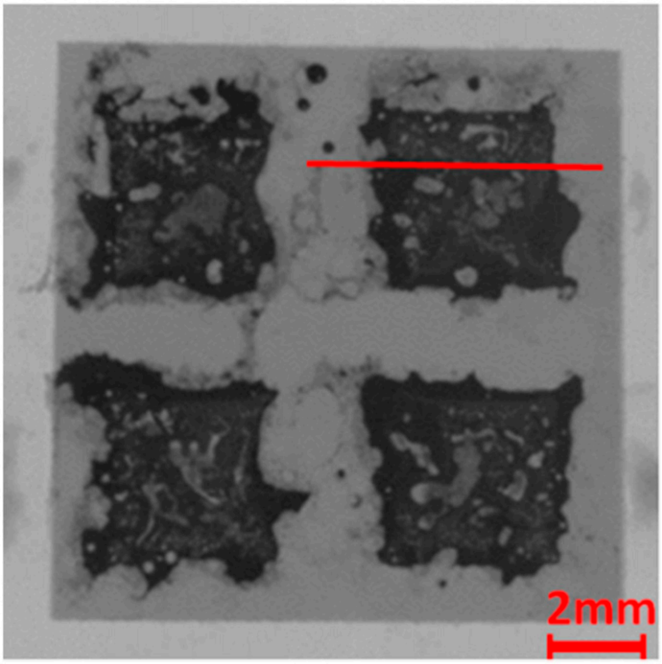

Fig. 7. x-ray image of an intermetallic connection (red line marks the cross section position).

The remelting temperature of soldering and brazing alloys is currently determined and standardized only in the state Russian GOST standard [7]. Based on requirements described in this standard the test method for the determination of remelting temperature was developed at the Institute for Electronic Appliances and Circuits at the University of Rostock [5].

A forced convection oven of type N30-45HA from the company Nabertherm was used to set the environmental temperature. First, the solder joints should be tested for remelting temperatures of up to 300°C, which requires temperature stable materials for test equipment and measuring cables. Solder joints should be static loaded with shear force by different weights.

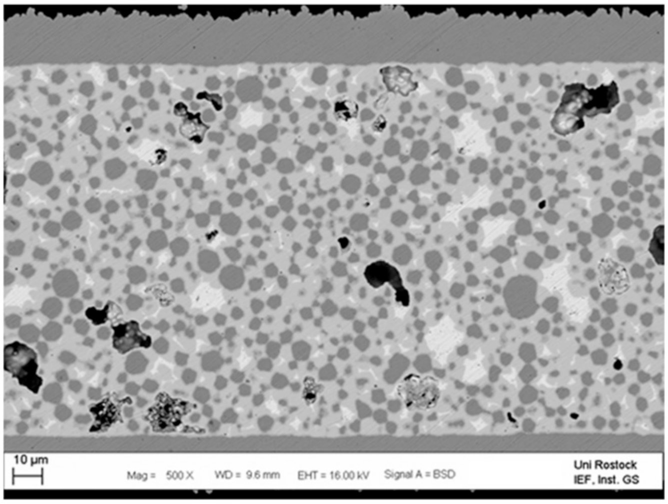

Fig. 8. SEM image of a cross section of an intermetallic connection.

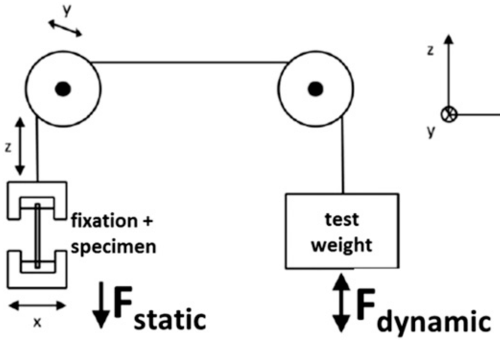

Fig. 9. Principle of investigation of remelting temperature [5].

Because the chamber space is limited, the samples will be loaded by weights over deflection rollers (Fig. 9 and 10). In this way up to three samples can be analyzed simultaneously in one test cycle to get a minimal data for statistical evaluation.

Test sample consists of two copper substrates (dimensions: $25 \times 5 \times 1$ mm^3) with overlapping soldering connection (area: 25 mm^2) made from standard solder alloy in the form of solder paste or preform or from modified composite solder material for production of intermetallic connections. The holes at the ends of the substrates serve for clamping with the sample holder and test weight (Fig. 11).

After first tests with one stencil printing step the application of soldering material was changed in similar way like on the PCB demonstrator. Copper paste was printed on the connection area (ovelapping area) and solder paste was dispensed close to the gap, so that it can infiltrate the copper prints and build intermetallic connection (Fig. 12).

Fig. 10. Chamber with test equipment and samples.

Fig. 11. Test samples after soldering.

Large area of solder connection, limitation of soldering time and infiltration only from one side (direction is marked with arrow in Fig. 13) restrict the complete filling of copper particle matrix. Intermetallic compounds start to grow immediately after wetting, so that the isothermal solidification decelerates the infiltration process. Partly filled connections fulfill the goal anyway although with reduced connection area.

The mechanically fixed specimens are electrically contacted at both ends. This is used to get a signal to the control unit outside the oven, which can be used to measure whether and for how long the sample pieces are connected by the solder joint (mechanical and electrical). In addition, a thermocouple (type K) on a reference sample (mechanically unloaded) detects the temperature in the oven and passes it on to the control unit. When a test cycle is started, the oven continuously heats up to 300°C. During this time, each sample is loaded by a 1 kg test weight. Relative to the area of the soldered connection (in case of complete wetting or infiltration), a shear stress of approx. 0.4 MPa is set. When the furnace has reached the remelting temperature of the solder joint, the solder joint breaks and the electrical contact is interrupted. The control unit records the time and temperature of the soldered sample (Fig. 14).

As the test is constructed for temperatures up to 300°C, it is possible to measure the remelting temperature lower than this value or to get the verification for thermal stability up to 300°C. That was proved for samples with different soldering times, with variation of copper print thickness (between 50 and 100 μm) and two different solder alloys: eutectic SnCu and eutectic SnAgCu. All of these samples can withstand the mechanical load at the temperature of 300°C for 3 h that confirms the bridging of the solder gap by intermetallic compounds.

It has to be mentioned that the remelting test conditions such as temperature and time have an influence on the structure of the

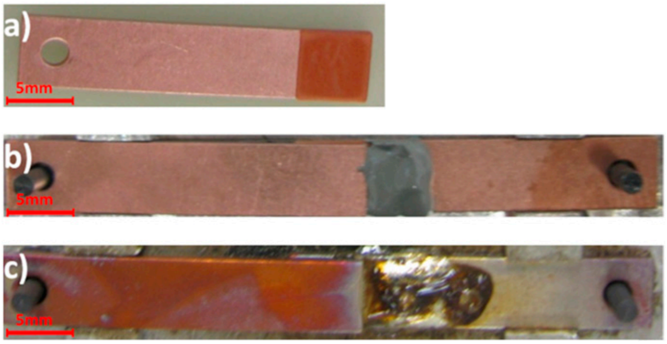

Fig. 12. Production of intermetallic connection of the remelting test sample: (a) printing of copper paste, (b) dispensing of solder paste, and (c) after soldering.

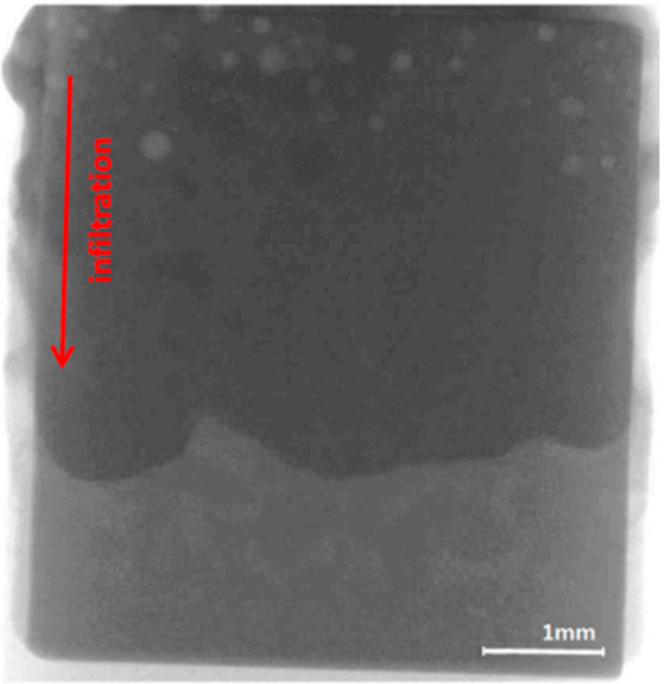

Fig. 13. x-ray image of intermetallic connection of the remelting test sample.

solder joint and intermetallic connection as the diffusion is driven by these parameters. It means that the sample is changing during the test. In case of Sn–Cu binary intermetallic compounds, the tin-rich phase transforms to the copper-rich phase, provided enough copper is available. This is illustrated in Fig. 15 exemplary with a sample after 3 h at 300°C.

This transformation further increases the remelting temperature because of the higher melting temperature of the copper rich intermetallic compound.

For the measurement of the remelting temperature greater than 300°C, a simple test bench outside of the oven was constructed and realized. In this bench the solder joint was loaded also by weights (without deflection roller), and the heating was performed by a blowlamp (Fig. 16). In this simple way, the remelting temperature of the solder joints can be tested up to 800°C. Another advantage of this method is the very high heating rate of up to 40 K/s so that the influence of test conditions on the structure of solder joints is minimized.

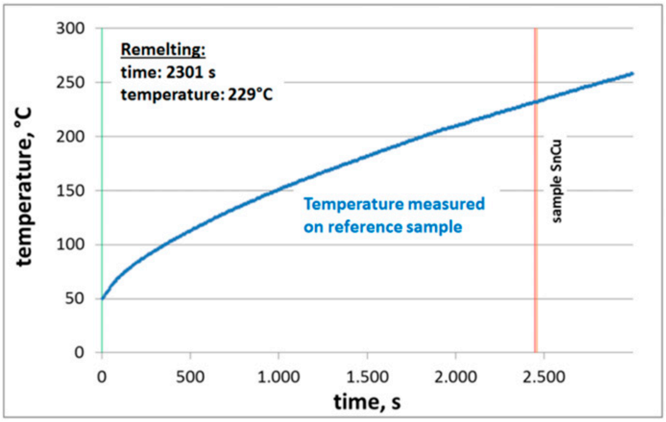

Fig. 14. Measured remelting curve of standard SnCu1 solder joint.

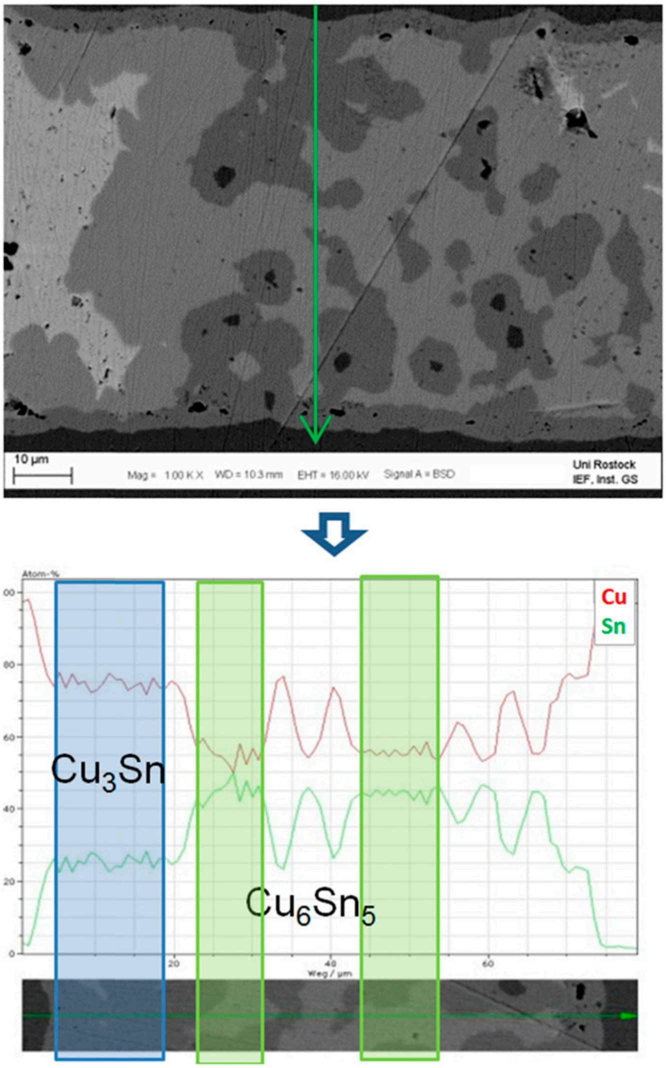

Fig. 15. SEM/EDX image of cross section of intermetallic connection after remelting testing.

In Fig. 17 one can see the measured curves (temperature over time) during the heating of samples. The temperature drop indicates the remelting of the solder joint. The difference between two samples can be explained by the domination of the intermetallic compound in the solder joint. The solder joint with dominating tin-rich IMP remelts at 441°C, whereas the solder joint with dominating copper-rich IMP remelts at 651°C.

SUMMARY AND FUTURE WORK

In this article, the technology for producing of intermetallic connections that was developed as part of founded project for new technology in the automotive market together with high-power modules for e-mobility (HPC) was presented. In contrast to other SLID and TLPS technologies, this technology enables higher stand-off of solder joints by printing copper paste and solder paste with close proximity and infiltration of the solder into the copper paste matrix during melting. The technology was

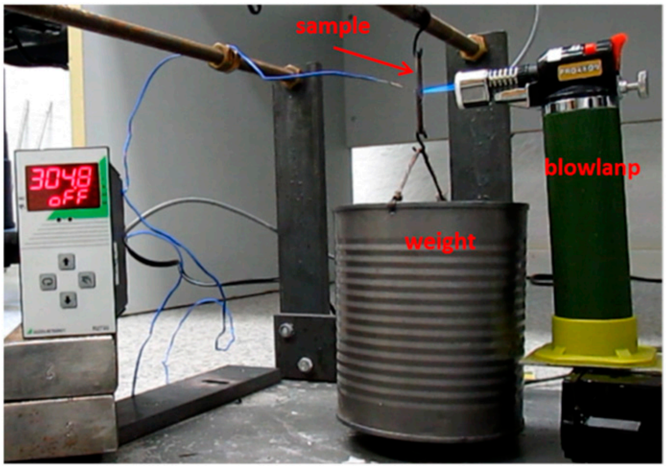

Fig. 16. Test for testing of remelting temperature.

successfully transferred to industrial soldering process of electronic components on standard printed circuit board.

Such intermetallic connections are suitable for high temperature applications. This was proved by the investigation of remelting temperature and thermal stability of the solder joints. The developed bench for the testing of remelting temperature of the solder joints was presented. According to the requirements of the founded project, it was constructed for testing up to 300°C. In the simplified form and local heating of the samples, it is possible to test the solder joints up to 800°C.

The higher melting temperature of Cu–Sn compounds on one hand but also their brittleness on the other hand have to be considered during designing the electronic modules and reliability testing. Thermomechanical stress that is normally reduced through plastic deformation of solder material will remain in intermetallic connections and also transfer to substrate and chips. This can lead to new failure phenomena.

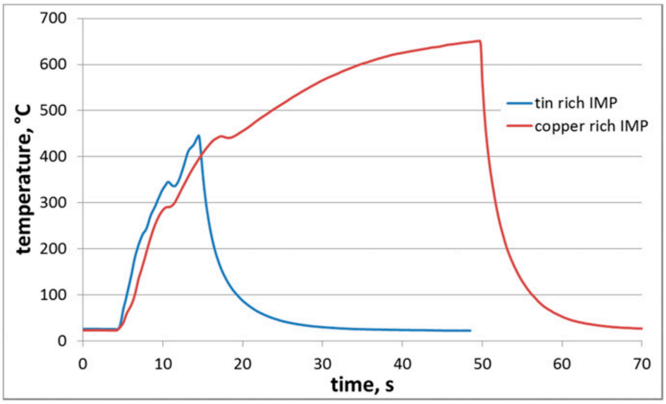

Fig. 17. Investigation of remelting temperature of intermetallic connections.

In future work other intermetallic connections can be produced in this way, and its thermal stability can be investigated with the help of the developed bench construction.

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