Assembly Materials for High Temperature Application

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Abstract
Based on the trend for new technology in the automotive market including high power modules for e-mobility, and a combination of logic and power which will be developed for the future market with economic, safety and reliability effects.
One of the most important challenges are electrical systems and the realization of complete energy management. The connection between sensor, logic and control units, as well as power transmission for electrical vehicles, is the assembling technology for electronics (eAVT).
This paper will discuss and show results of reliability with soft soldering alloys (based on lead free) for higher temperature (>125°C - 175°C) as well as possibilities for different applications. Therefore, it will present the basis of the material and the realization for processes for the e.AVT. Furthermore alternatives and development stages for temperature more than 200°C will be discussed

Introduction
CO2 and reduction of dust as well as saving of energy and efficiency are basis elements for climate, environmental and saving of resource. The results for that target collected the main requirements for efficiency, reliability and cost effectiveness for the assembled electrical devices.
One of the most important challenges are electrical systems and the realization of complete energy management. The connection between sensor, logic and control units, as well as power transmission for electrical vehicles, is the assembling technology for electronics (eAVT). An example of a power module, figure 1.

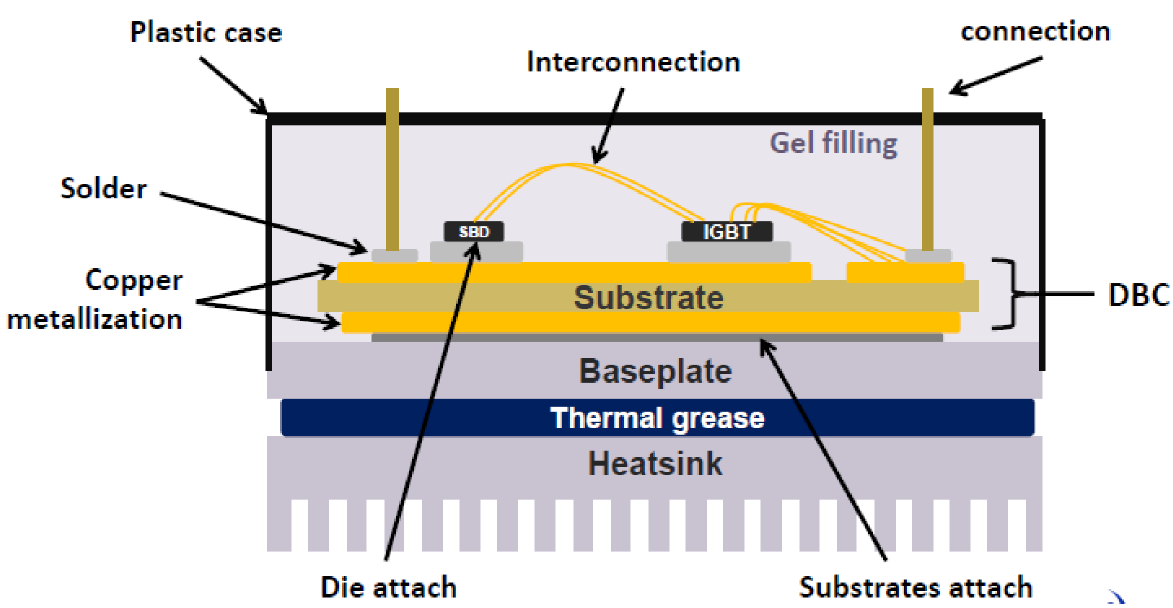


Figure 1 Assembly of a power module

Substantially for power devices as well as the combination with logic are the follow requirements:

- High power density
- High reliability
- High heat Conductivity
- Ambient condition more than 150°C
- Lead Free technology
- Life time more than 15 years
- Costs
- Combination Power and Logic

The total of all requirements needs assembly materials with improved properties.

As state of the art for power modules preforms and/or solder paste are based on eutectic Thin/Silver (SnAg3.5) or Thin/Silver/Copper (SAC) with 3 or 4% Silver. Especially the eutectic SnAg3.5 alloy has worked in a condition up to 125°C for years. For temperature above 125°C alternatives can be used:

- Special alloys for soft soldering e.g. HT1
- Sinterpaste / Sinteradhesive
- Diffusion soldering e.g. HotPowCon (HPC)

Soft solder Alloy

The table in Figure 2 shows a list of soft solder alloys that already in use for the electronic. All alloys are based on Tin (Sn) and aren't a low temperature alloy like SnBi.

Table 1: Table of soft solder alloy for the electronic

Alloy	Melting-Temperature [°C]	Remark
Sn96.5 Ag3.5	**221**	SnAg eutectic
Sn96.5 Ag3 Cu0.5	**217**	SAC Standard-alloy Under eutectic
Sn95.5 Ag4 Cu0.5	**217**	SAC with 4% Ag, above eutectic
InnoRel Innolot® Sn Ag3,5 Cu0,7 Ni0,125 Sb1,5 Bi3	**206-218**	Higher reliability on pcb Higher operation temperature, e.g. 150°C
InnoRel HT1 Sn /Ag2, 5/Cu0,5/In2/KM[2)]	**210-217**	Higher reliability on TF and DCB Higher operation temperature, >150°C

SAC alloys use for standard application on organic substrates (pcbs) in the electronic for years. The eutectic SnAg3.5 are mostly used for thick film application (TF) as well as power electronics based on direct copper bonding (DCB) for temperatures up to 125°C, in some applications even higher. The application field for Innolot on pcbs is a temperature up to 150°C as well as a higher number of cycles [1 till 3] on organic substrates (pcbs). But for power or TF applications Innolot is not possible. In such applications the HT 1 alloy has been developed.

Metallurgical Aspect for HT1

Based on an investigation for BGA balls an alloy has been developed for increasing the resistance of thermal cycling with higher temperature differences. Due to the fact that for BGA balls it needs a high quantity of Ag inside, therefore it wasn't possible to realize a powder production for soft soldering alloys, because it Ag3Sn intermetallic had been created during the process, figure 3 and figures 4 a till e.

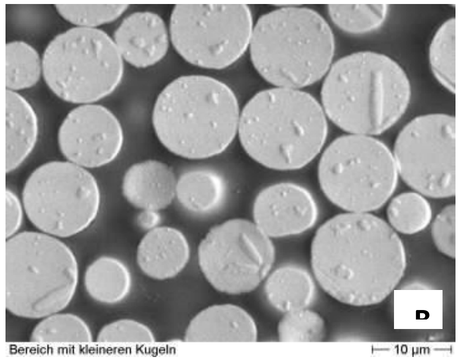


Figure 3: Cross section after powder production (source: Müller, NMB 160804)

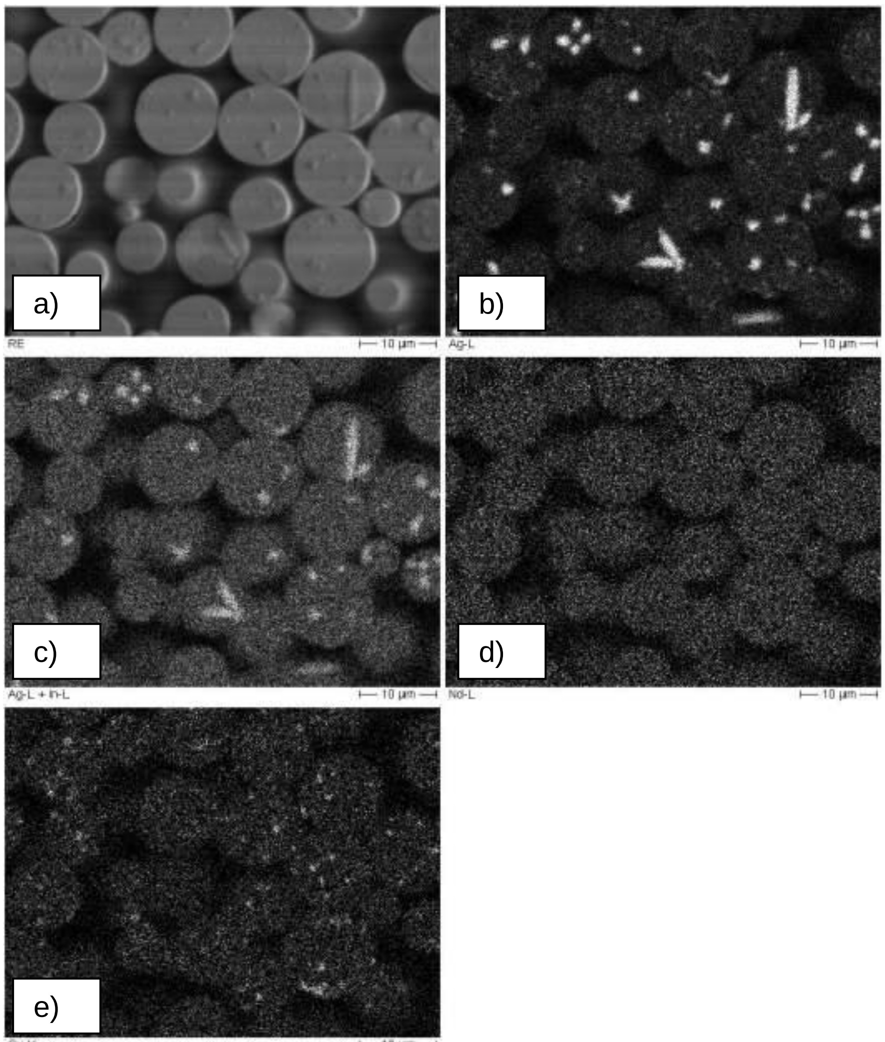
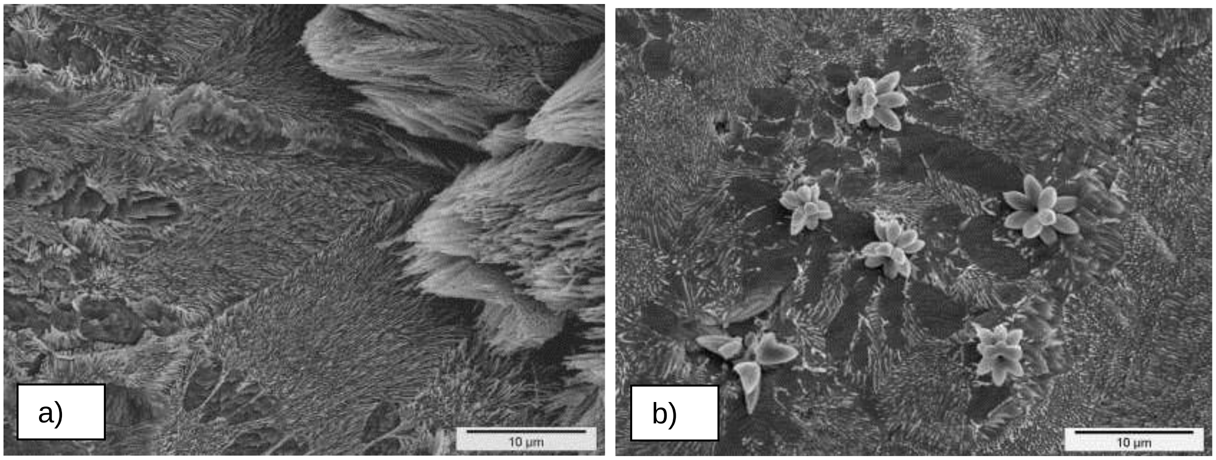


Figure 4: a till e Mapping of the powder; figure b Ag (=Ag3Sn) (source Müller, NMB, 160804)

The first modification for changing the Ag3Sn structure was developed by using a crystal modification. Figures 5 a and b compare the structure with and without that modifiers (KM).



Figures 5 a and b, a) SAC + In (without modifier) and b) SAC+In+KM (source Müller, NMB, 160804)

One major advantage is that the structure of critical Ag3Sn intermetallic has changed to three dimension structures (star structure). One of the ideas for this phenomena is the critical nucleus radius due to the fact that Ag3Sn and NdSn2 have nearly the same radius [5]. Never the less another important fact is the content of Silver. Different Ag content 2%, 2.5%, 3% and 3.75% for that has been invested. Different alloys were soldered on substrates and analyzed by cross sections. Figure 5 shows intermetallic by a quantity of 3,75% Ag and that means the Silver content was fixed at 2.5%.

Figure 6: Cross section with 3.75% Ag, Ag3Sn

A further investigation was done by a DSC analyses to finalize the melting point/rang of those alloys, figure 7. As result of that DSC, the alloy with 2.5% Ag has a melting range from 210°C to 216(217)°C and was selected for the final alloy.

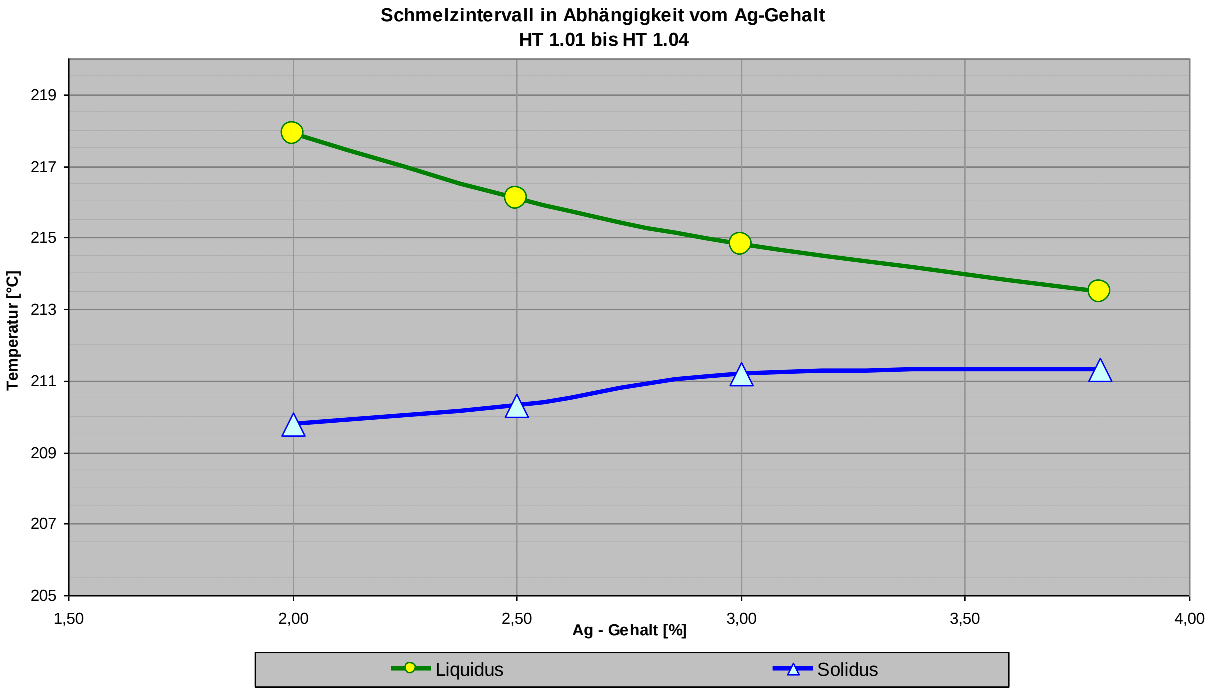


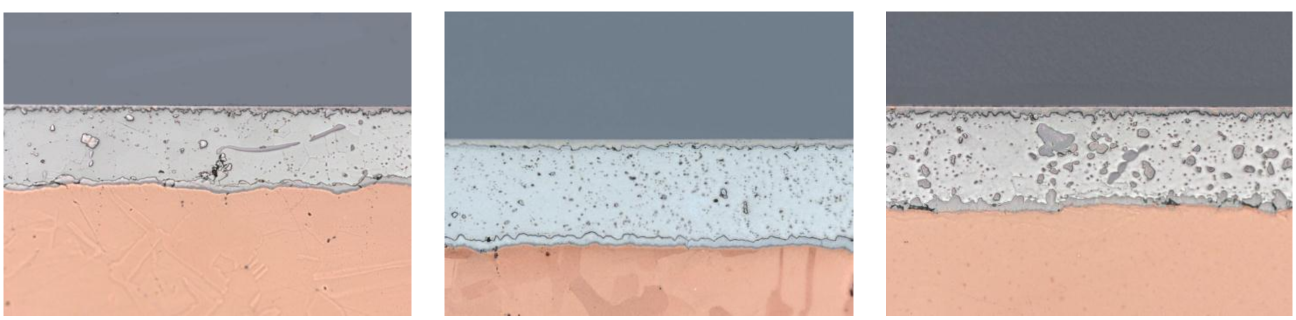
Figure 7: Soldering range HT1

Technology qualification for HT1

Different solder pastes/alloy on real DCBs were qualified for the technology. The steps for the qualification were

- Printing and measurement of the solder deposits after printing
- X-Ray
- Cleaning with two mediums and cleaner
- TCT 30'/10''/30 with -40/+125 and -40/175°C

The first interpretation of the results are focused on cross section results after N=500 by -40/+175, figures 8a till c.



Figures 8: a) SnAg.5 b) HT1 c) Innolot

In these cross sections there are not really any differences to the interface between SnAg3.5 and HT1. The HT1 is finely dispersed, and more homogeny and the SnAg3 show Ag3Sn intermetallic. The Innolot already shows some defects between the substrate and the solder joint inside the interface. Another effect with the Innolot was some Die losing after the TCT which means there was a complete crack inside the assembly. Based on that result a product qualification with SnAg3.5 and HT1 was made.

Product qualification for HT1

The current requirements for such DCB product qualification are N=1000 at -04/+125°C with 30'/10''/30' without any electrical defects. Therefore, the passive test was made with these requirement and the electrical analyses as well as some cross sections after N=250/500/750/1000/1500/2000 …+….End of Live (EoL). The result after the technical requirement was, that both alloys fulfill it, which means after N=1000 there was no electrical failure. The first electrical failure came after 1500 cycles for both alloys but the reason was not a defect inside the assembling, figure 9. All defects were based on wire bond defects.

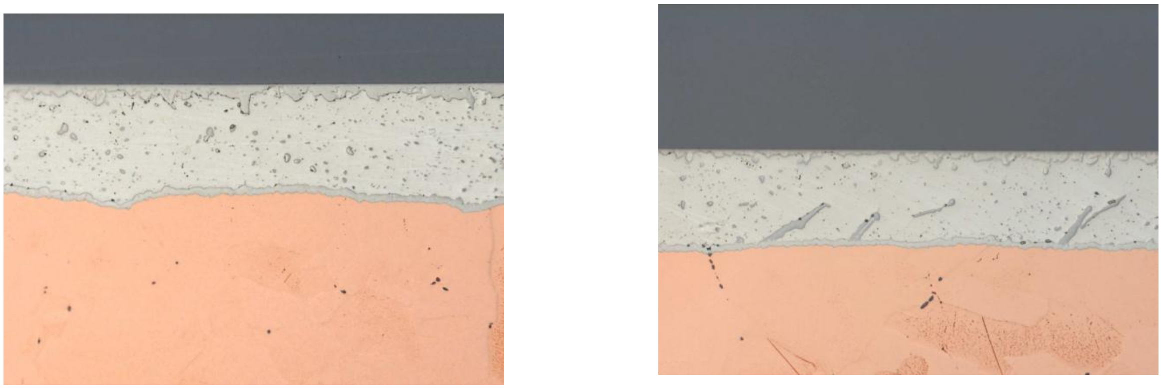


Figure 9: Cross section after N=1500 a) HT1 and b) SnAg3.5

After N=2000 there was a delamination with the SnAg3.5 alloy between Die and solder, figure 10. That effect was temporary, which means that it wasn't for all. For example another cross section after N=3000 doesn't show that effect, figure 11.

Figure 10: Cross section SnAg3.5 after N=2000

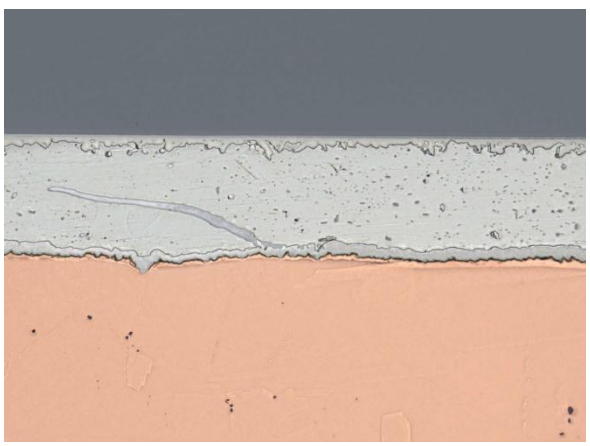


Figure 11: Cross section SnAg3.5 after N=3000

No delamination showed the HT1 alloy after all cycles. Figure 12 shows the results after 4000 cycles.

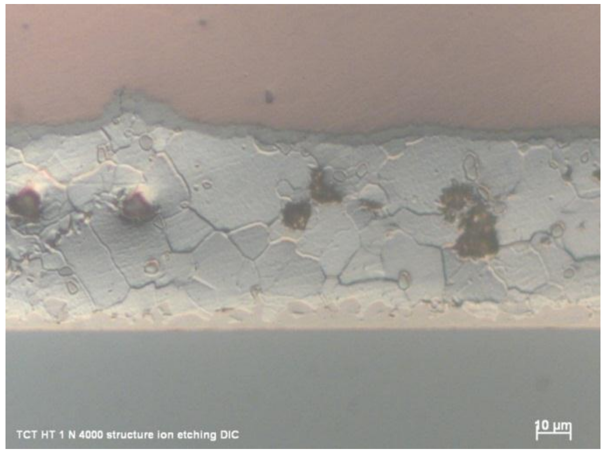


Figure 12: Cross section HT1 after N=4000 (source: Faunhofer ENAS)

As a summary of that investigation for standard application it uses SnAg3.5 but when it needs an improvement for higher temperatures the HT1 is the selected alloy.

Sintering

Soft solder alloys with or without additives does have a limit of electrical and thermal conductivity. For devices which need more of those physical properties or with higher operation of temperatures (200°C) it needs alternatives for the assembly technology including the material. One of these possibilities is sinter technologies. A comparison between soft solder alloy and sinter technology is described in figure 13.

Table 2: Table with the most important properties

Property	Sintering	High Lead Solder	SnAg3.5
Electrical Conductivity	10.5 - 40 MS/m	4.8 MS/m	7,8 MS/m
Thermal Conductivity	>100 W/(m?K)	25 W/(m?K)	70 W/mK
CTE	19 ppm/K	29 ppm/K	28 ppm/K
Melting Point	961 °C	<300 °C	221 °C
Process-Temperature	220 °C	340 °C	250 °C
Shear strength @ 25 °C	20 MPa	15 MPa	20 MPa
Shear strength @ 300 °C	10 MPa	n/a	n/a
Tensile strength @ 25 °C	55 MPa	29 MPa	30 MPa
Homologous temperature (operation temperature 175°C)	36 %	78 %	91 %

On one hand Silver has a higher melting temperature (961°C) than Sn based soft solder alloys. Due to that fact that there are no ageing effects by operation of temperatures at higher temperatures e.g. 200°C. On the other hand the thermal conductivity is much higher than soft solder alloys. That guarantees a higher thermal management and that means higher junction temperature is transformed and more effective.

State of the art is sinter materials with Nano silver particles inside (NTV) [6 and 7]. This technology needs operation pressure by >30MPa for Die placing. The challenge for this technology is reduction of pressure and process temperature [8]. By using Nano silver [9] it is possible to come to technology without any pressure [10]. The limited factor is thickness of silver layers up to 10 µm. With higher layers the shrinking makes an inhomogeneous structure and that limits the adhesion to the Die or substrate. Another factor could be the roughness for the finish itself e.g. copper on DCB. For that challenge a concept with micro silver has been developed. This allows a process without pressure or with low pressure at 220°C.

Diffusion Soldering/HotPowCon (HPC)

Different investigations described [11, 12] an increase of thermal stability by using a dissolution process for creating intermetallic connections and, therefore, an increase of the reliability performance after temperature cycling [3], means a combination of thermal solidification and isothermal solidification which could be the basis for a new quality of interconnection, Figure 14 and 15.

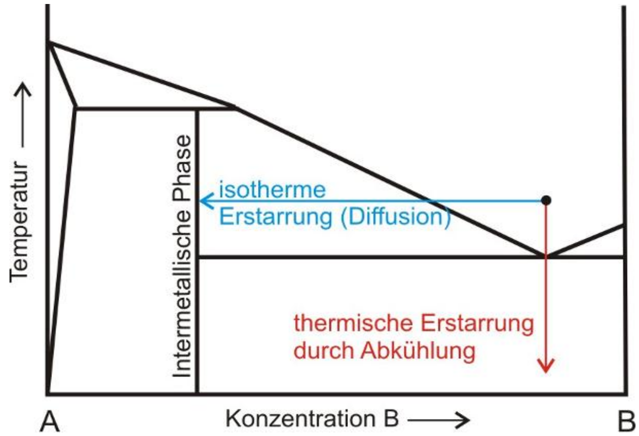


Figure 14: Phase diagram of a two element system

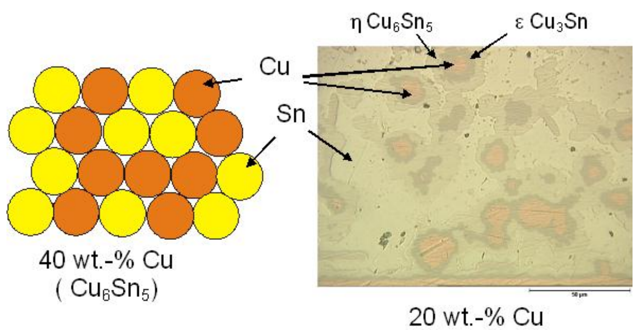


Figure 15: Creating of intermetallic with Cu in a SnCu system. (Source: Fraunhofer IZM)

From this basic investigation the idea of this project was approached. For creating structure designs through creating high melting intermetallic by using soldering with solder paste. For this purpose a soft solder alloy will be used based on Sn with a high metal concentration and additives, the possibility of isothermal solidification at low/standard solder temperatures as well as operation temperature higher than liquidus temperature after soldering.
Before the project started, an investigation had been carried out on realistic DCBs with IGBTs. The process was printing with a 20 µm stencil, pick and place of IGBTs and soldering in vapor phase with vacuum. The solder paste was based on type 6 eutectic SnCu powder with and without Cu powder in different sizes. The result after soldering without Cu powder is showed in Figure 16.

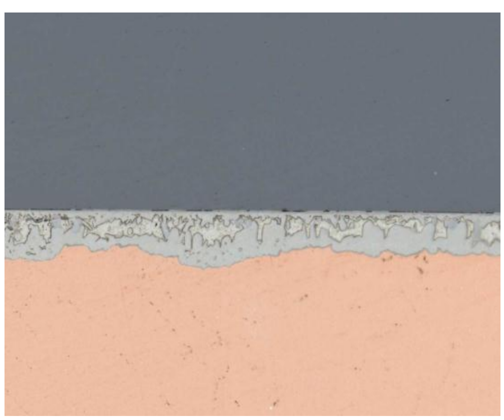


Figure 16: IGBT on DCB with SnCu solder paste (type 6) produced with a 20µm stencil

By using the process intermetallic in a selective connection between substrate and die has been created. By using additional Cu powder, Figure 17, most of the solder joint was created with the standard interconnection based on the soft solder alloy and selective intermetallic of the Cu powder.

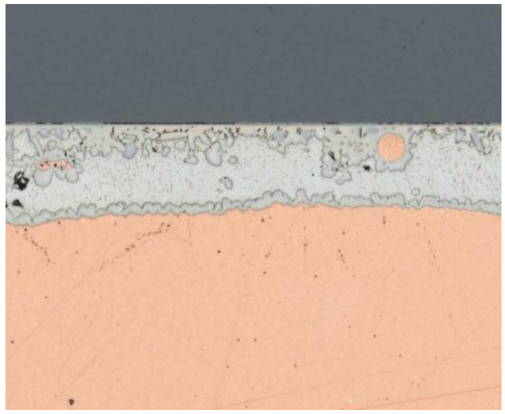


Figure 17: IGBT on DCB with SnCu solder paste (type 6) and Cu powder produced with a 20µm stencil

In this investigation possibilities were created which were given a basis for starting a project with some experts from different companies. One of the first steps was to adjust some major questions for a final solution, e.g.:

- Printability with type 6 paste, what about thinner stencil and type 7 or 8 paste
- Dispensing
- Copper Ball quality and quantity (size)
- Temperature profiling
- Tempering
- Combination power electronic and smt
- How may IMC are necessary
- Vacuum and/or soldering with pressure
- Thermal and electrical conductivity
- Etc.

From these question points different work packages were developed inside the project structure, figure 18

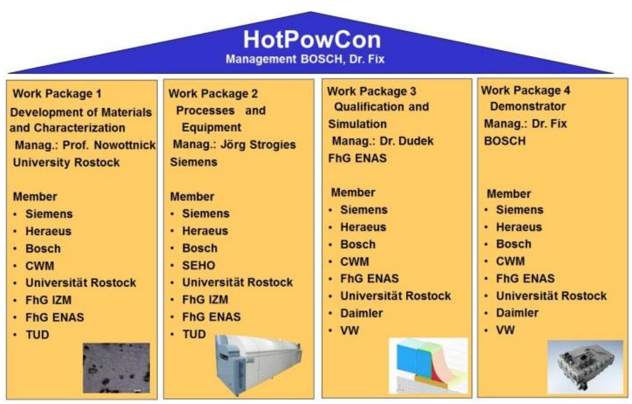


Figure 18: Transformation and structure of this project.

Literature

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Assembly Materials for High Temperature Application

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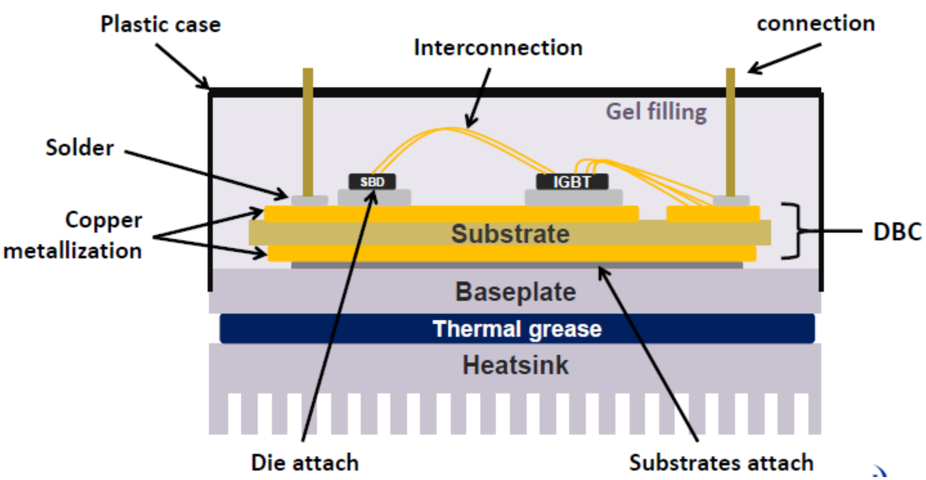
Agenda

- Introduction
- Soft Solder Alloys
- Sintering
- HotPowCon (HPC)
- Summary

Introduction



Assembly of a power module

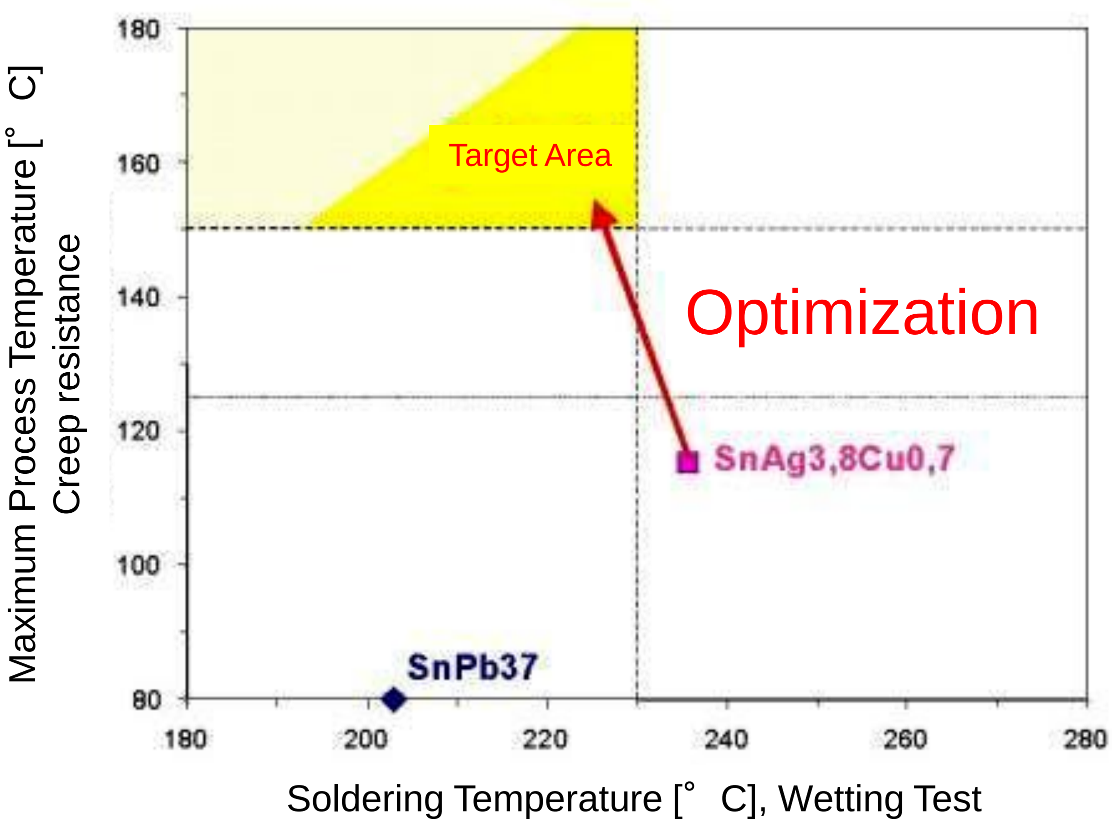
Requirements:

- High power density
- High reliability
- High heat Conductivity
- Ambient condition more than 150° C
- Lead Free technology
- Live time more than 15 years
- Costs

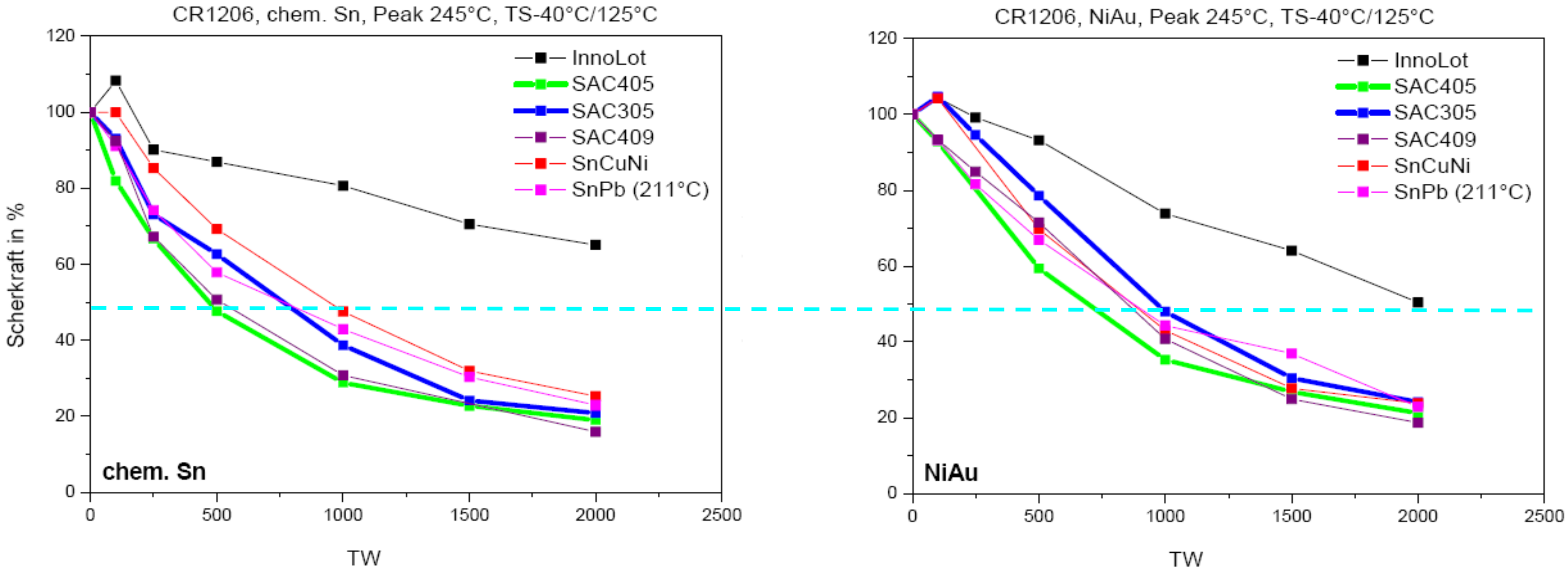
Soft Solder Alloys

Alloy	Melting-Temperature [°C]	Remark
Sn96.5 Ag3.5	221	SnAg eutectic
Sn96.5 Ag3 Cu0.5	217	SAC Standard-alloy Under eutectic
Sn95.5 Ag4 Cu0.5	217	SAC with 4% Ag, above eutectic
InnoRel Innolot® Sn Ag3,5 Cu0,7 Ni0,125 Sb1,5 Bi3	206-218	Higher reliability on pcb Higher operation temperature, e.g. 150°C
InnoRel HT1 Sn /Ag2,5/Cu0,5/In2/KM [2]	210-217	Higher reliability on TF and DCB Higher operation temperature, >150°C

Special Soft Solder Alloy: Innolot

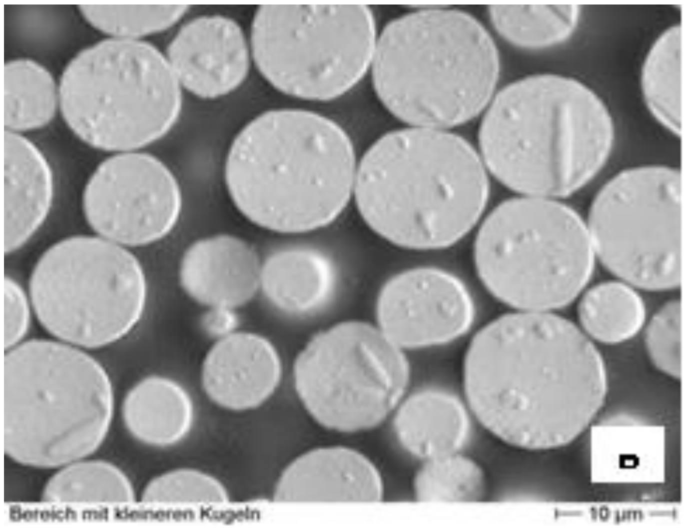


Special Soft Solder Alloy: Innolot

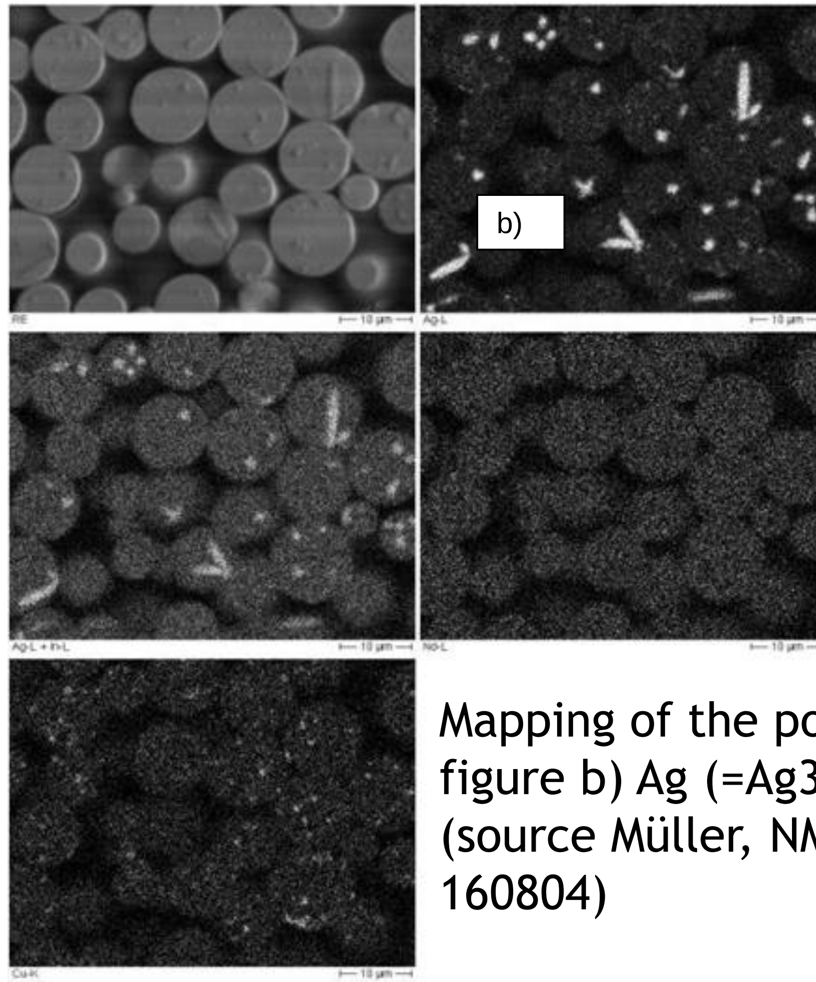


Source: Abschlusspräsentation BMBF-Projekt LIVE; Akzeptanzkriterien thermisch hochbelasteter, miniaturisierter Lötverbindungen; J. Albrecht Siemens AG, CT MM6; Berlin 17.9.2008

Special Soft Solder Alloy: HT1

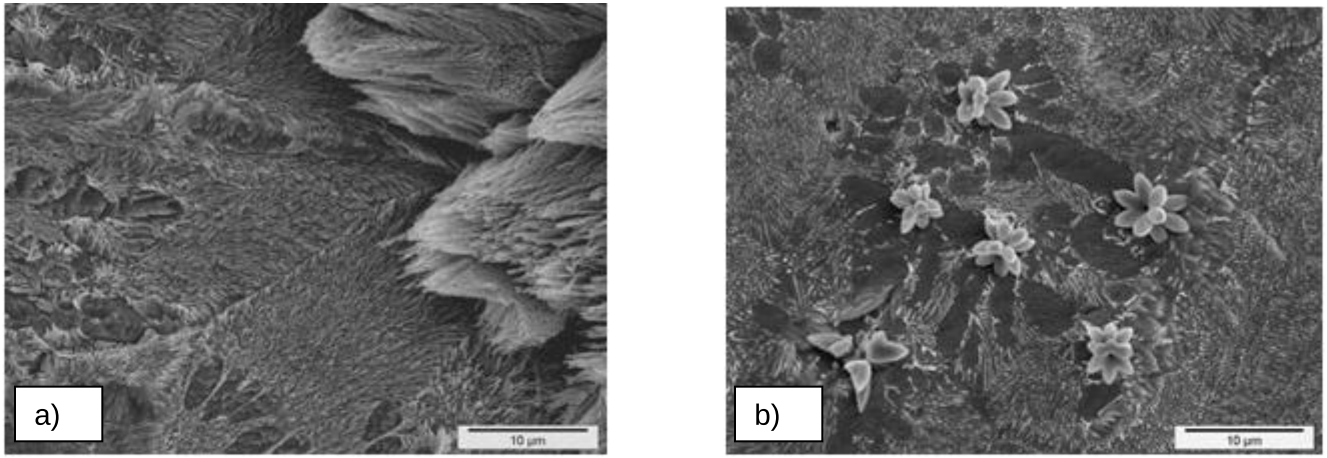


Cross section after powder production (source: Müller, NMB 160804)



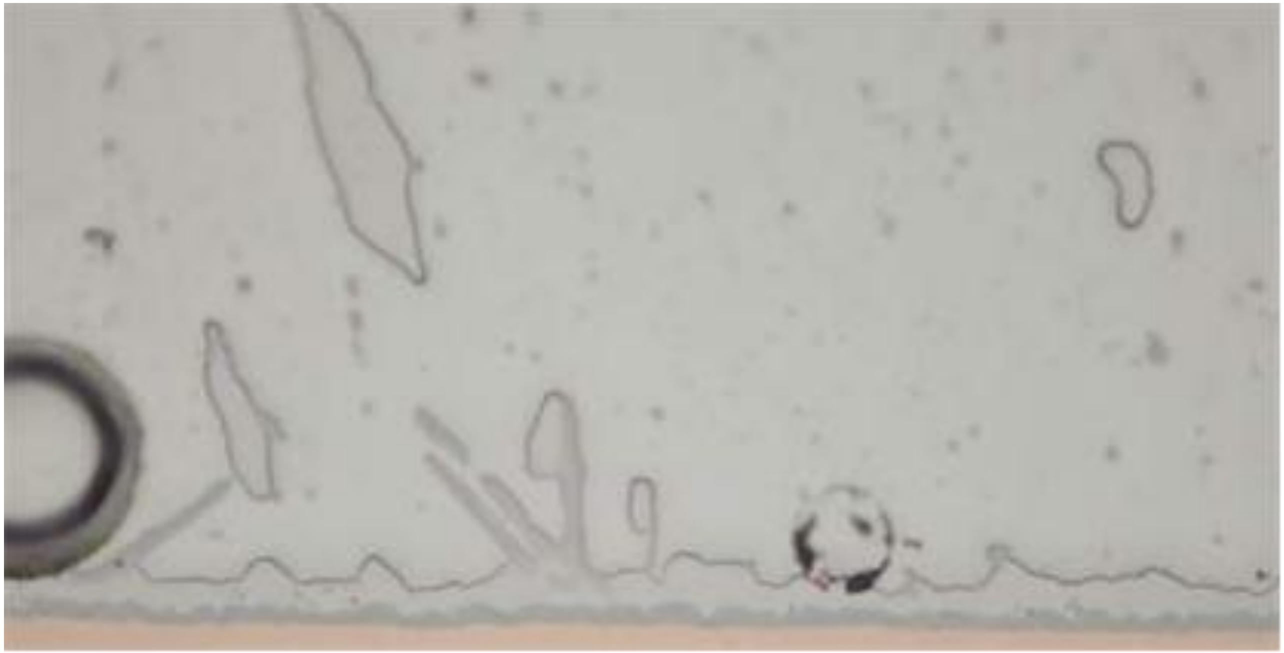
Mapping of the powder; figure b) Ag (=Ag3Sn) (source Müller, NMB, 160804)

Special Soft Solder Alloy: HT1



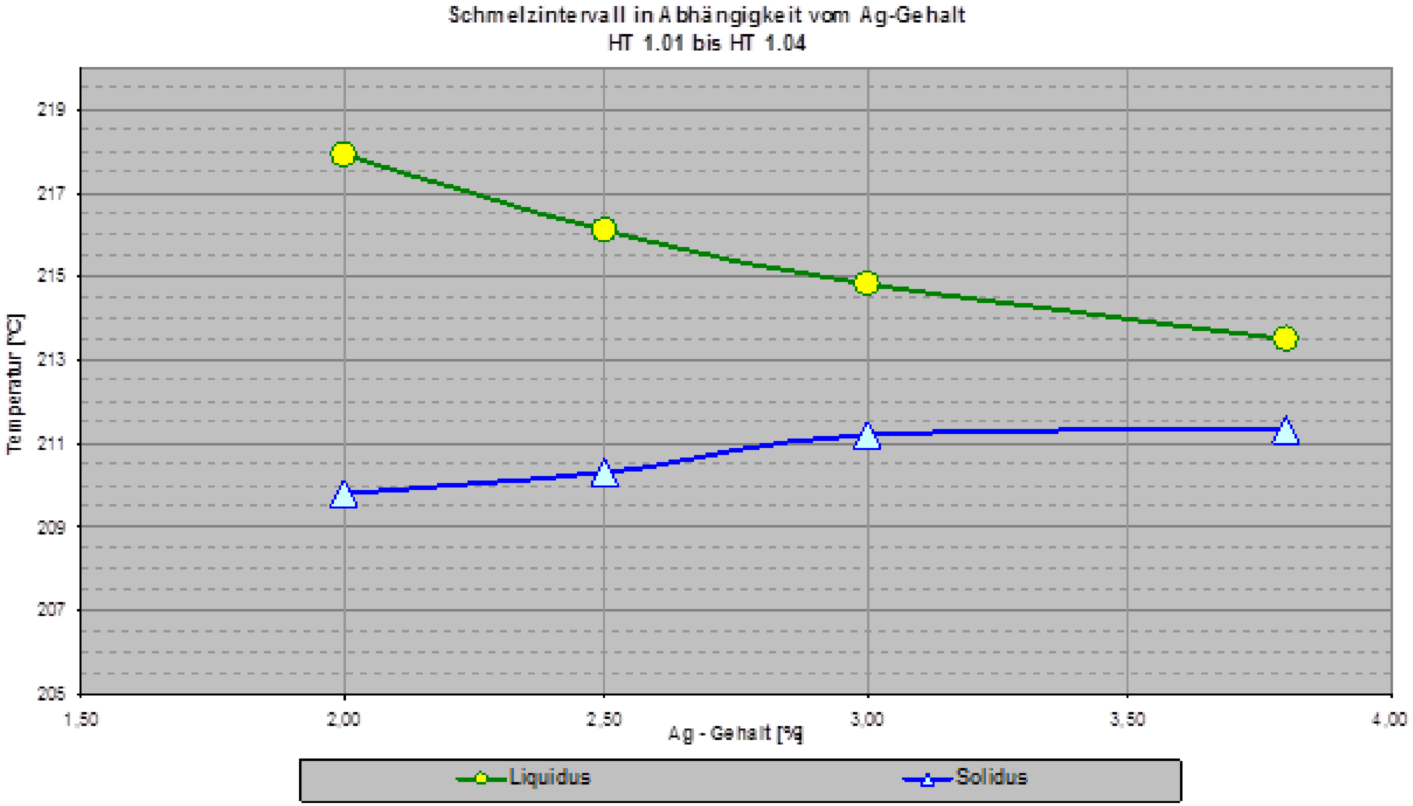
a) SAC + In (without modifier) and b) SAC+In+KM (source Müller, NMB, 160804)

Special Soft Solder Alloy: HT1



Cross Section with 3,75% Ag, Ag3Sn

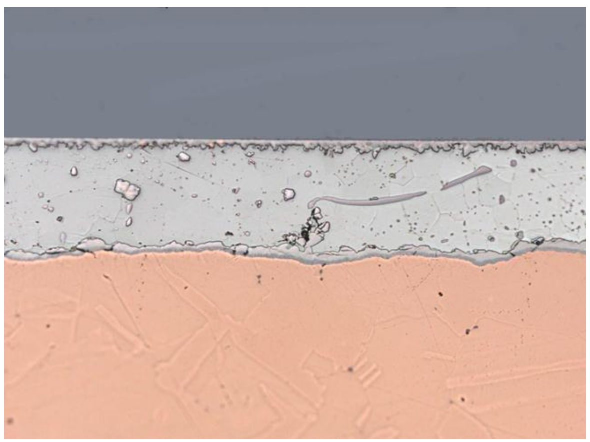
Special Soft Solder Alloy: HT1



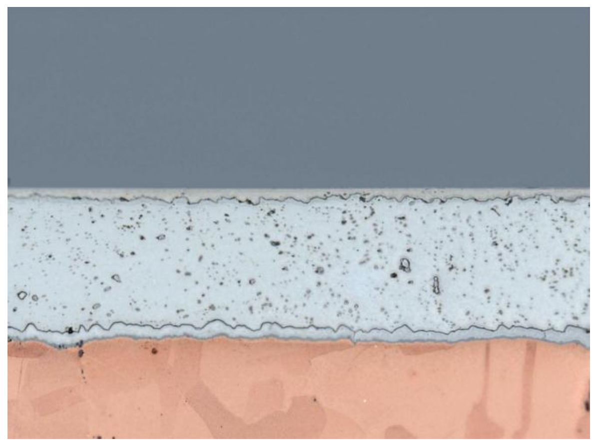
Melting Range (Liquidus and Solidus)

Special Soft Solder Alloy: HT1

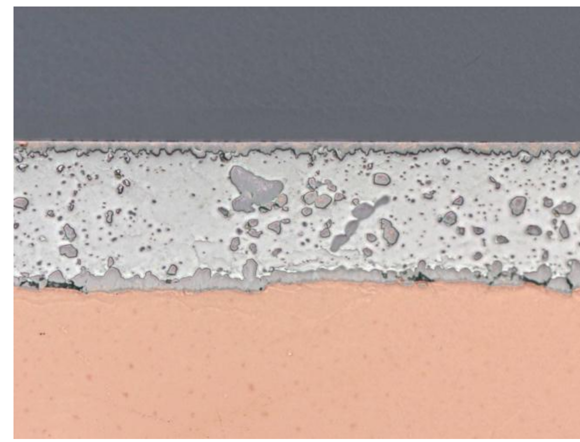
Technology Qualification TCT 30’/10’’/30’@-40/+175 N=500



SnAg3.5



HT1



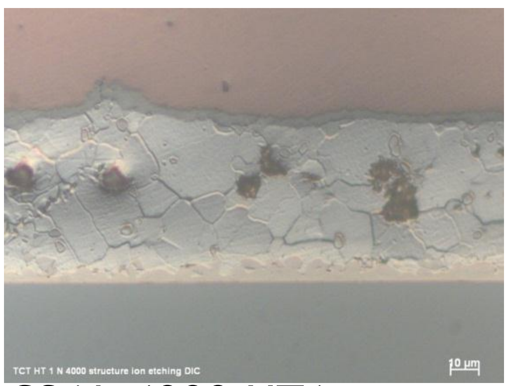
Innolot

Special Soft Solder Alloy: HT1

Product Qualification TCT 30’/10’’/30’@-40/+125 N=1500/2000/3000/4000

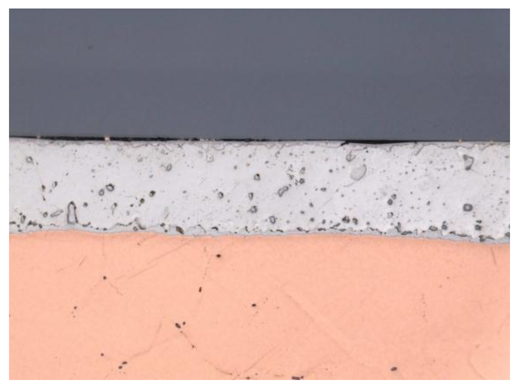
CS N=1500 HT1

CS N=1500 SnAg3.5

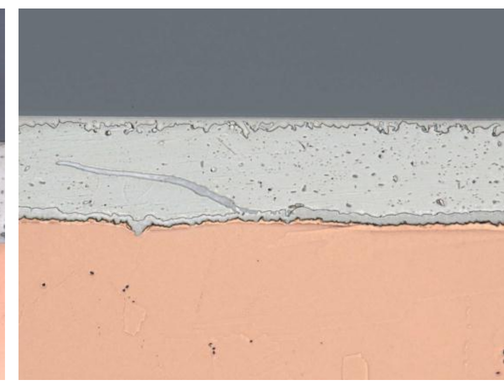


CS N=4000 HT1

Source: Dudek, Fraunhofer ENAS



CS N=2000 SnAg3.5



CS N=3000 SnAg3.5

Sintering

Property	Sintering	High Lead Solder	SnAg3.5
Electrical Conductivity	10.5 - 40 MS/m	4.8 MS/m	7,8 MS/m
Thermal Conductivity	>100 W/(m?K)	25 W/(m?K)	70 W/mK
CTE	19 ppm/K	29 ppm/K	28 ppm/K
Melting Point	961 °C	<300 °C	221 °C
Process-Temperature	220 °C	340 °C	250 °C
Shear strength @ 25 °C	20 MPa	15 MPa	20 MPa
Shear strength @ 300 °C	10 MPa	n/a	n/a
Tensile strength @ 25 °C	55 MPa	29 MPa	30 MPa
Homologous temperature (operation temperature 175°C)	36 %	78 %	91 %

Table with the most important properties

Sintering

Processing mAgic 016

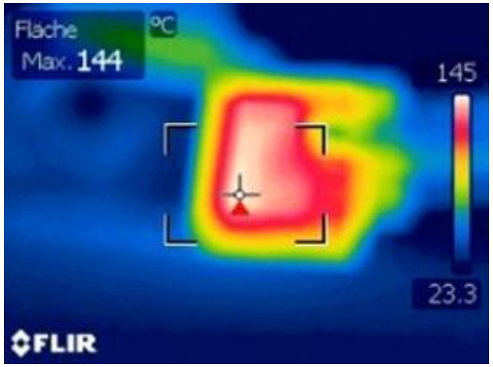
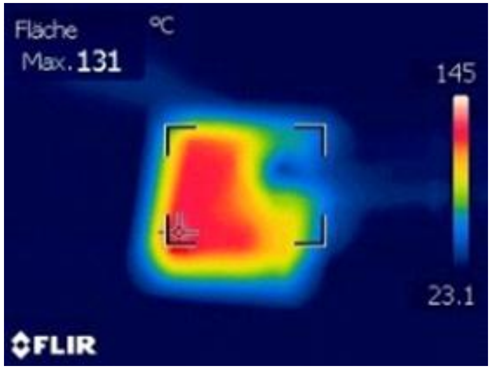
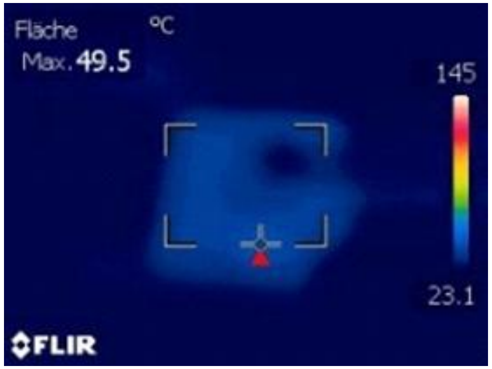
Items	Paste Application	Paste Drying	Die Placement	Sintering
Process	Stencil printing	Drying of printed sinter paste	Placement of die	Sintering Step
Equipment	convetional printing equipment	Conventional Box oven	Die placemer with heated substrate holder	Sinter press
Parameter	• Stainless steel or PU squeegees • Print Speed 30-70 mm/s	• Drying time 5-15 min • drying temperature 60-120° C • Drying in air	• Die Placement temperature 80-130° C • Die Placement force min 0.03 MPa	• Sinter Pressure 20-40 MPa • Sinter Temperature 230° C-280° C • Sinter time 1-2 Minutes in air

Sintering

Processing mAgic 016 with DIE size 100mm^2

Items	Paste Application	Die Placement	Sintering
Process	Printing/Dispensing	Placement of Die	Sintering Step
Equipment	Standard equipment	Standard Die placer	Box Oven
Parameter	• Standard Parameter	Standard die Placement Parameter	• Peak Sinter Temperature 230° C-280° C • Sinter time 240 Minutes

Sintering

Solder Paste **SnAg3.5-Leg.** Vacuum	**Sinter Paste** **ASP131** 0 MPa Sinter pressure	**Sinter Paste** **ASP016** 20 MPa Sinter pressure
		

Thermography

Diffusion Soldering HPC

HotPowCon

Laufzeit 05.2011 – 04.2014

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Diffusion Soldering HPC

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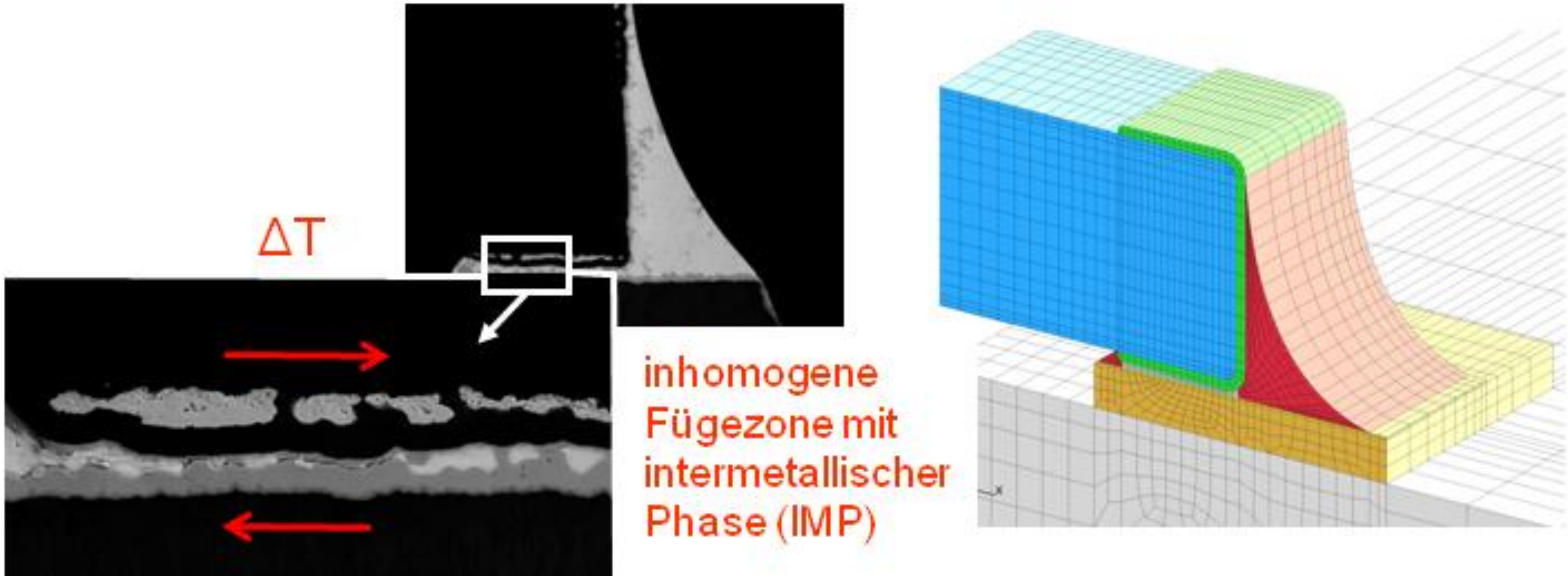
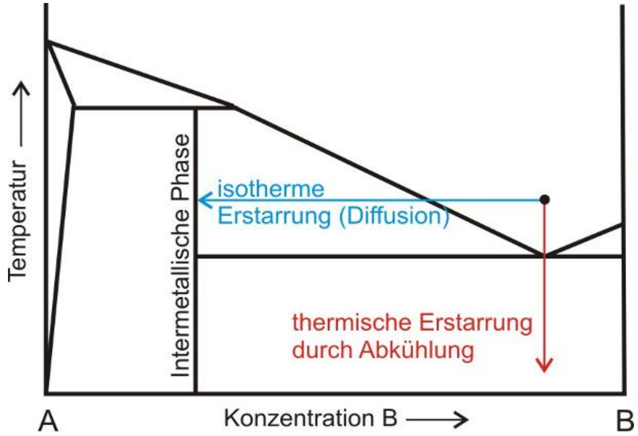
Diffusion Soldering HPC



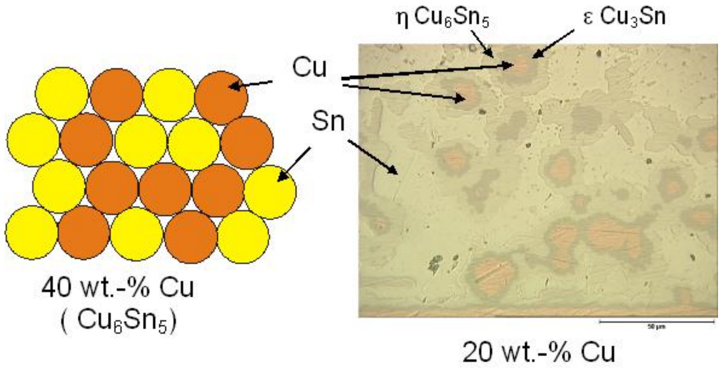
Investigation of thermo/mechanical reliability by experiment and simulation, source: Fraunhofer ENAS

Diffusion Soldering HPC

Combination of thermal solidification and isothermal solidification could be the basis for a new quality of interconnection



Phase diagram of a two element system

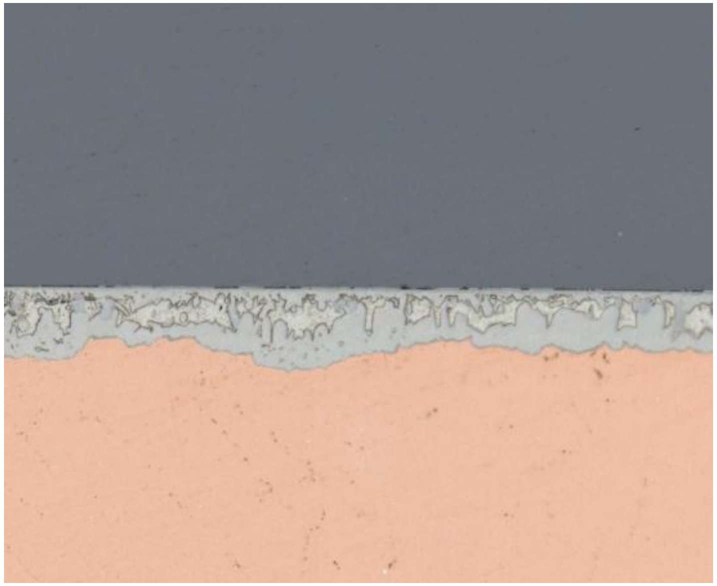


Creating of intermetallic with Cu in a SnCu system. (Source: Fraunhofer IZM)

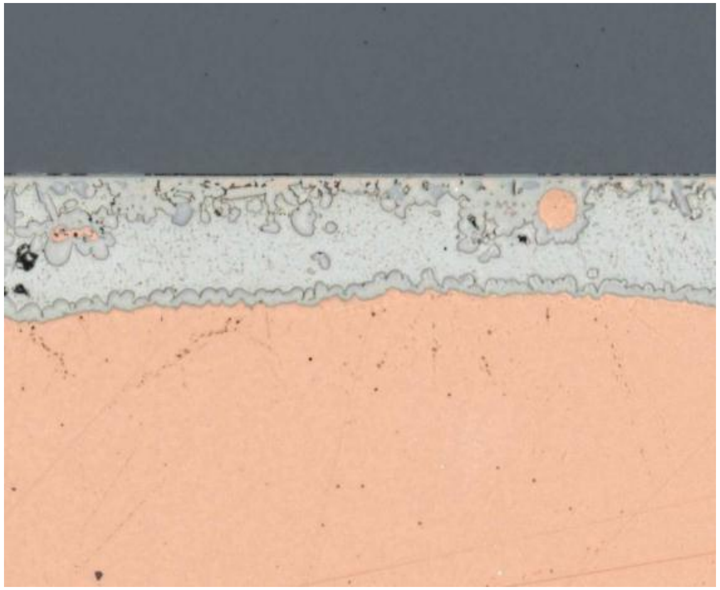
- Structure design through high melting intermetallic by using soft solder alloys based on solder paste
- soft solder alloy will be used based on Sn with a high metal concentration and additives
- Isothermal solidification at low/standard solder temperatures
- operation temperature higher than liquidus temperature after soldering

Diffusion Soldering HPC

Combination of thermal solidification and isothermal solidification could be the basis for a new quality of interconnection



IGBT on DCB with SnCu solder paste (type 6) produced with a 20µm stencil

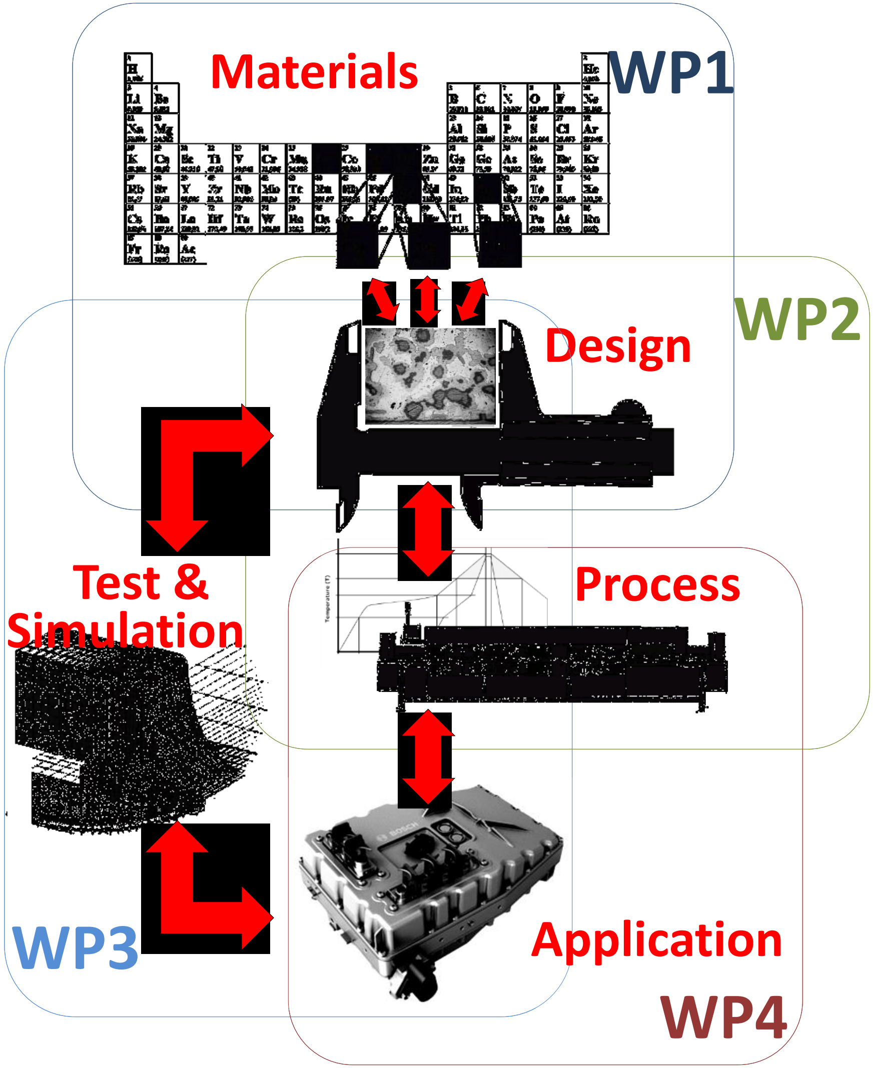


IGBT on DCB with SnCu solder paste (type 6) and Cu powder produced with a 20µm stencil

Diffusion Soldering HPC

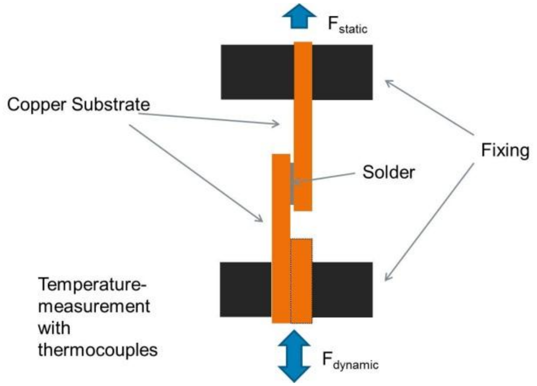
Workpackage and Milestones

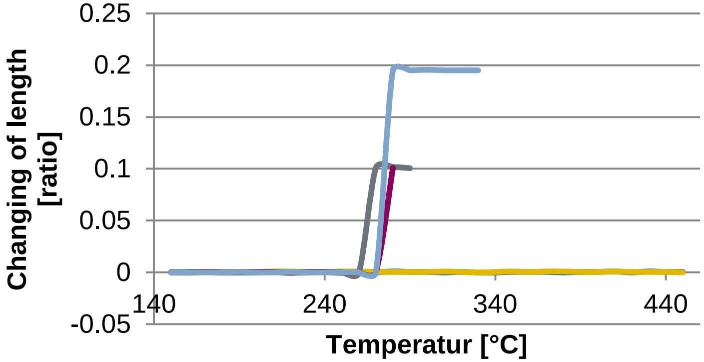
- M1 describes a combination of materials as well as the realization of that combination based on a lab application
- M2 has fixed the processes including a qualification of test equipment.

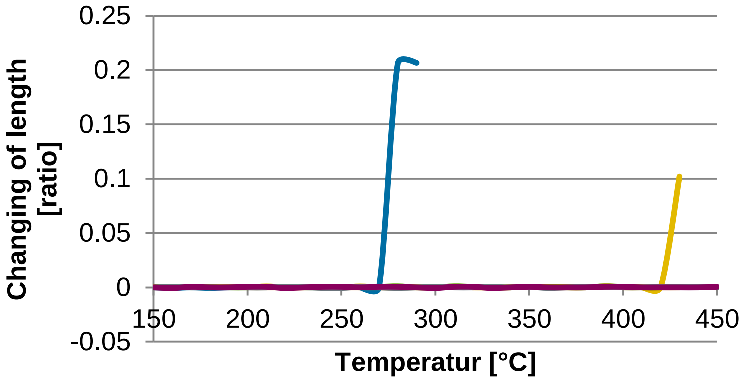


Diffusion Soldering HPC

Results DMA



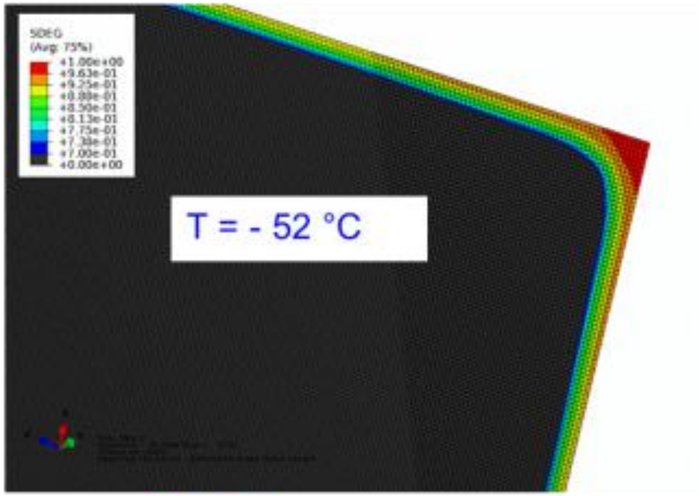


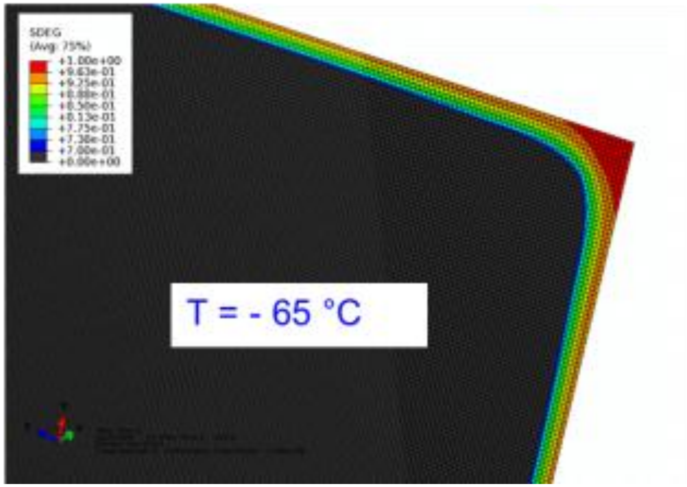


DMA with Cu particles Q1and SnCu reference, after soldering. There is no difference between Ref. and Paste with Copper in this Q1 quality.

DMA with Cu particles Q2and SnCu reference, after soldering the temperature to melt again is more than 400° C.

Summary





FEM: By the local damage-parameter D (read area 0,96 < D < 1 = delaminated) it shows a delamination at the corner of the Die. Means the delamination starts at app. -35° C.