RELIABILITY OF LEAD-FREE SOLDERS FOR DIE ATTACH IN AUTOMOTIVE POWER MODULES

Bettina Ottinger[1,2], Joshua Holverscheid[1], Sebastian König[1], Edgar Jerichow[1], Sebastian Lunz[1], Mario Sprenger[1], Dr. Lars Müller[1], Dr. Christian Goth[1], Prof. Dr. Jörg Franke[2]
Vitesco Technologies Germany GmbH[1], Institute for Factory Automation and Production Systems Friedrich-Alexander University Erlangen – Nürnberg [2]

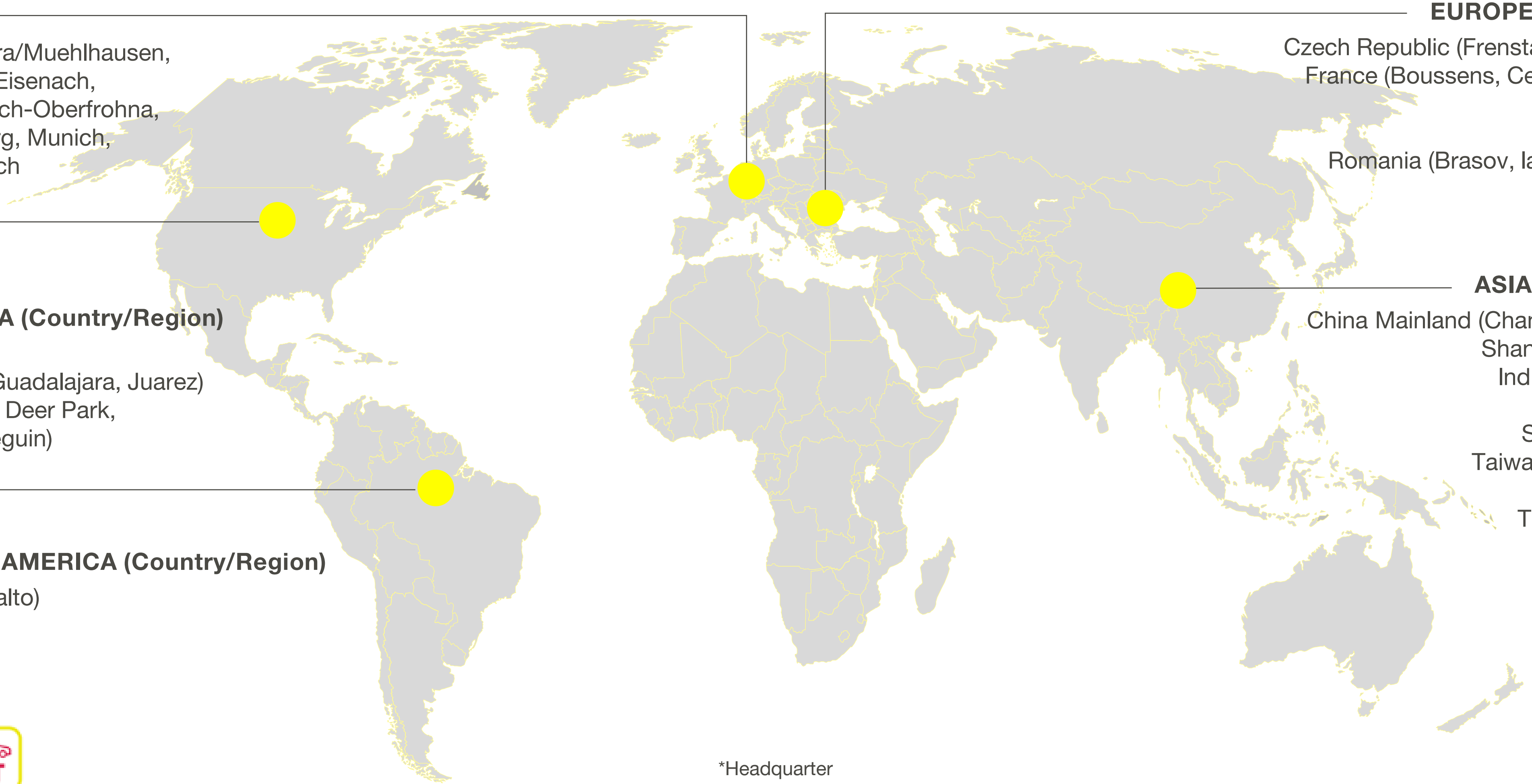
based on a presentation at EPTC 2022 in Singapore [*]

[*] https://ieeexplore.ieee.org/document/10013246/

ELECTRIFIED. EMOTION. EVERYWHERE.

OUR VISION

GLOBAL FOOTPRINT



GERMANY

Regensburg*, Bebra/Muehlhausen,
Berlin, Dortmund, Eisenach,
Gruenstadt, Limbach-Oberfrohna,
Lohmar, Nuremberg, Munich,
Roding, Schwalbach

EUROPE (Country/Region)

Czech Republic (Frenstat, Ostrava, Trutnov)
France (Boussens, Cergy, Foix, Toulouse)
Hungary (Debrecen)
Italy (Pisa)
Romania (Brasov, Iasi, Sibiu, Timisoara)

NORTH AMERICA (Country/Region)

Canada (Chatham)
Mexico (Cuautla, Guadalajara, Juarez)
USA (Auburn Hills, Deer Park,
Newport News, Seguin)

ASIA (Country/Region)

China Mainland (Changchun, Chongqing,
Shanghai, Tianjin, Wuhu)
India (Bangalore, Pune)
Japan (Yokohama)
South Korea (Icheon)
Taiwan (Luchu Township/
Taoyuan County)
Thailand (Amata City)

SOUTH AMERICA (Country/Region)

Brazil (Salto)

*Headquarter

ELECTRIFICATION TECHNOLOGY ET

AGENDA

1 INTRODUCTION

2 METHODS

3 RESULTS AND DISCUSSION

4 SUMMARY

5 OUTLOOK

INTRODUCTION – POWER MODULE

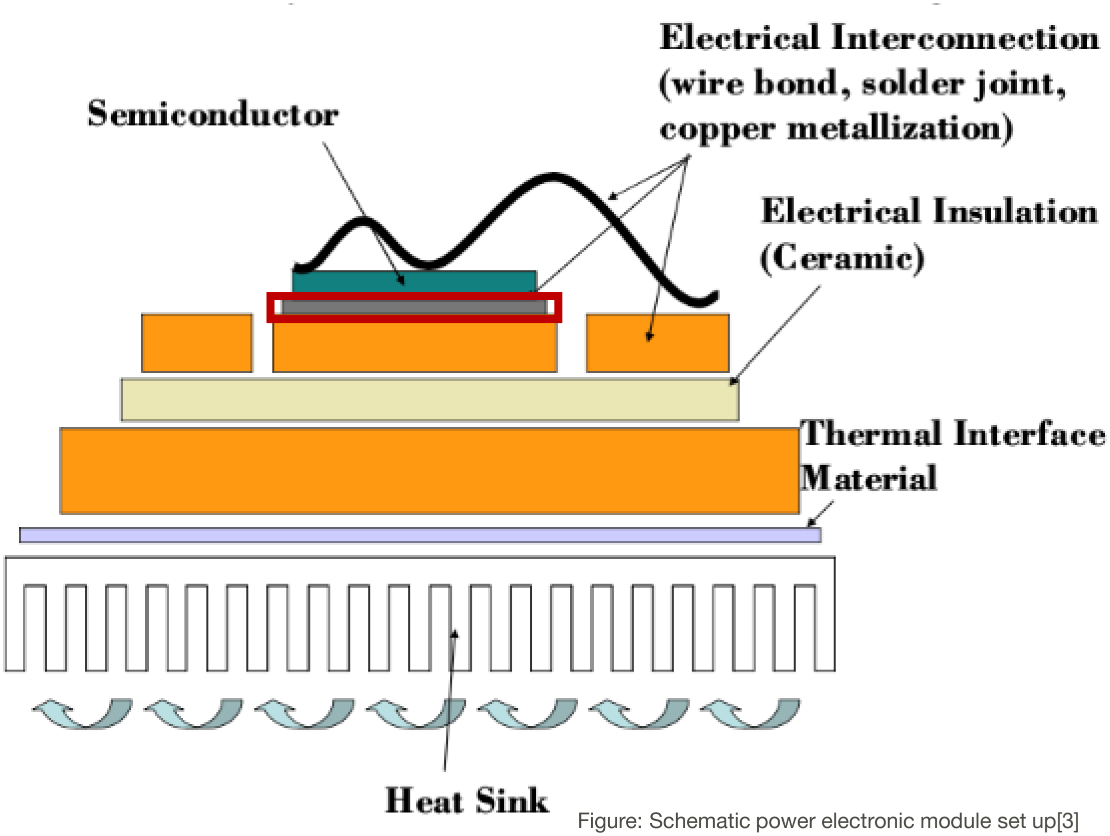


Figure: Schematic power electronic module set up[3]

Comparison of four Sn-based die attach materials during active power cycling under equal conditions

---

[3] Egelkraut, S., et al., "Evolution of Shear Strength and Microstructure of Die Bonding Technologies for High Temperature Applications during Thermal Aging," *12th Electronic Packaging Technology Conference* (2010)

INTRODUCTION – POWER MODULE

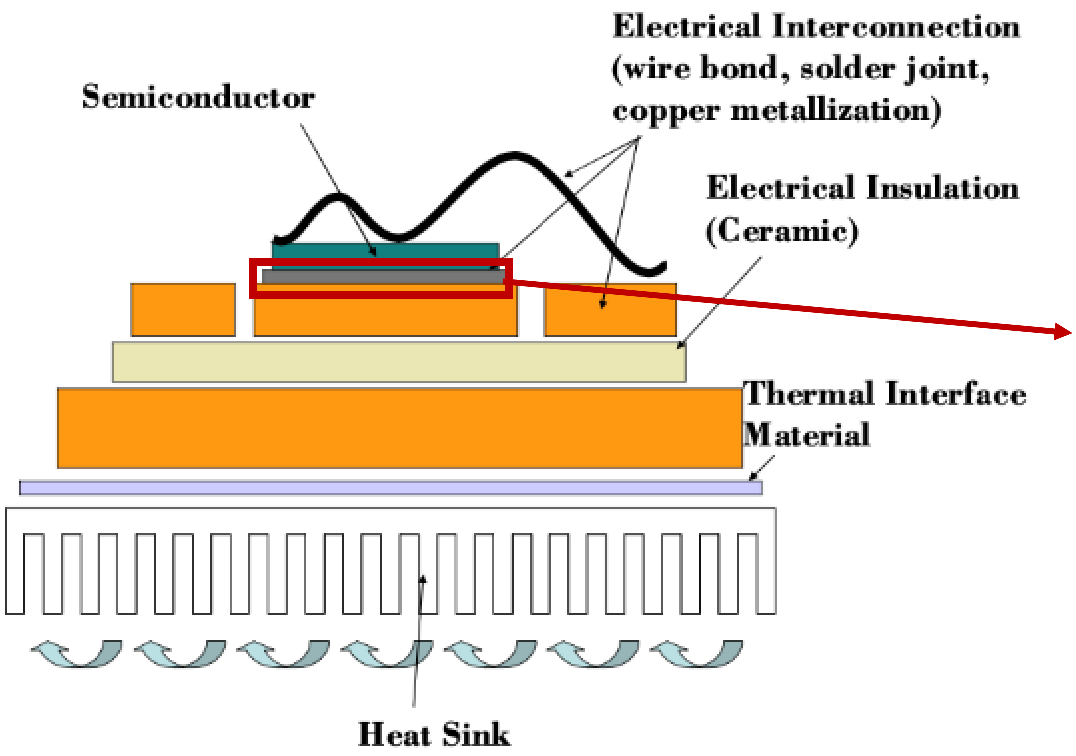
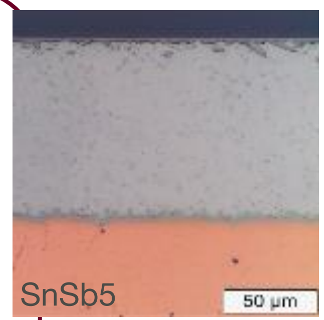


Figure: Schematic power electronic module set up[3]

- SAC305
- SnSb5
- SnSb10
- PFDS400®

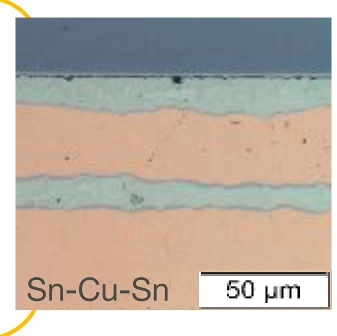
Bulk alloyed solder materials:

- Sn-based solder alloy with additives like Ag, Cu or Sb
- Intermetallic compound (IMC) layer at the interfaces ➜ metallic bond



Layered diffusion solder materials:

- Layered structure of Sn-based solder alloy and Cu
- Growth of IMC over the entire Sn-alloy-layer



Comparison of four Sn-based die attach materials during active power cycling under equal conditions

---

[3] Egelkraut, S., et al., “Evolution of Shear Strength and Microstructure of Die Bonding Technologies for High Temperature Applications during Thermal Aging,” 12th *Electronic Packaging Technology Conference* (2010)

AGENDA

1 INTRODUCTION

2 METHODS

3 RESULTS AND DISCUSSION

4 SUMMARY

5 OUTLOOK

METHODS - ACTIVE POWER CYCLING TEST

Design of the active power cycling test:

- Based on the ECPE Guideline 324 (AQG 324) [5]
- Applying a constant load current of about 250 A
- Temperature swing ΔT=100K (T_{min}= 40 °C and T_{max}= 140°C)
- Duration of each cycle t_{on}=3s and t_{off}=6s

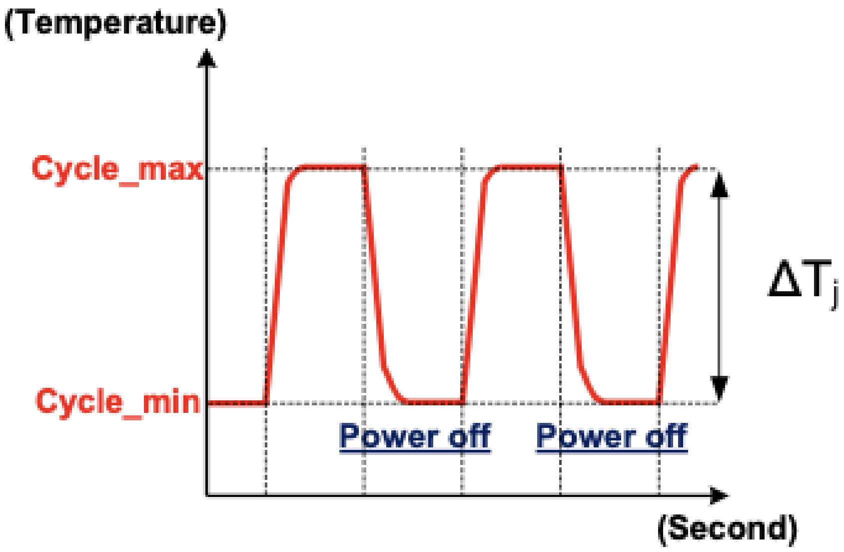


Figure: Schematic junction temperature history [4]

[4] Liao,L. et al., "Power cycling test and failure mode analysis of high-power module," *ICEP Proceedings* (2016), pp. 372-377
[5] Automotive AQG 324, "https://www.ecpe.org/index.php?eID=dumpFile&t=f&f=23930&token=ab9f61d08229d223b108cb44f00aa4db948ad4e4" (Accessed: september 20, 2022)

METHODS - QUALITY OF THE DIE ATTACH

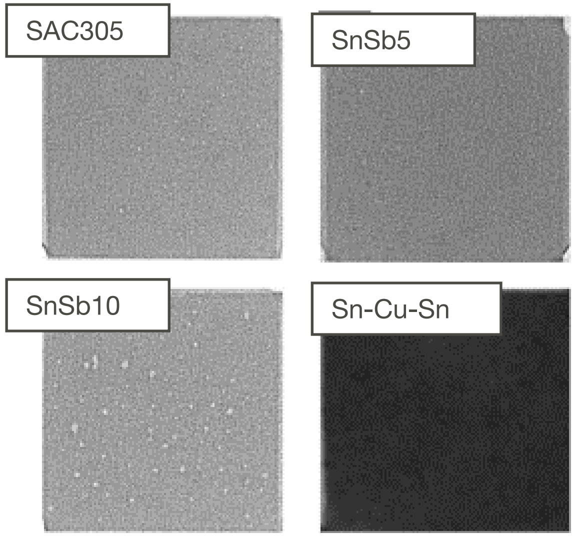


Figure: Image of X-ray or SAM analysis

Solder material	Ratio of the maximum void area %
SAC305	0.03
SnSb5	0.03
SnSb10	0.17
Sn-Cu-Sn	0.01

< 5%

Quality of the soldered die interconnection via X-ray analysis or SAM analysis:

- Measuring the local maximum void of each die
- Calculation of the maximum void area ratio over the total die surface

→ All soldered die attaches are lower than the limited maximum void area ratio of (5-10%) [6]

---

[6] Chang, J. et al., “Finite Element Modeling Predicts the Effect of Voids on Thermal Shock Reliability and Thermal Resistance of Power Devices." *Welding Journal* (2006), pp. 63 -70

AGENDA

1 INTRODUCTION

2 METHODS

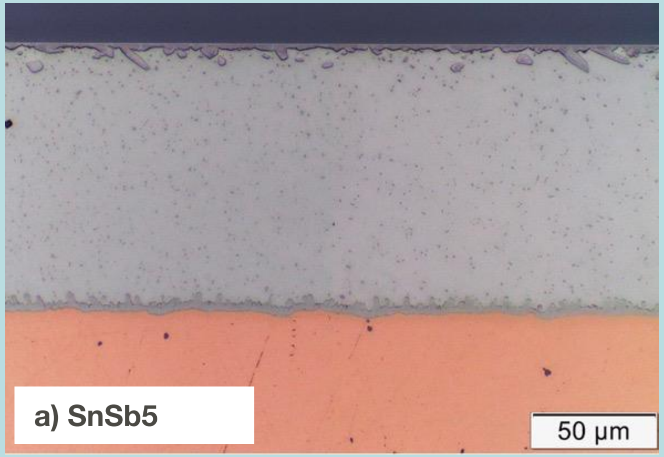
3 RESULTS AND DISCUSSION

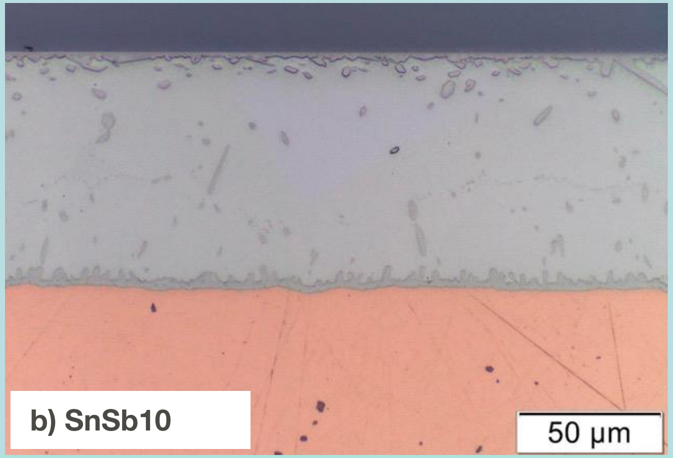
4 SUMMARY

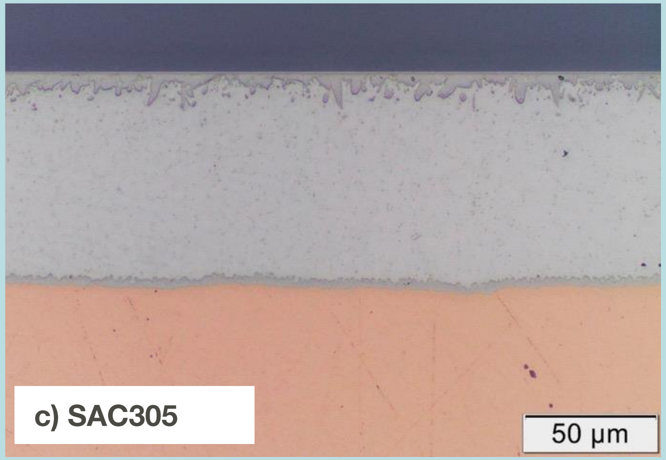
5 OUTLOOK

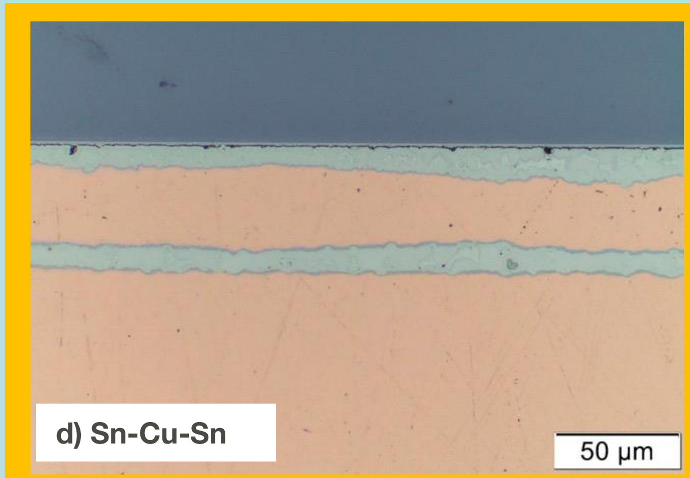
RESULTS - INITIAL MICROSTRUCTURE

Bulk alloyed solder materials



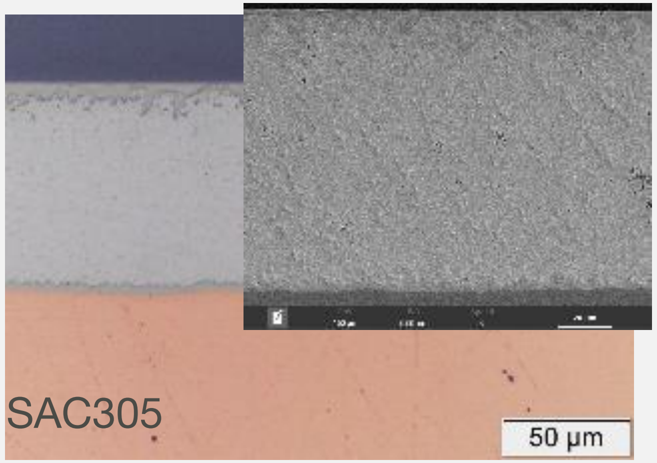
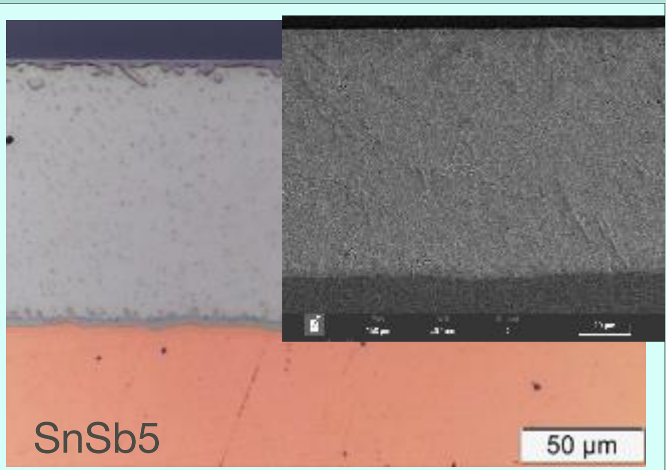
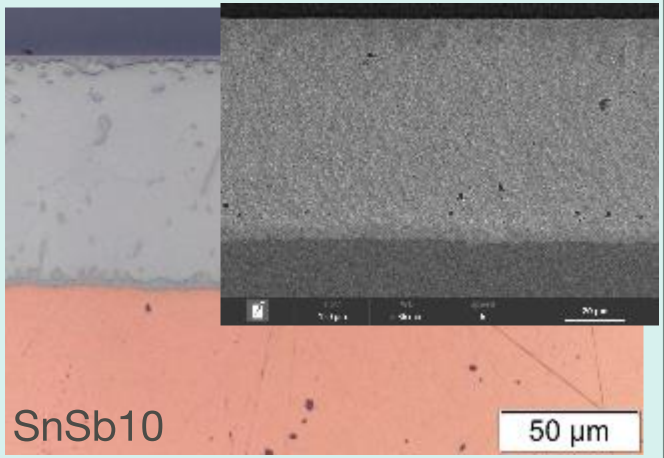
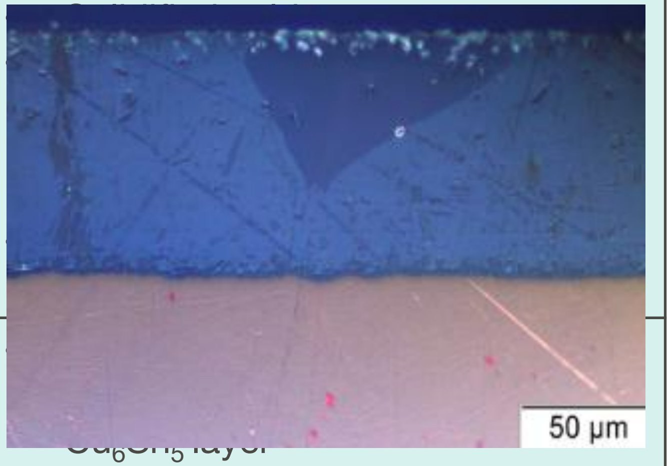




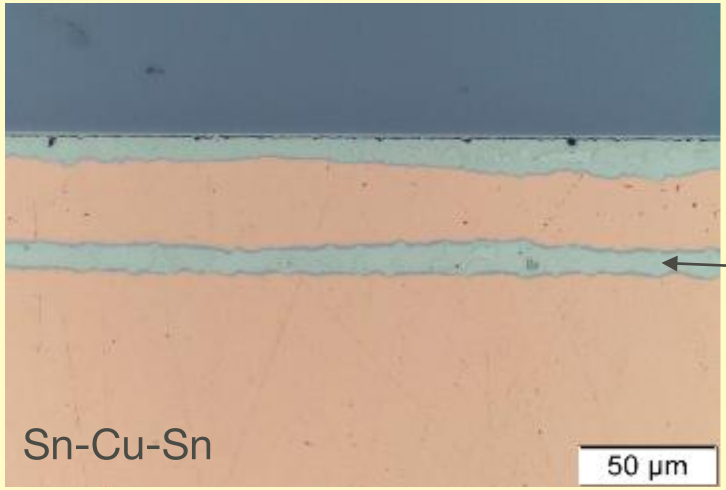


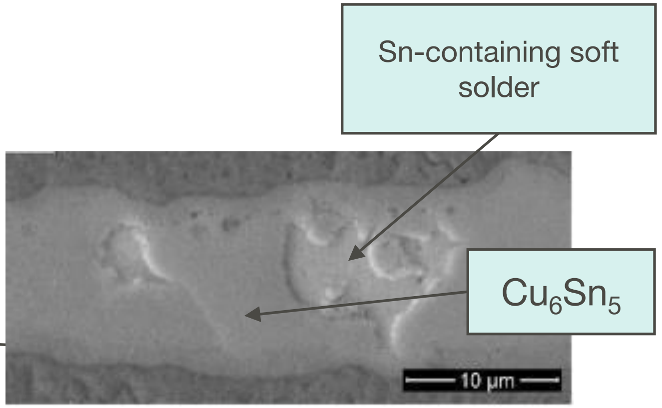
Layered diffusion solder materials

RESULTS - INITIAL MICROSTRUCTURE

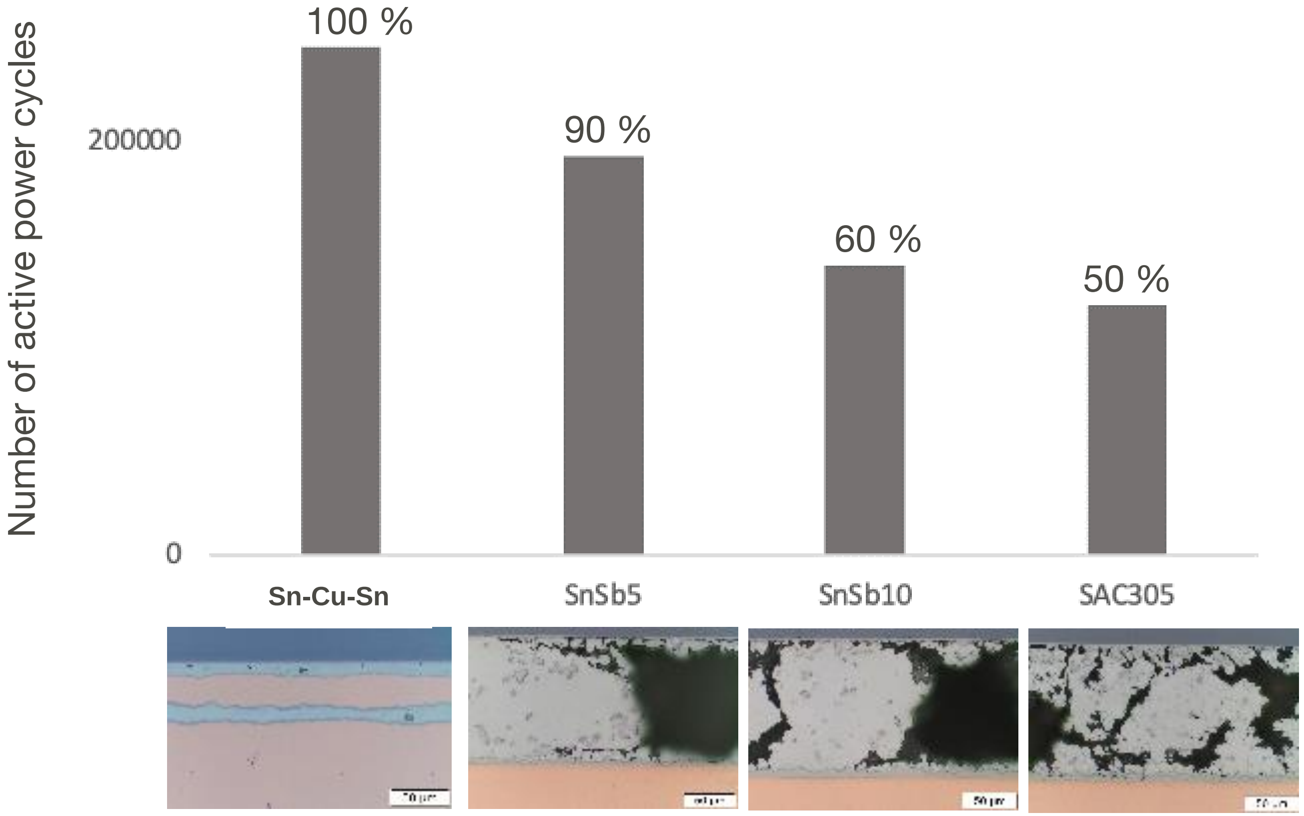
Bulk alloyed solder materials			
Basic microstructure of the bulk solder	- Fine and homogeneous microstructure of the bulk solder	- Solidified solder structures - Homogeneous microstructure of the bulk solder	
IMC at the interfaces	- Homogenous and needle-like crystalline structure of the IMC Cu_6Sn_5 layer - 2-3 µm thickness of Cu_6Sn_5 IMC layer	- Homogenous and needle-like crystalline structure of the IMC Cu_6Sn_5 layer - 2-3 µm thickness of Cu_6Sn_5 IMC layer	- 2-3 µm thickness of Cu_6Sn_5 IMC layer

RESULTS - INITIAL MICROSTRUCTURE

Layered diffusion solder materials	
Basic microstructure bulk solder	• Layered structure • Sn-layer is transformed into Cu_6Sn_5 (columns) with “Sn-islands” in the middle of the Sn-solder layer • Thickness of copper layer remains constant
IMC at the interface	• Column-structure of Cu_6Sn_5 over the entire Sn-solder layer ➔ connecting the interfaces • At the interface of Cu and Sn the IMC Cu_3Sn can be detected

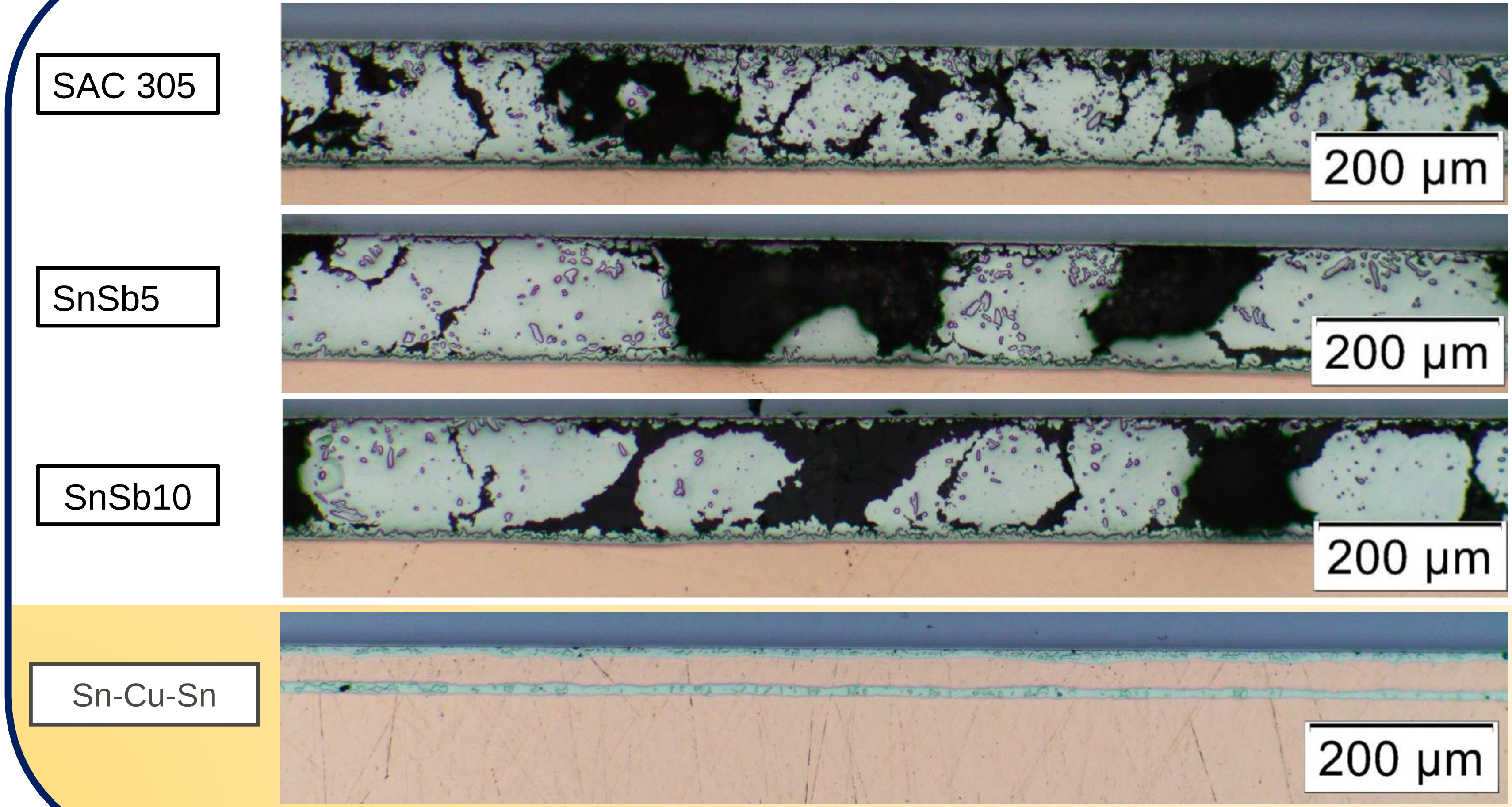


RESULTS - ACTIVE POWER CYCLING TEST

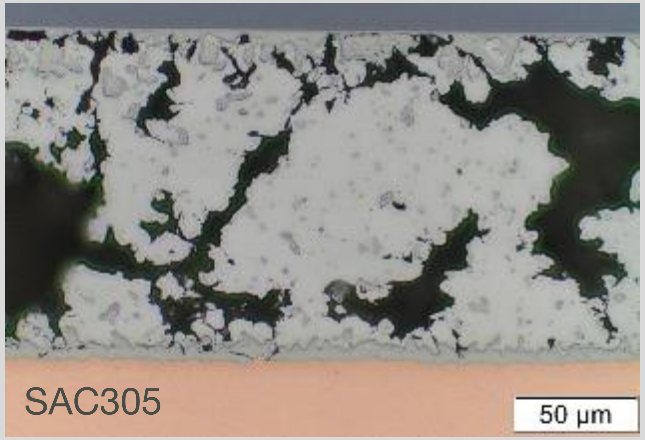
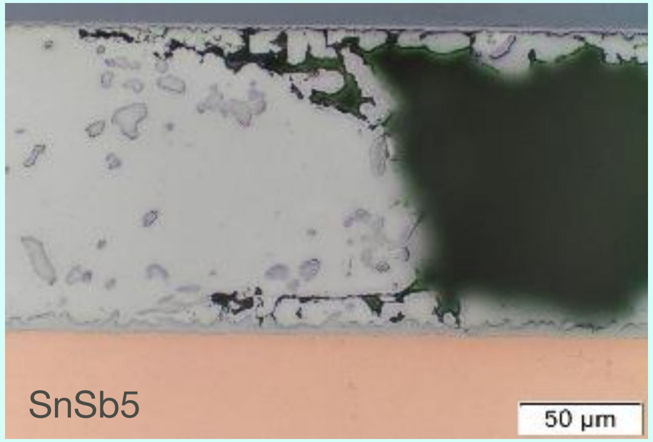
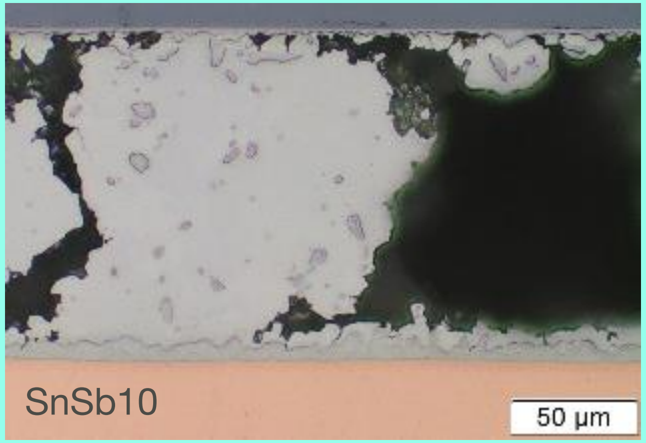


50 % higher lifetime with layered diffusion solder material Sn-Cu-Sn compared to SAC305

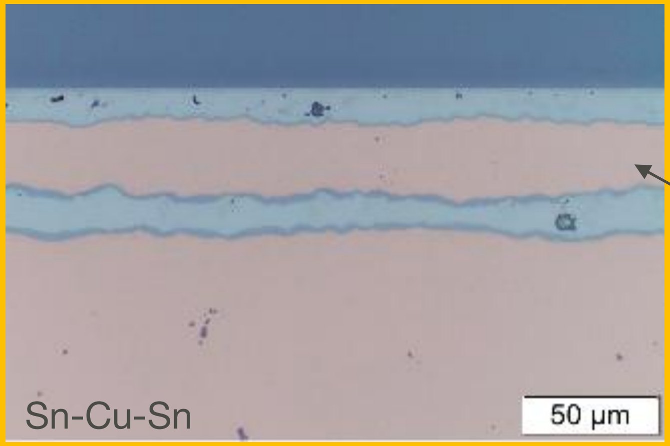
RESULTS - MICROSTRUCTURE AFTER POWER CYCLING

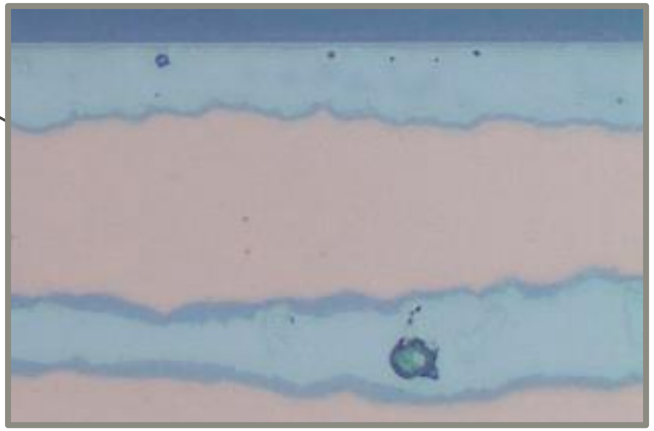


RESULTS - MICROSTRUCTURE AFTER POWER CYCLING

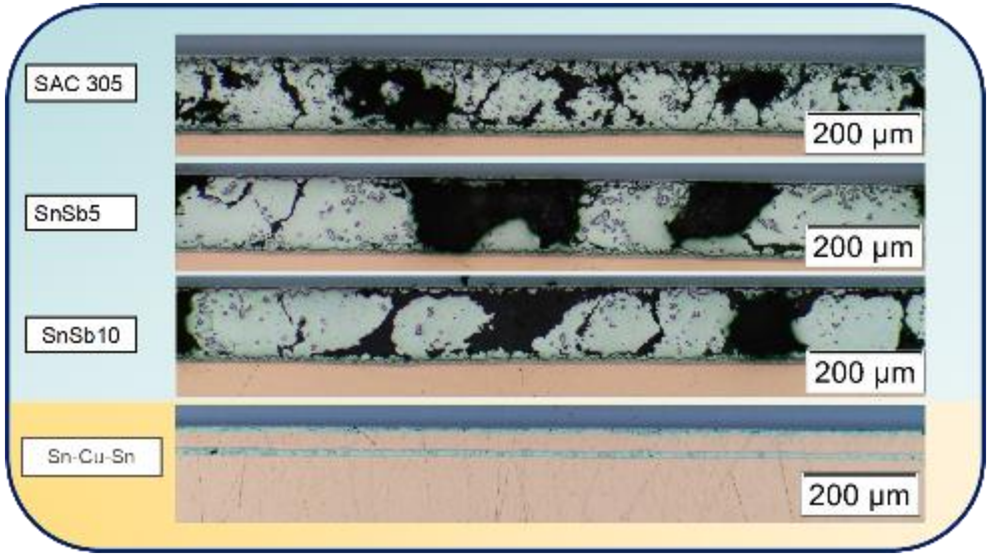
Bulk alloyed solder materials			
Basic microstructure bulk solder	• Coarsening of the microstructure • Cu_6Sn_5 IMC in the middle of the solder layer • Defect zones over the entire solder • Crack initiation inside the bulk solder	• Coarsening of the microstructure • Cu_6Sn_5 IMC in the middle of the solder layer • Large local defect zones • Crack initiation inside the bulk solder	• Coarsening of the microstructure • Cu_6Sn_5 IMC in the middle of the solder layer • Blocky phases couldn’t be detected ➔Large local defect zones • Crack initiation inside the bulk solder
IMC at the interfaces	• Levelled needle-like crystalline structure at the IMC	• Levelled needle-like crystalline structure at the IMC	• Levelled needle-like crystalline structure at the IMC

RESULTS - MICROSTRUCTURE AFTER POWER CYCLING

Layered diffusion solder materials	
Basic microstructure bulk solder	• Layered structure • Cu_6Sn_5 columns over the entire Sn-layer • Reduced amount of “Sn island” thickness of copper layer remains constant • No defects visible
IMC at the interface	• Increase of the column-structure Cu_6Sn_5 connecting the interfaces • Increase of the Cu_3Sn intermetallic compound at the interface of Cu and Sn



DISCUSSION



The bulk alloyed solders SAC 305, SnSb5 and SnSb10:

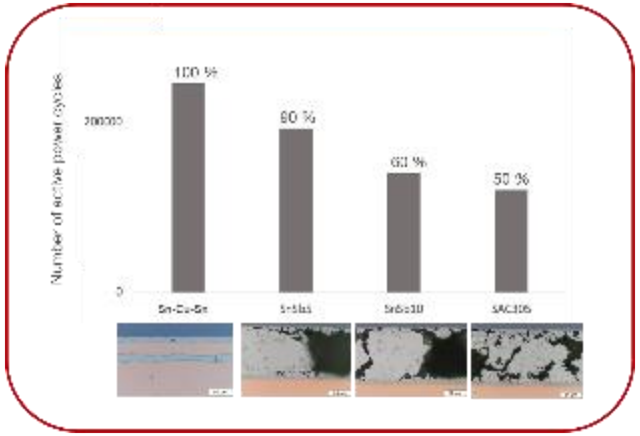
- Strong metallic bond at the interfaces with Cu_6Sn_5
- Growth of IMC in the the solder layer ➜ crack initiation
- Higher homologous temperature at T_{max}=140 °C indicates earlier material fatigue

The layered diffusion solder (Sn-Cu-Sn):

- Strong metallic bond at the interfaces with Cu_3Sn and Cu_6Sn_5
- Cu_6Sn_5 columns over the entire Sn-solder layer stabilized and hardened the die attach against thermo-mechanical stress

Table: Material properties [7,8]:

Solder	SAC 305	SnSb5	SnSb10	Cu_6Sn_5	Cu_3Sn	Cu	Sn
Melting temperature T_m	217 °C	240 °C	250 °C	415 °C	676 °C	1085 °C	232 °C
Homologous temperature at 140 °C	0,64	0,58	0,56	0,34	0,21	0,13	0,60
CTE ppm/K	21	27	/	16,3	18,2 – 19,0	17,3	21



[7] Ehrhardt, Christian, Matthias Hutter, Constanze Weber, and Klaus-Dieter Lang, "Active Power Cycling Using Copper Tin TLPB Joints as New Die-Attach Technology," *PCIM Europe Nuremberg*, Germany, 19-21 May 2015, pp. 1268-1275
[8] Syed-Khaja, Aarief. "Diffusion Soldering for the High-Temperature Packaging of Power Electronics," FAU University Press (2018), pp. 31-33

AGENDA

1 INTRODUCTION

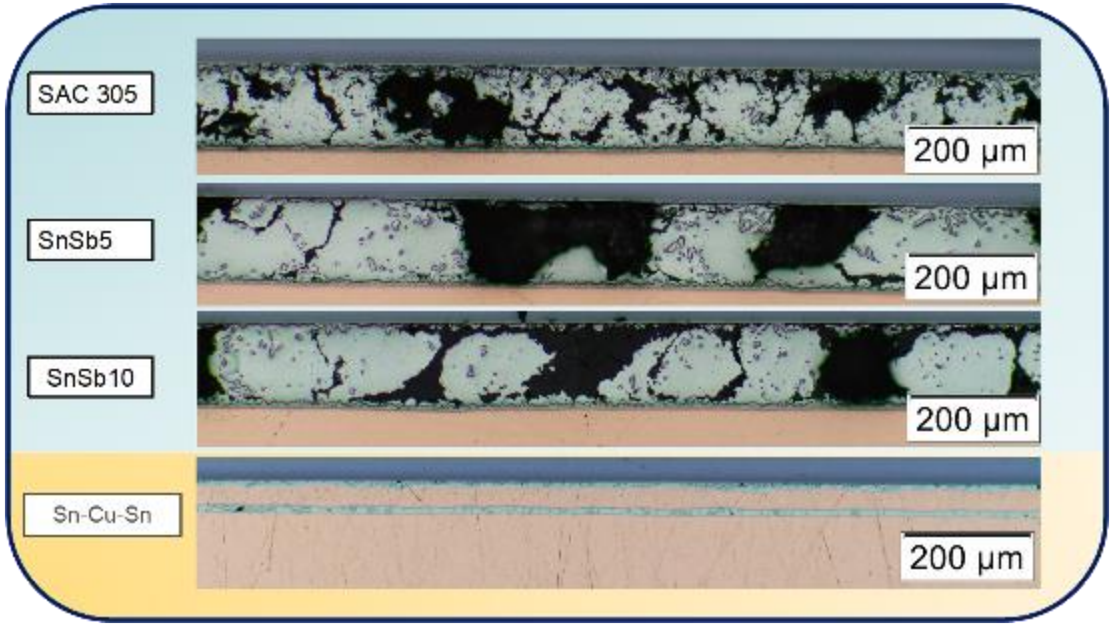
2 METHODS

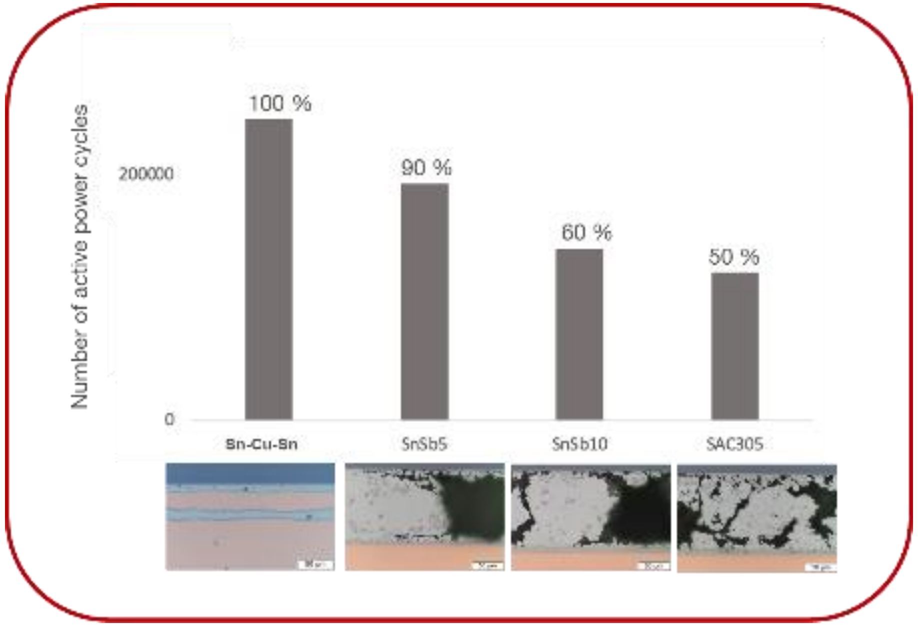
3 RESULTS AND DISCUSSION

4 SUMMARY

5 OUTLOOK

SUMMARY





50 % higher lifetime with layered diffusion solder material PFDS400®

SUMMARY

- DOE study has been performed on the power module
- A slight increase of maximum principal stresses is observed when increasing with IMP thickness - stresses are not critical
- Cyclic equivalent plastic strain decreases with increase in IMP thickness – low chances of die attach failure
- Von Mises stresses on metallization layer at die attach interface – not critical
- Higher the IMP thickness tends to have higher the lifetime of the power module with respect to die attach

AGENDA

1 INTRODUCTION

2 METHODS

3 RESULTS AND DISCUSSION

4 SUMMARY

5 OUTLOOK

OUTLOOK

- Further investigations are planned with improved topside connection on SiC dies
- Additional FEM analysis will provide further insight in lifetime potential of TLPS layers
- Geometrical stress optimization will be supported by FEM
- Activities will be supported by FHG ENAS