Joint material for power semiconductors by Cu-Sn Intermetallic Compound (IMC)

Hiroaki Ikeda

Napra

May 25th , 2019

Contents

1. Motivation
2. Prior works and challenges
3. Our approach
4. Evaluation results
5. Conclusion and the next steps

Contents

1. Motivation
2. Prior works and challenges
3. Our approach
4. Evaluation results
5. Conclusion and the next steps

Power semiconductors and their power density

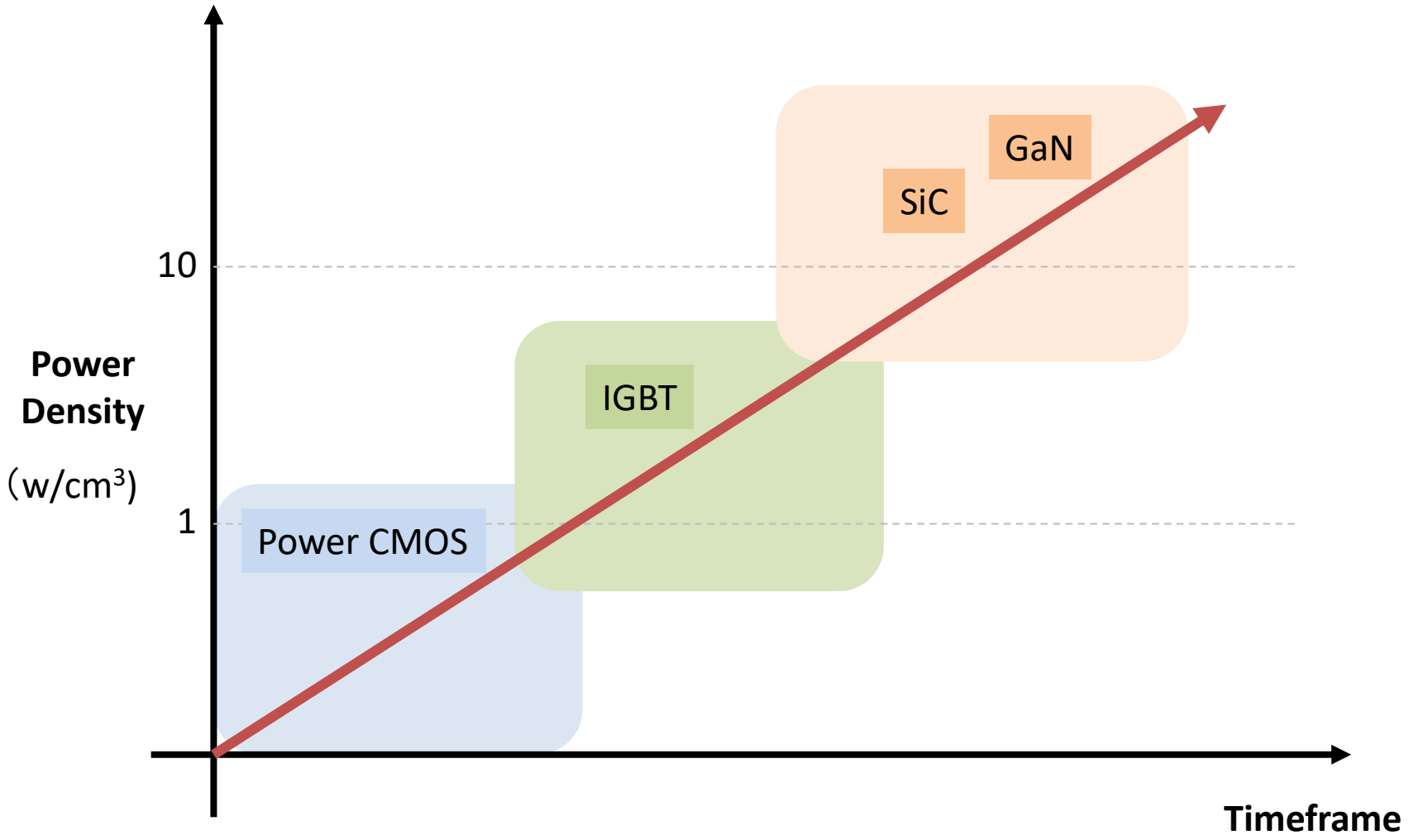
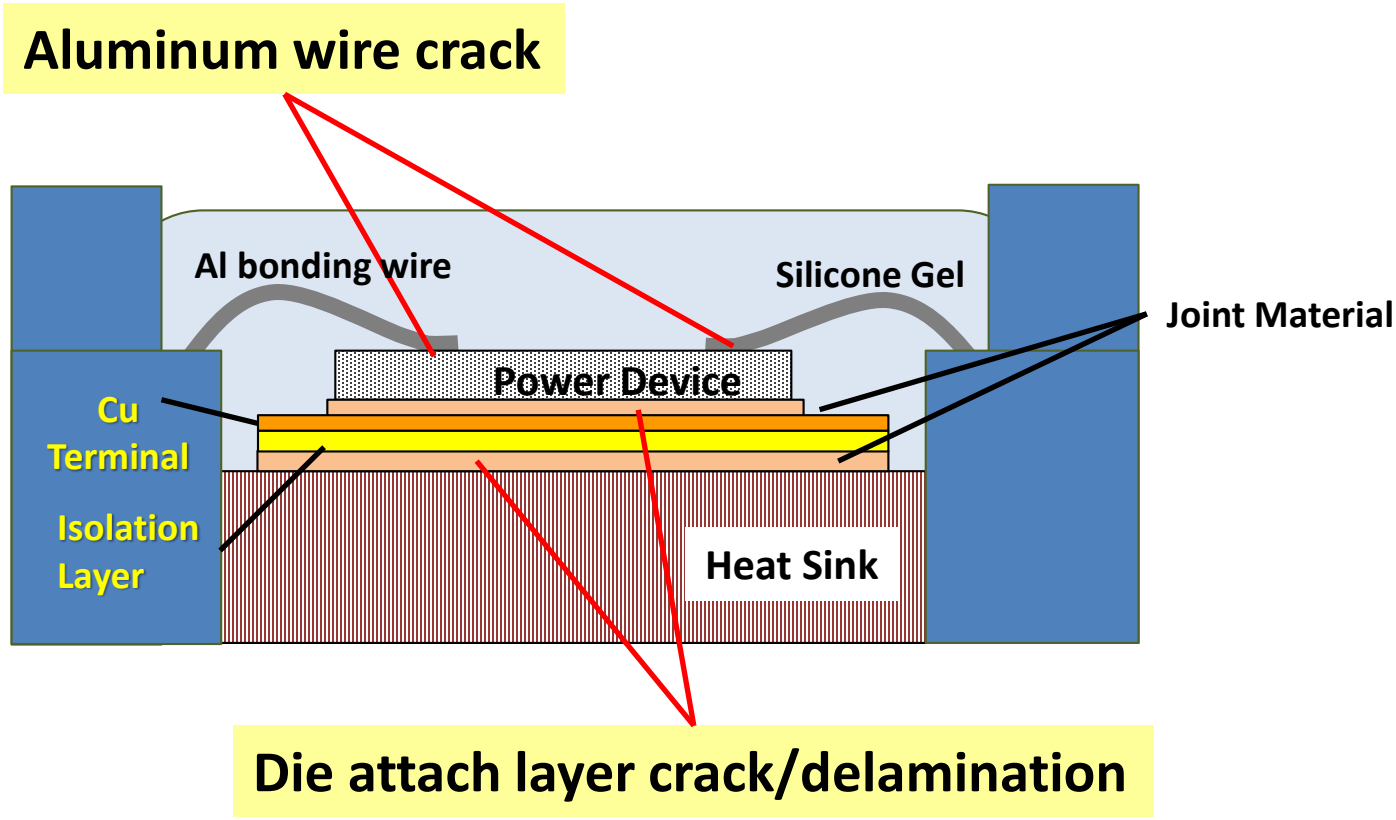


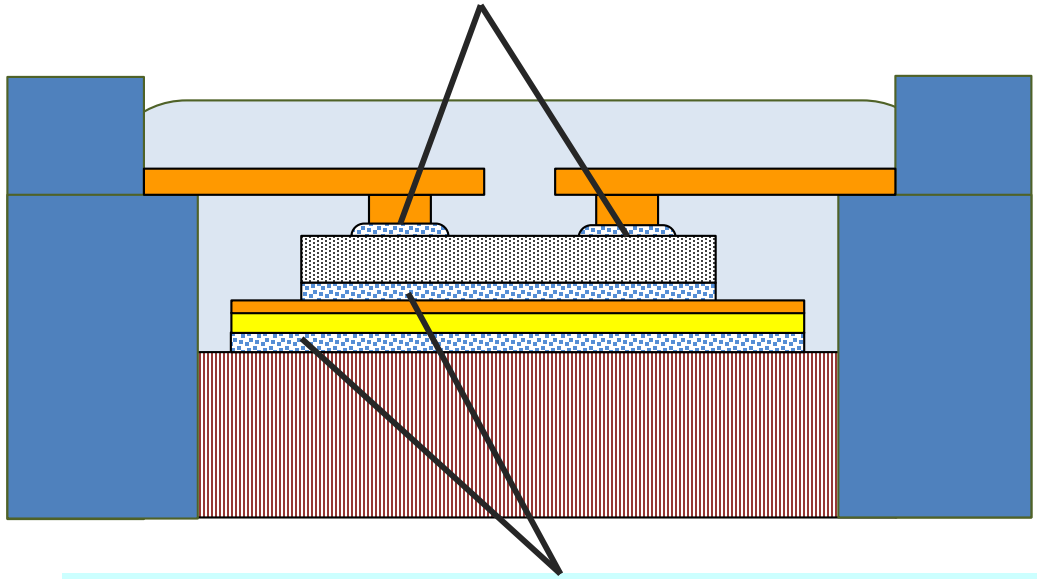
Fig.1

Issues of power semiconductor operation from 175°C to 250°C



Movements on packaging technology toward 250°C

Interconnect with Cu-pillar by joint material



Advanced heat-resistant die attach material
(This work)

Conventional candidates as high-temperature joint materials

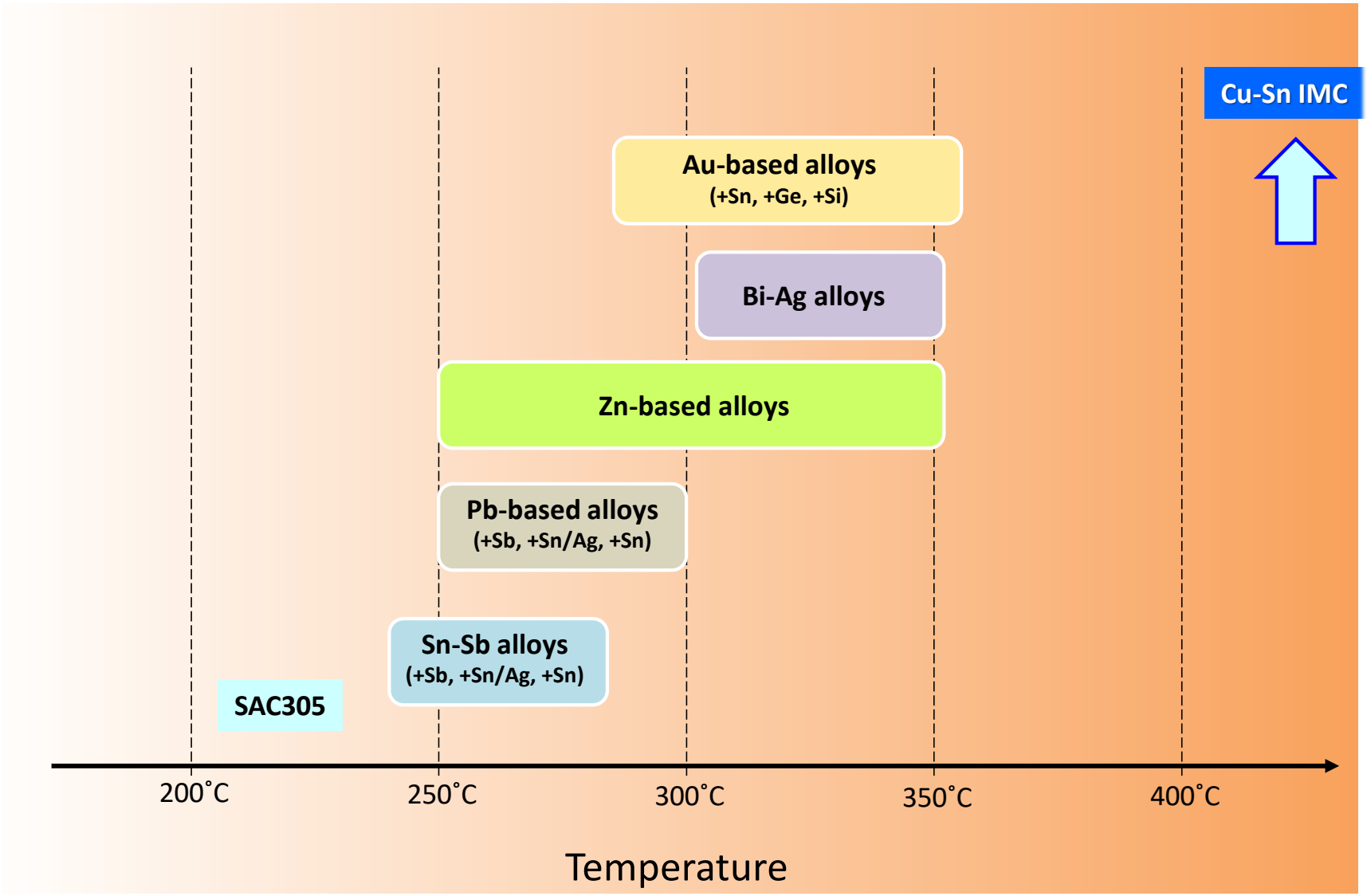
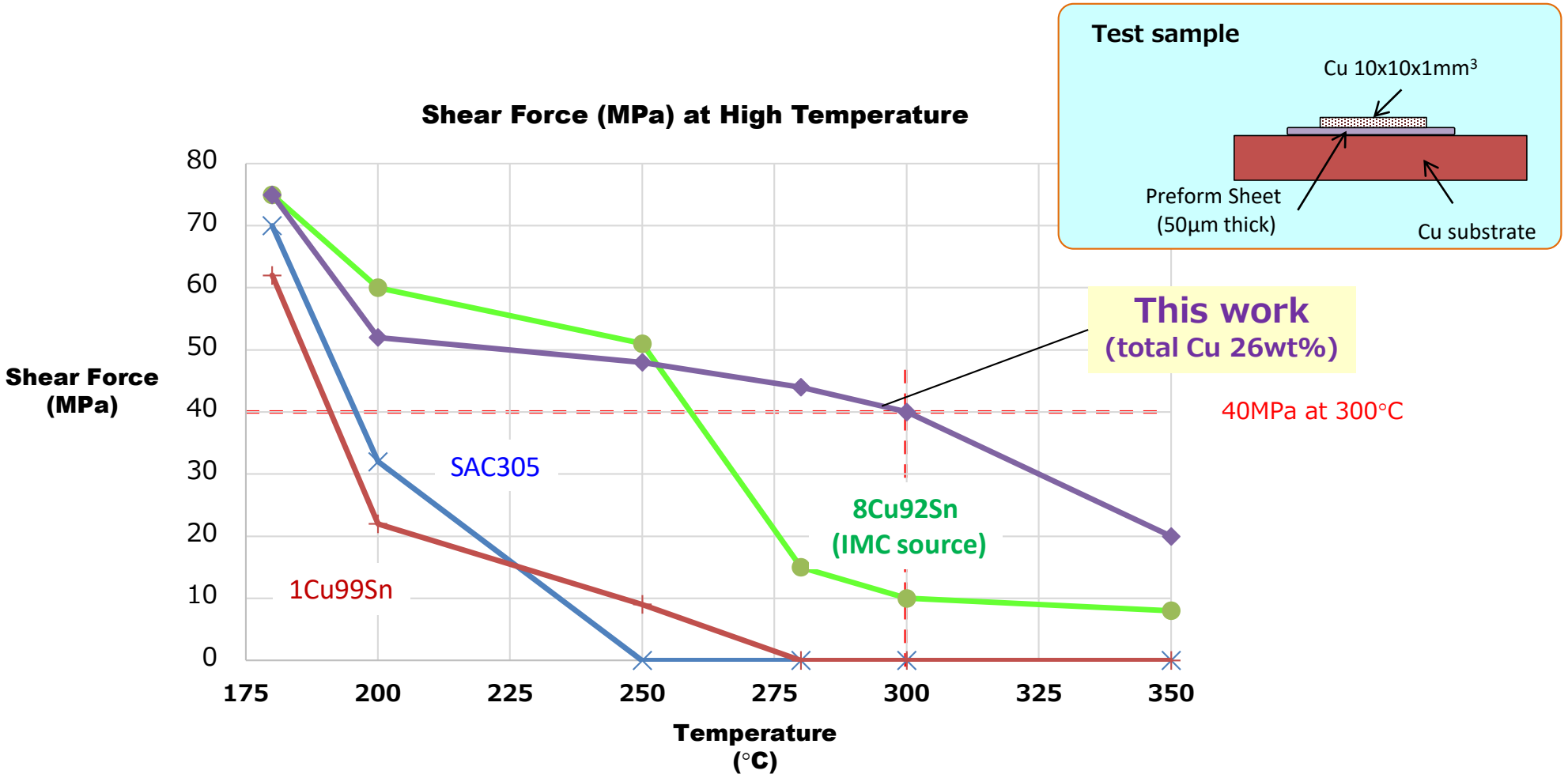


Fig.2

Napra's Joint Material Characteristic Example

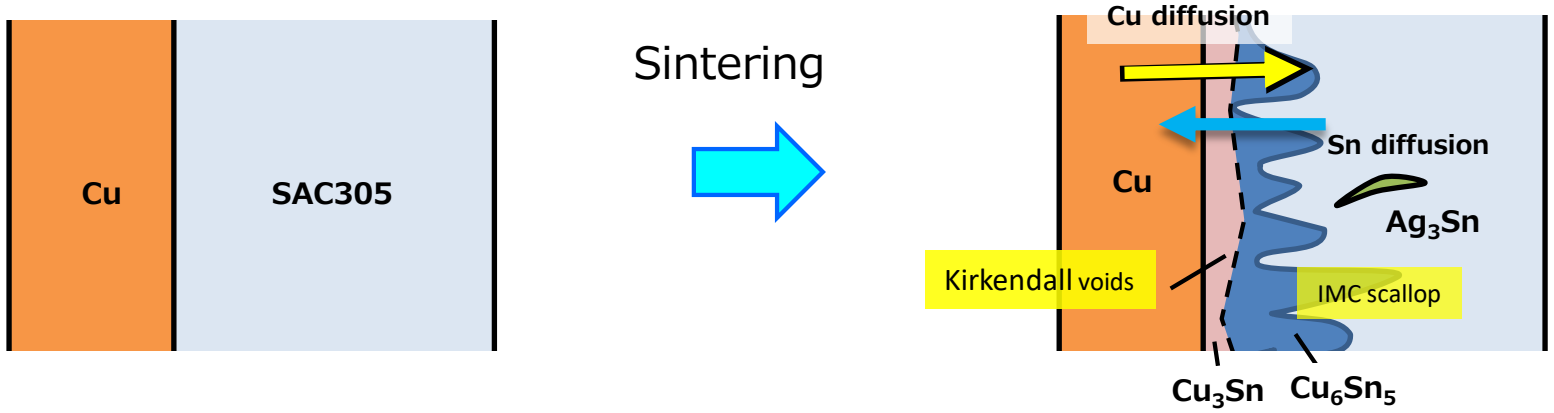
(Shear force evaluation at high temperature)



Contents

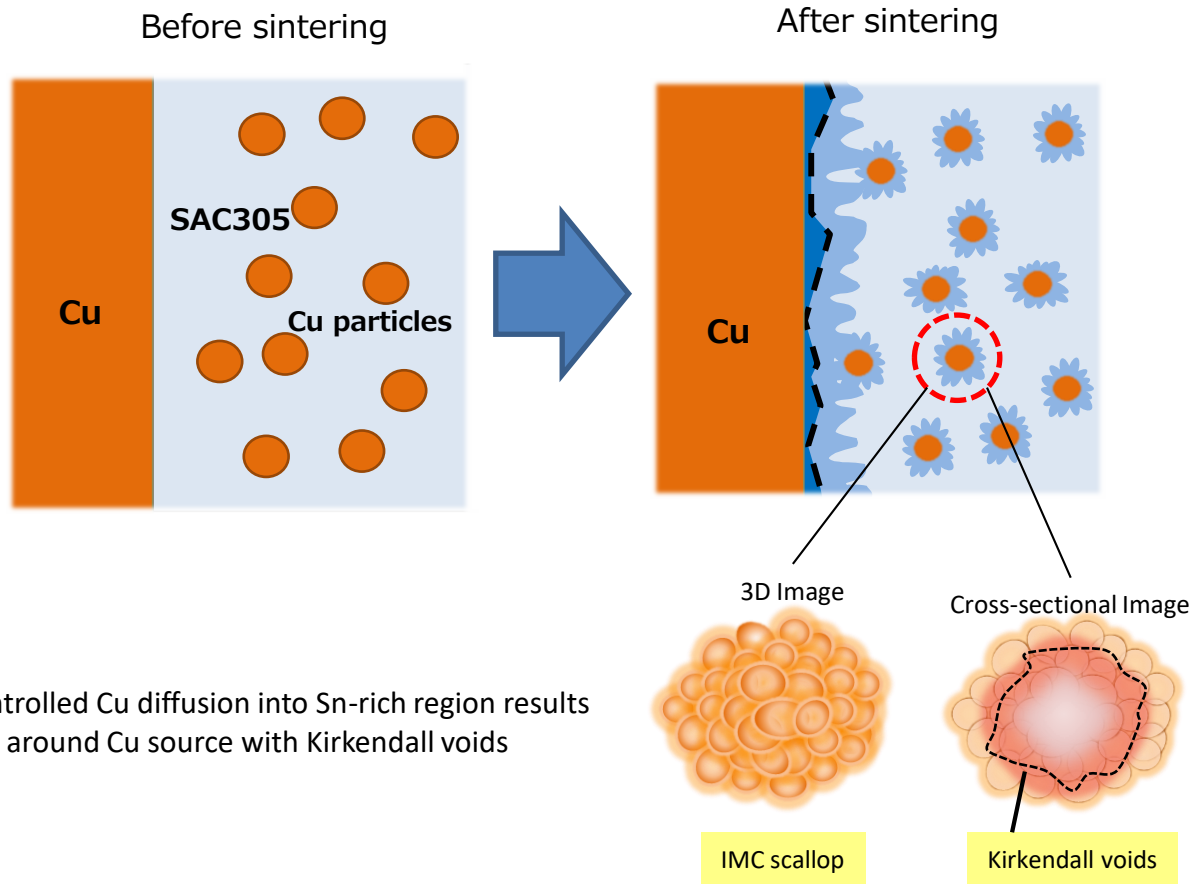
1. Motivation
2. Prior works and challenges
3. Our approach
4. Evaluation results
5. Conclusion and the next steps

Basic Interaction between Cu and SAC makes **IMC scallop** close to Cu source
Un-controlled Cu-Sn interaction makes **Kirkendall voids** between IMC layers



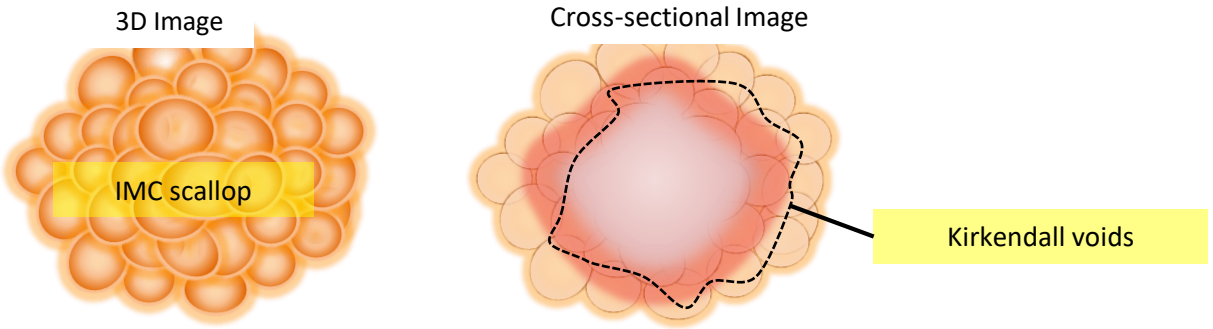
This structure is not suitable for high-temperature usage
So, joint materials for heat-resistant usage usually require noble metal composite such as AuSn, AuGe and sintered-(nano)Ag

Mixture of Cu particles into solder also resulted **IMC scallop around Cu particles** having **Kirkendall voids**



Un-controlled Cu diffusion into Sn-rich region results scallop around Cu source with Kirkendall voids

Actual example of prior work



IMC scallop with **Kirkendall voids** around Cu particle

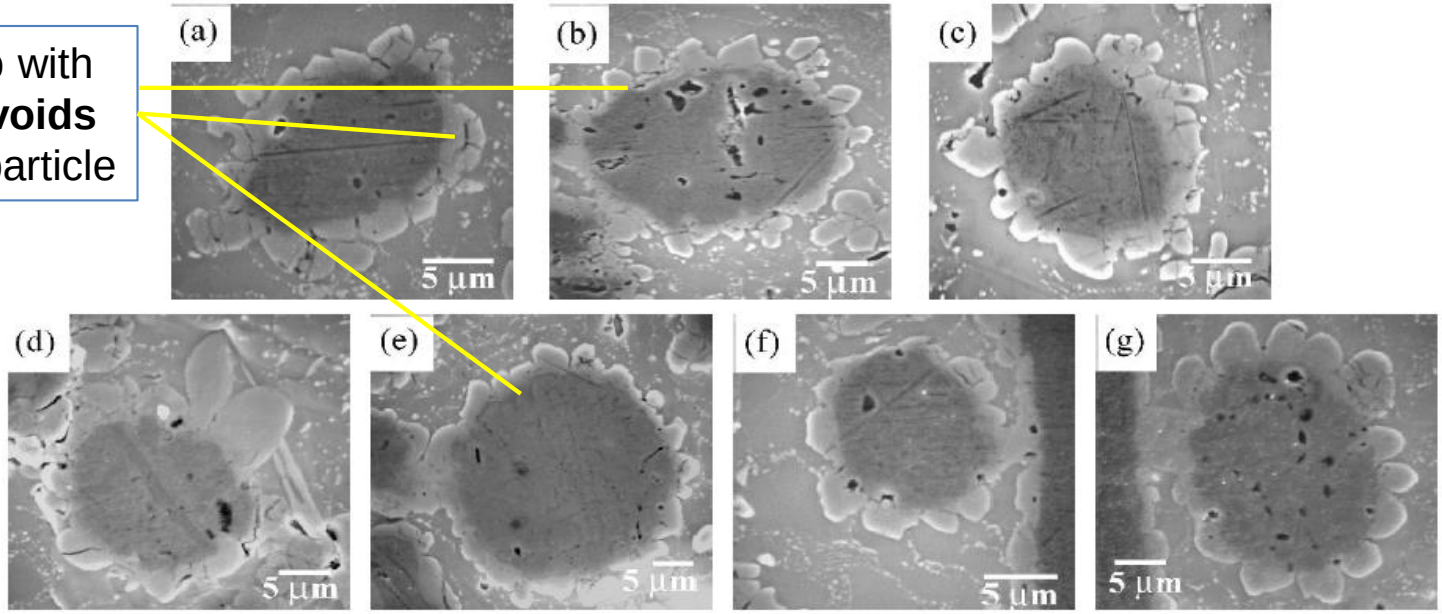
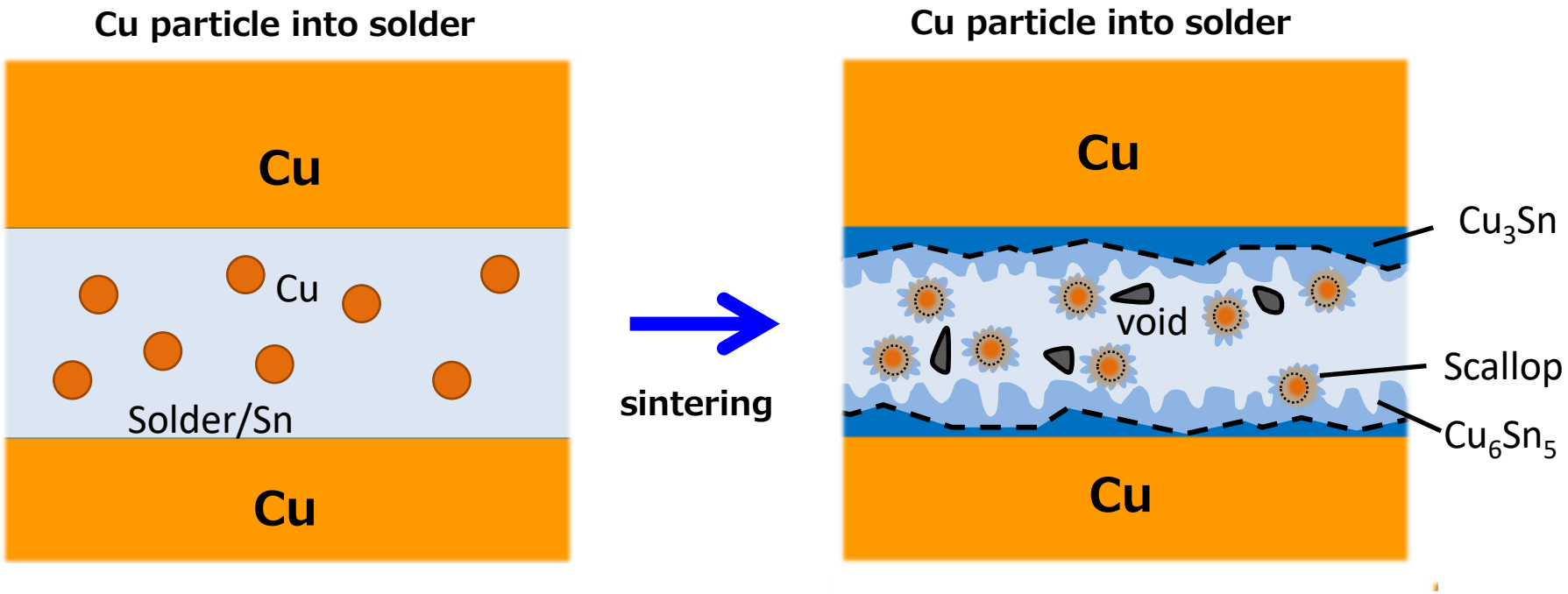


Fig. 2. The IMC morphology in the Cu composite solder after reflows with different cooling rates ((a)–(d) fixed fast heating rate): (a) the fastest cooling rate, (b) fast cooling rate, (c) slow cooling rate, and (d) the slowest cooling rate. The IMC morphology of the Cu composite solder after reflows with different heating rates ((e)–(g) fixed fast cooling rate): (e) fast heating rate at higher peak temperature (320°C), (f) medium heating rate, and (g) slow heating rate.

J. G. Lee, K. C. Chen, K. N. Subramanian, "Formation and growth of intermetallics around metallic particles in eutectic Sn-Ag solder" Journal of Electronic Materials November 2003, Volume 32, Issue 11, pp 1240–1248

Control of IMC forming
- simple mixture did not work (prior works) -

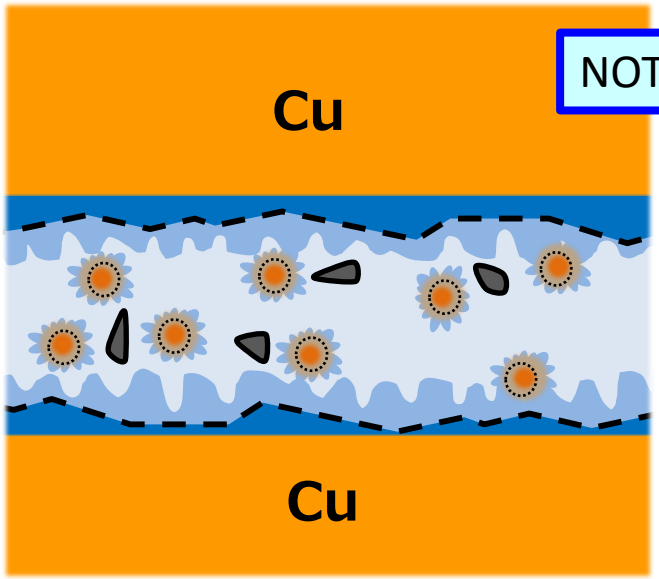


This doesn't work

Fig.3

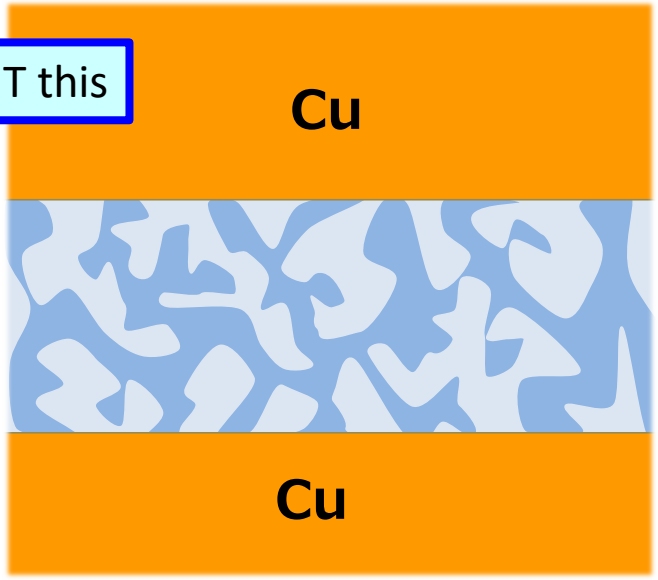
Control of IMC forming
- our approach-

Cu particle into solder



Forming IMC scallop with voids

Development Target



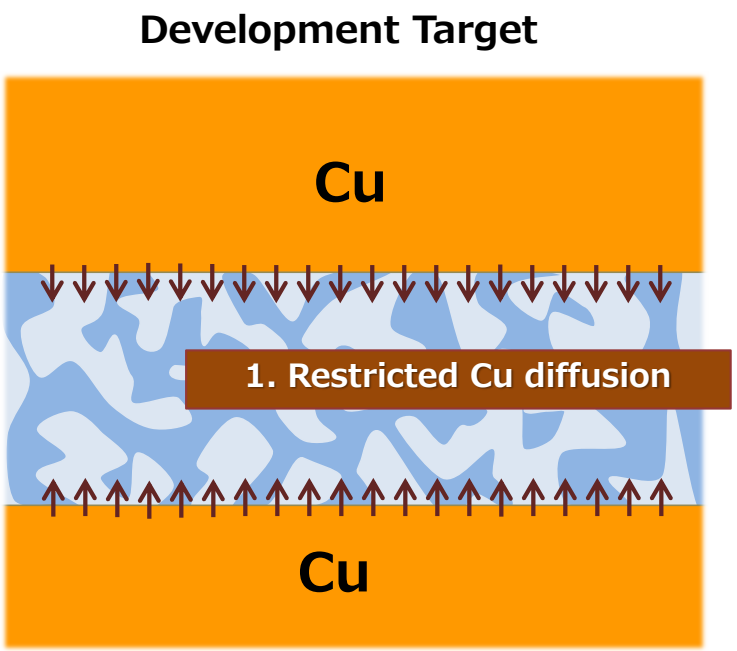
Forming IMC Skeleton

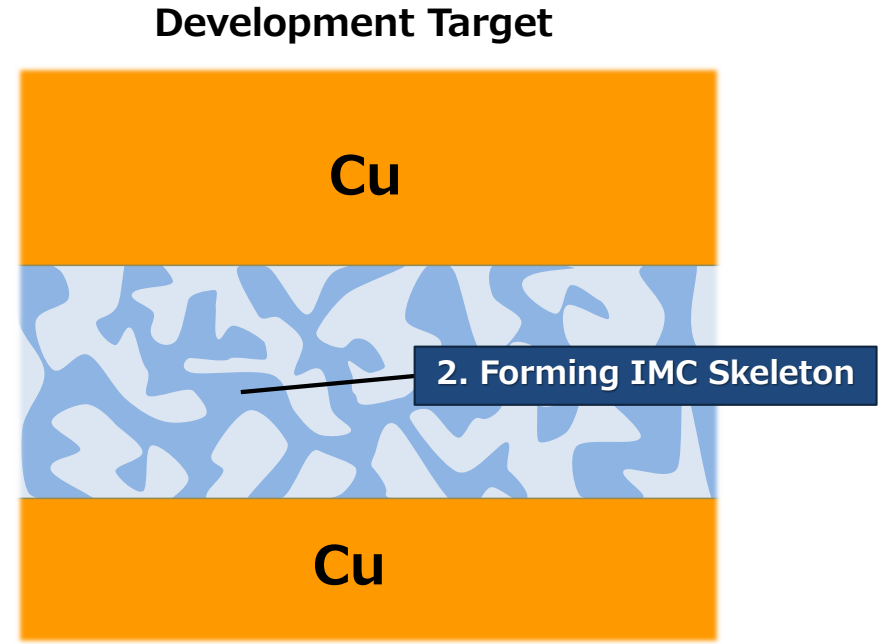
Fig.4

Contents

1. Motivation
2. Prior works and challenges
3. Our approach
4. Evaluation results
5. Conclusion and the next steps

Two key features for making IMC skeleton



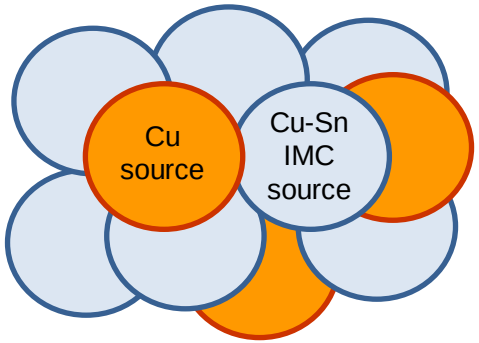


Basic concept to make Cu-Sn IMC structure

(IMCC* joint material)

* IMCC: **I**nter**m**etallic **C**omposition **C**omposite

before sintering



sintering

after sintering

Cu-Sn IMC

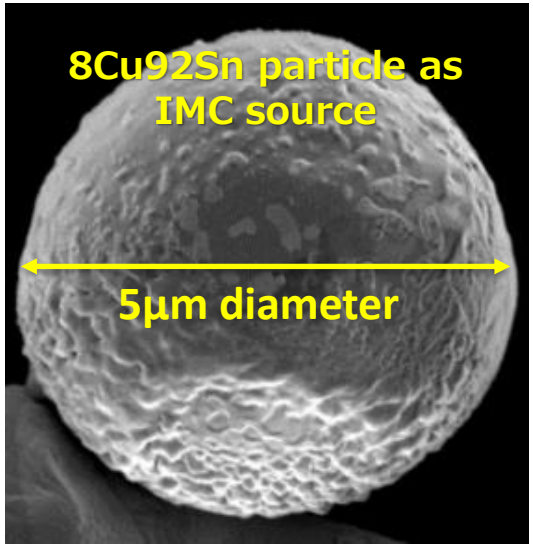
Cu-Sn IMC Liquidus Point

Cu_6Sn_5: 435˚C

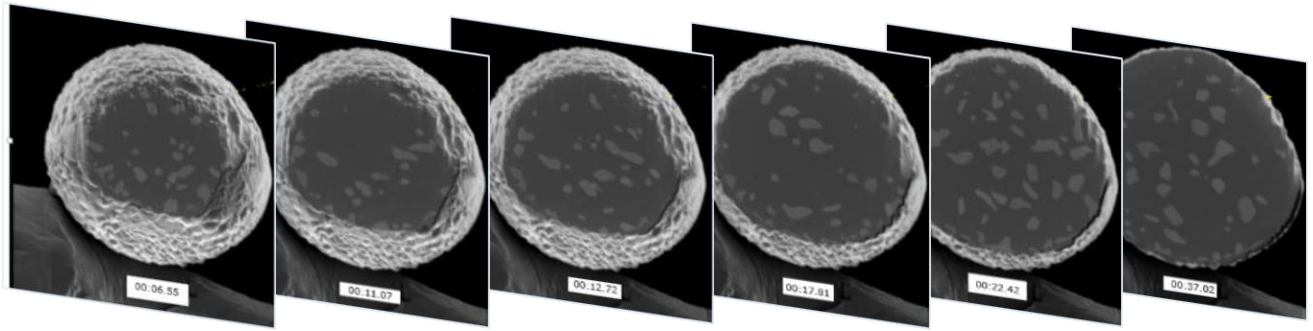
Cu_3Sn: 676˚C

Fig.5

IMC source is the key material for the purpose



FIB slices of IMC source



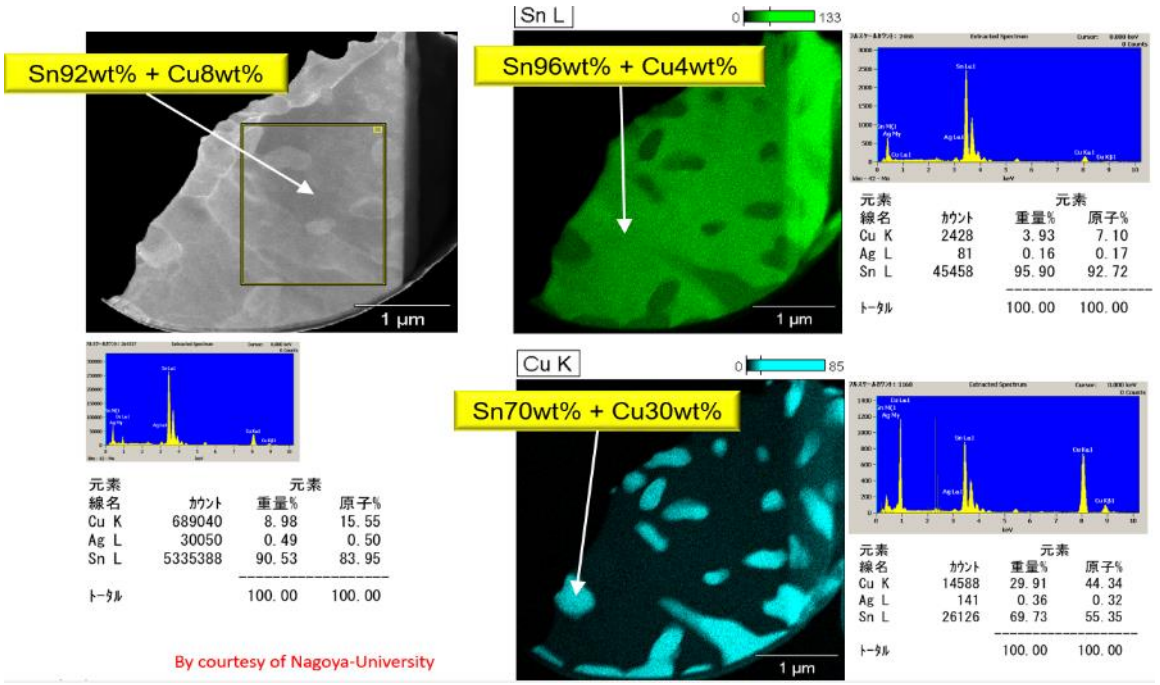
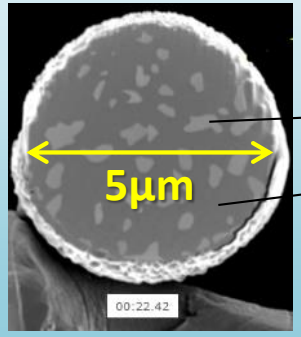


Fig.6

IMC skeleton generating process

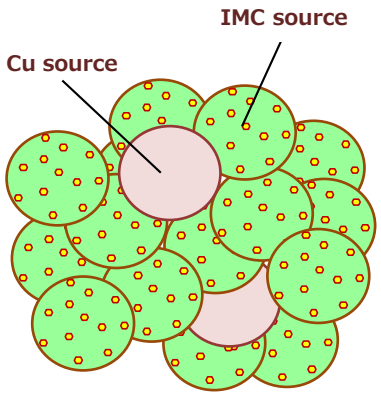
Structure of Cu-Sn IMC source
(8Cu92Sn)



IMC Colonies
(contains 30wt% Cu)

Cu-Sn basal phase
(contains 4wt% Cu)

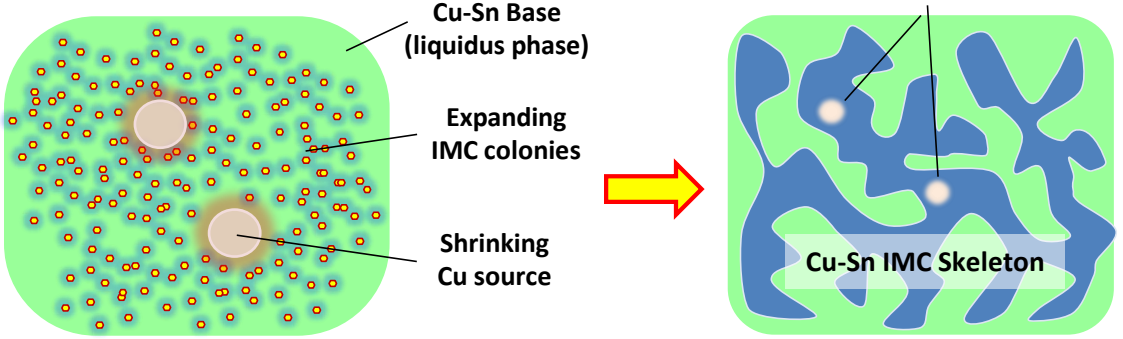
before sintering



while/after sintering

IMC colonies (in IMC sources) expand to generate skeleton

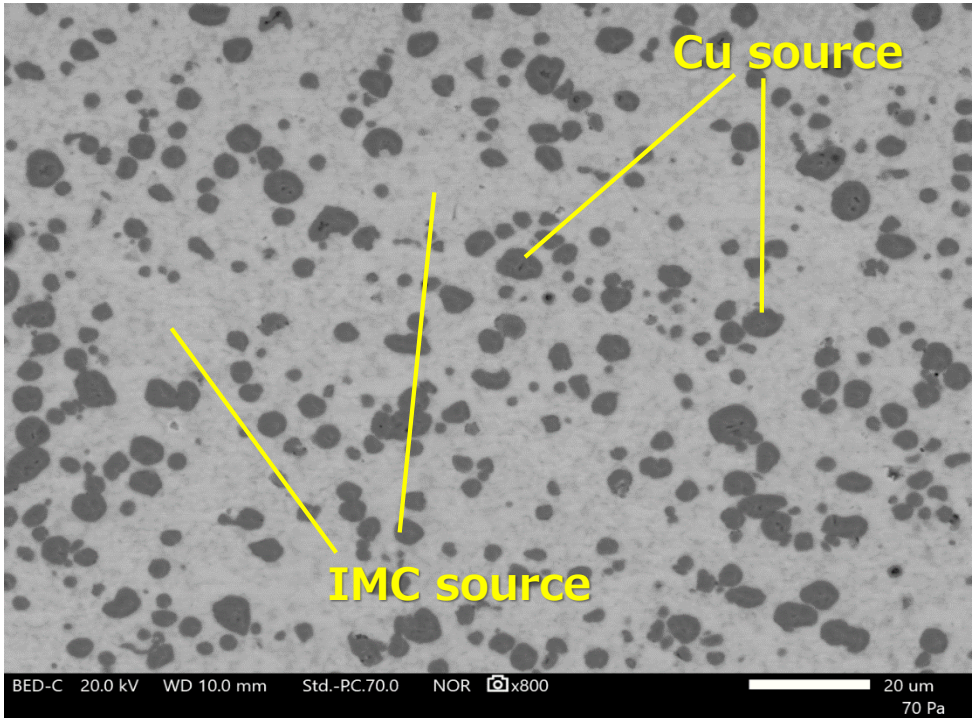
Cu sources are consumed by IMC forming
This reaction is restricted by pre-existing IMC colonies eliminating voids



Basic behavior of IMCC paste/sheet composition to make Cu-Sn IMC skeleton structure

Before Sintering

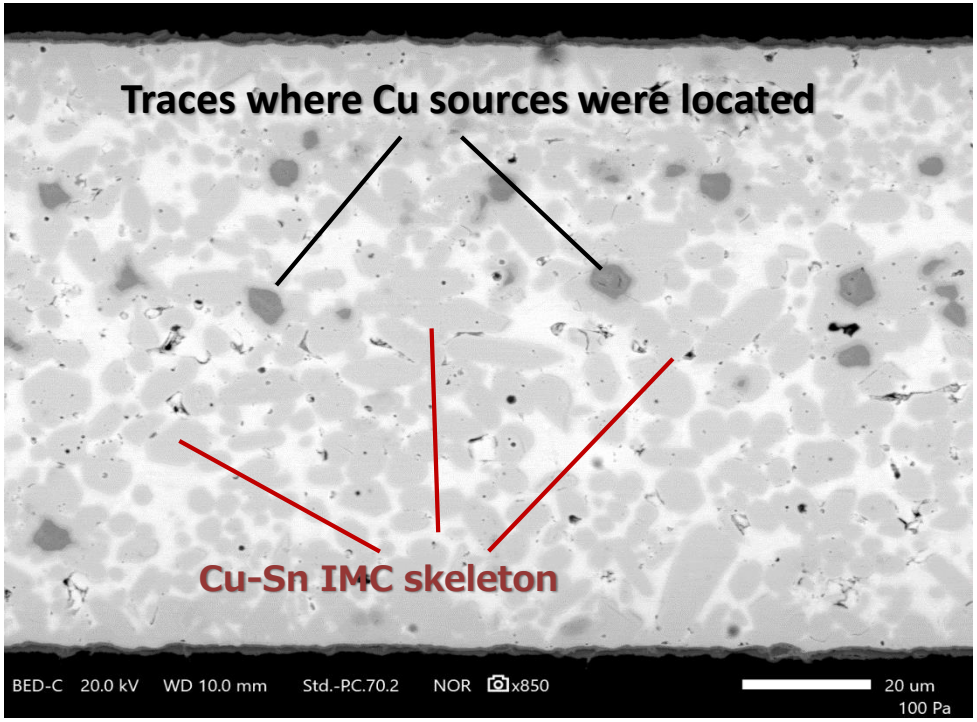
t1723



Cu contents ~ 28wt%
No SAC particles

After Sintering

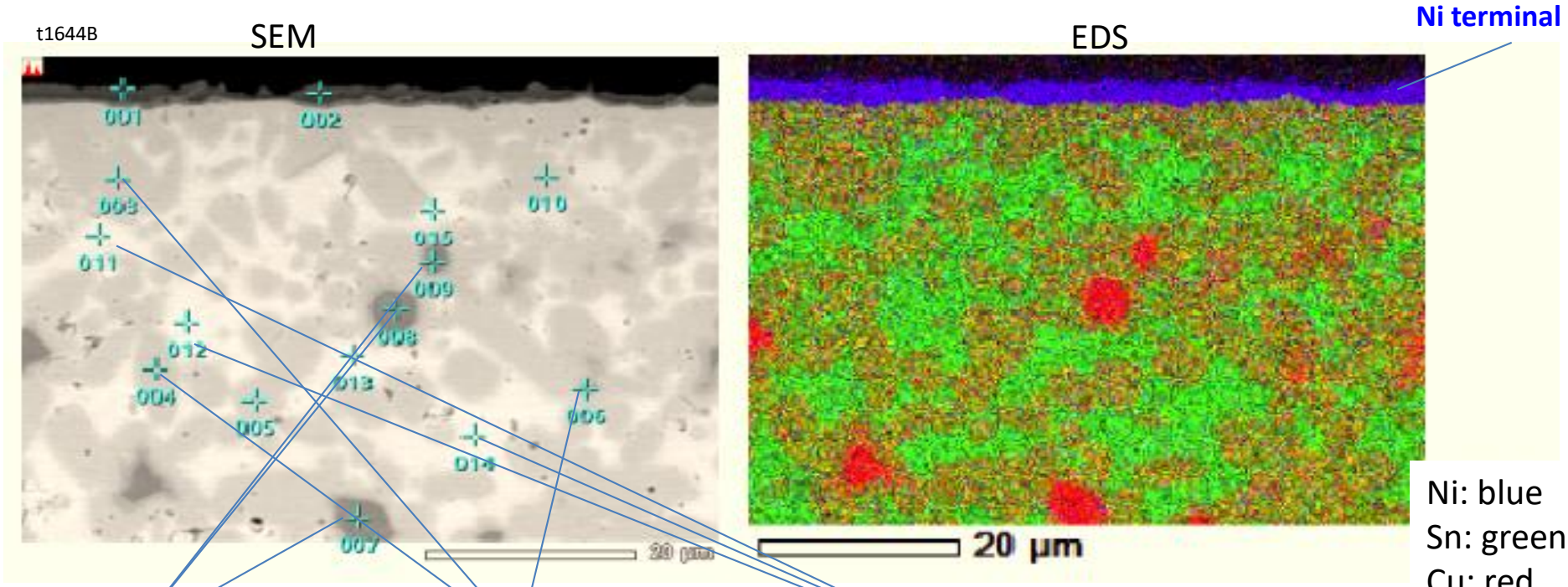
t1644B



Cu sources are completely spent to be Cu-Sn IMC
IMC sources control Cu-Sn IMC forming to be expected manner
Uniformly distributed Cu-Sn IMC makes stable skeleton structure

Fig.7

After Sintering



[Dark Area]

<007> Cu : Sn = 78:22

<008> Cu : Sn = 79:21

<009> Cu : Sn = 79:21

[Gray Area]

<003> Cu : Sn = 34:66

<004> Cu : Sn = 34:66

<006> Cu : Sn = 40:60

[Bright Area]

<011> Cu : Sn = 8:92

<012> Cu : Sn = 7:93

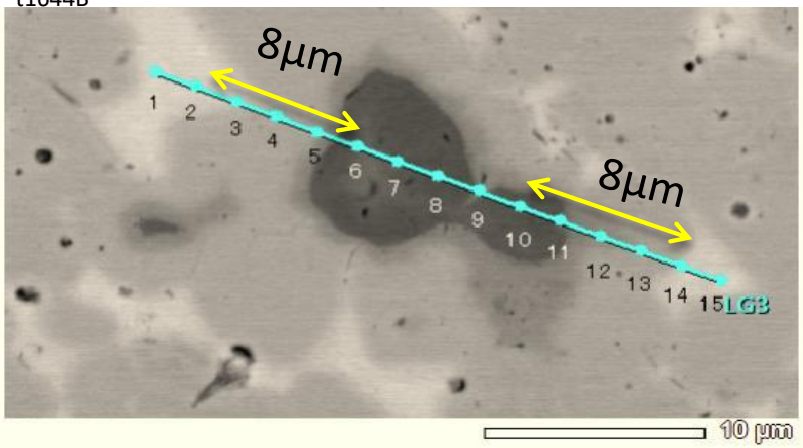
<014> Cu : Sn = 8:92

(wt% ratio)

No pure Sn or Cu region

Fig.8

t1644B



Voidless Cu/Sn gradient diffusion

After Sintering

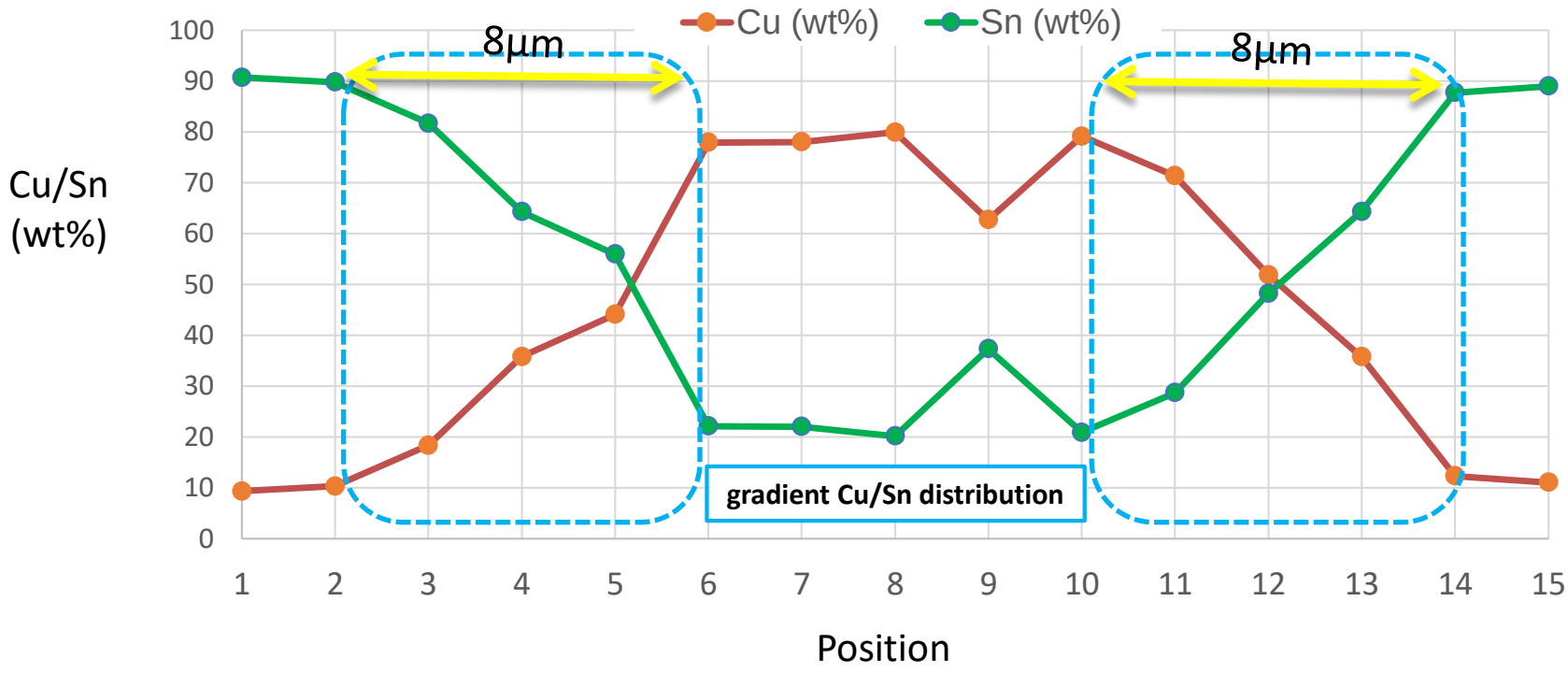
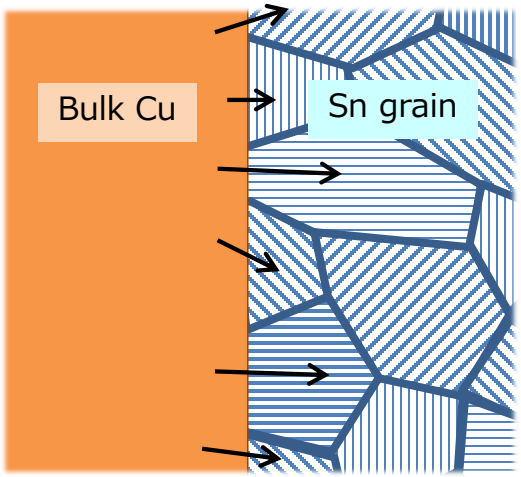


Fig.9

Microscopic Cu-Sn interaction model (1/2)

Restricted Cu diffusion

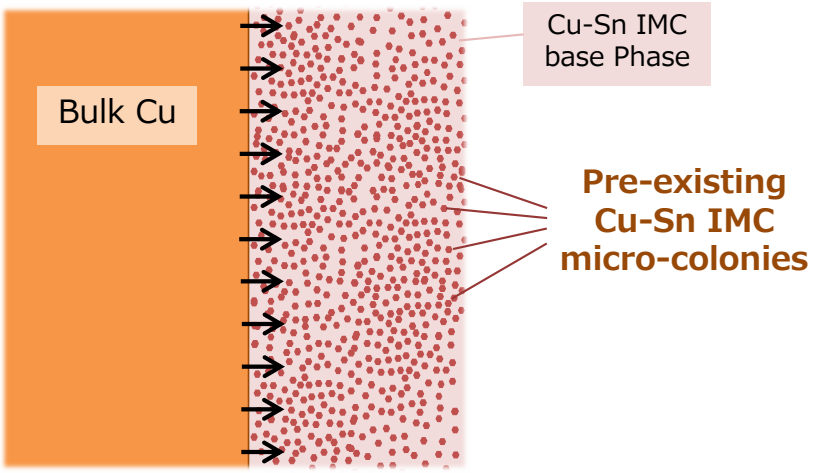
Conventional



Cu diffusion affected by Sn grains' crystal direction

Un-controlled Cu-Sn IMC forming results voids

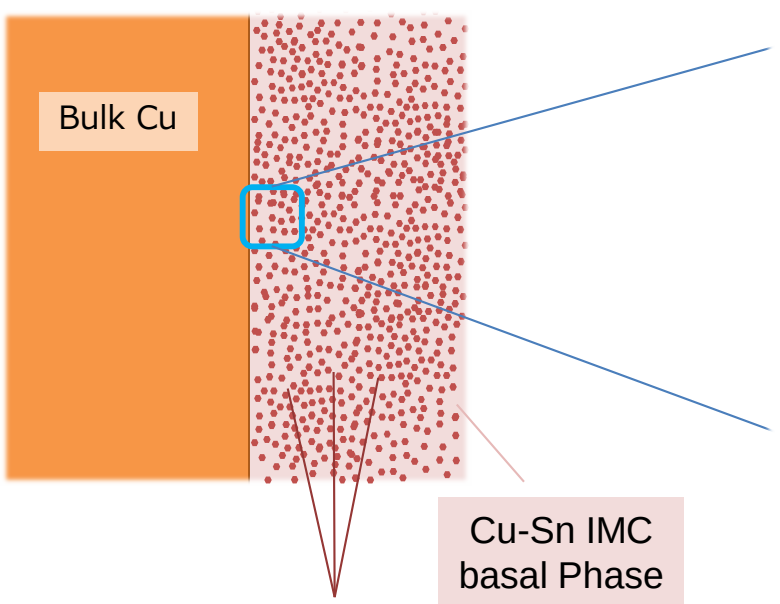
New Approach



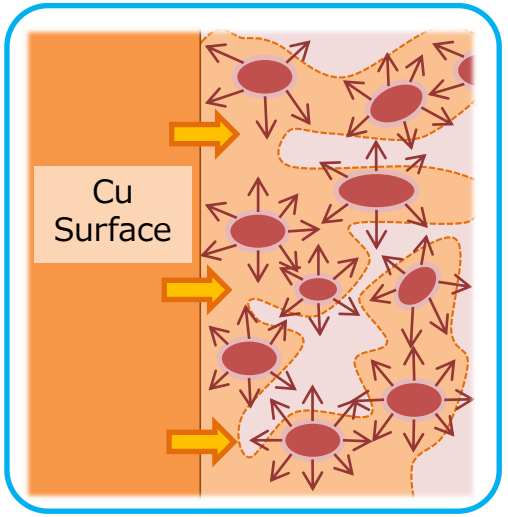
Restricted and uniform Cu diffusion affected by base phase bulk and IMC micro-colonies

Microscopic Cu-Sn interaction model (2/2)

Forming IMC Skeleton



Pre-existing Cu-Sn IMC micro-colonies



Expanding IMC micro-colonies fetch Cu and connect to each other forming IMC skeleton

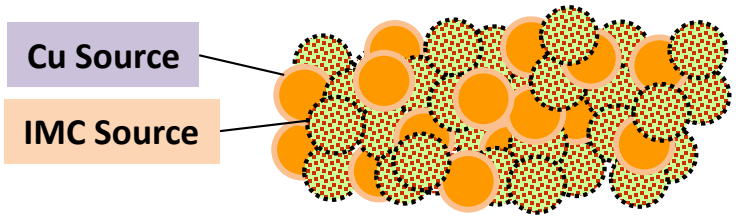
Contents

1. Motivation
2. Prior works and challenges
3. Our approach
4. Evaluation results
5. Conclusion and the next steps

IMCC* sheet

* **IMCC**; **I**nter**m**etallic **C**ompound **C**omposite

(Developed and in MP)



- Quite stable at high temperature exposure
- Thicker joint area

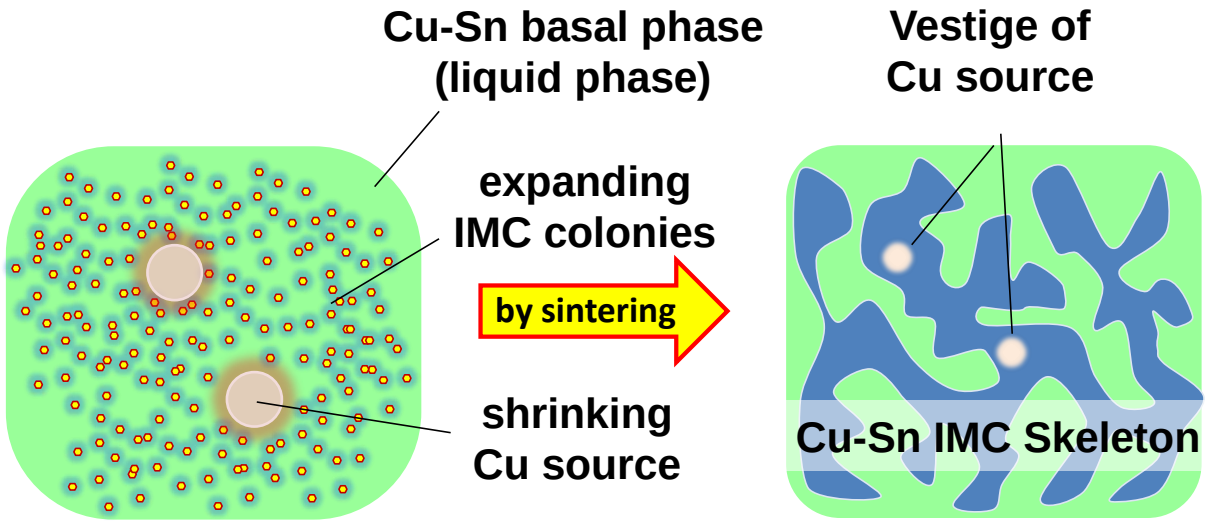
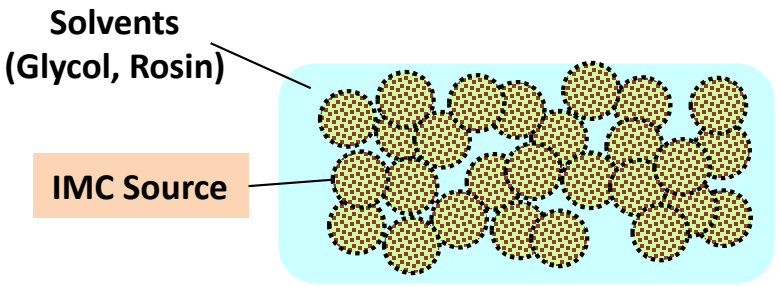


Fig.11

IMCC paste

(ES/CS)

- For thin joint region
- Better adoptability for applications



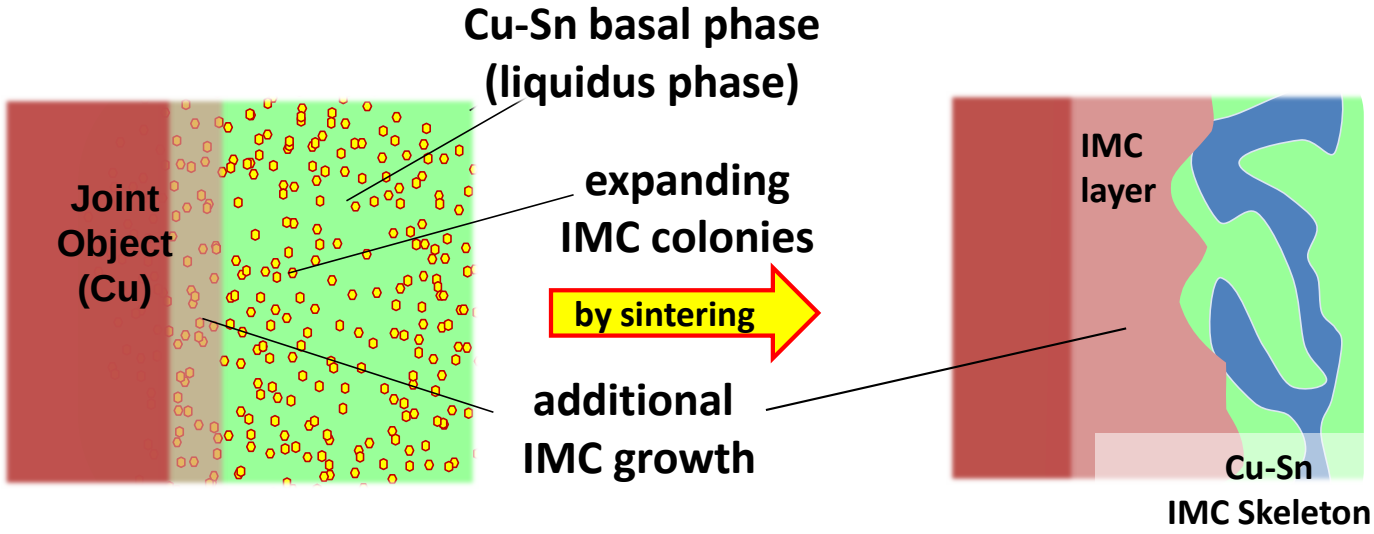
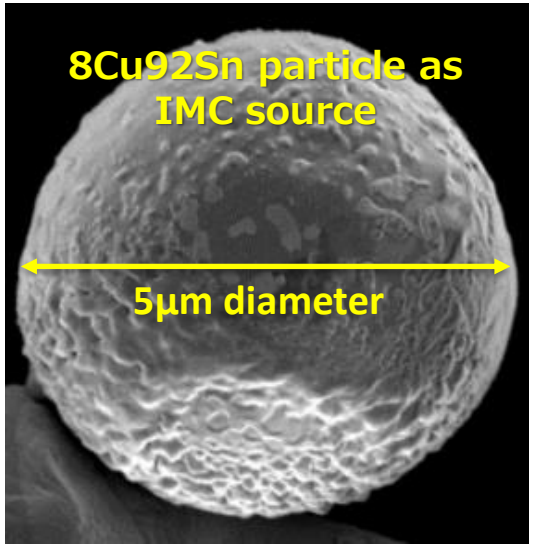
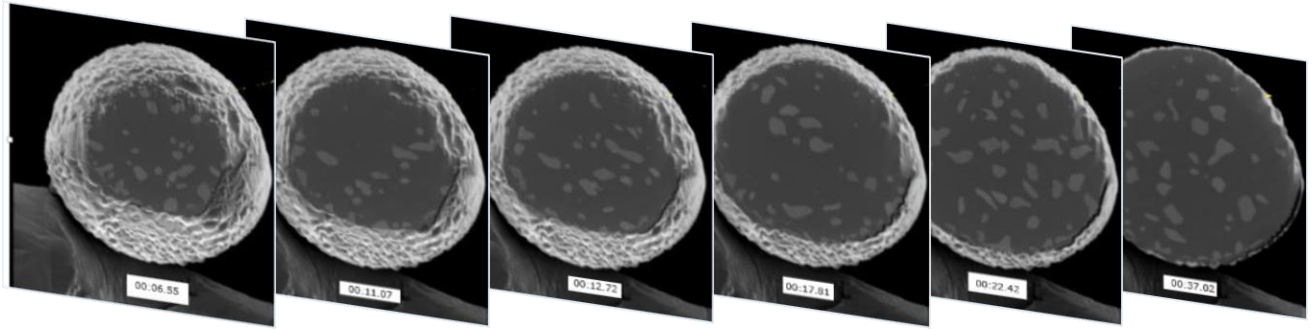


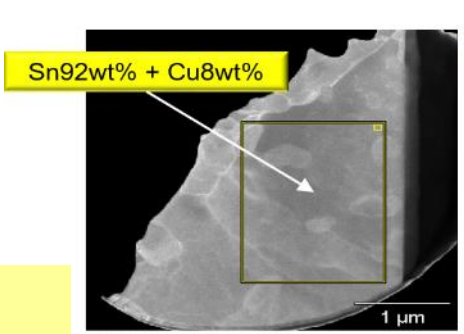
Fig.11

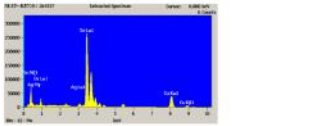
IMC source is the key material for the purpose



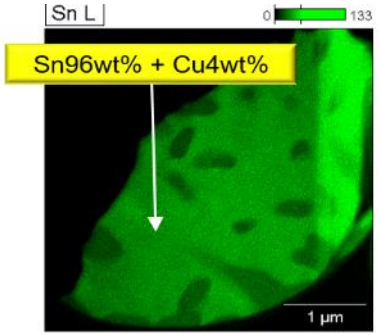
FIB slices of IMC source

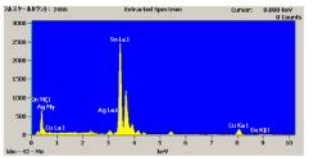




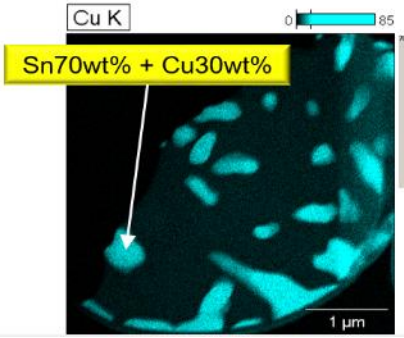


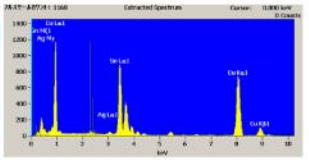
元素 線名	カウント	元素 重量%	原子%
Cu K	689040	8.98	15.55
Ag L	30050	0.49	0.50
Sn L	5335388	90.53	83.95
トータル		100.00	100.00





元素 線名	カウント	元素 重量%	原子%
Cu K	2428	3.93	7.10
Ag L	81	0.16	0.17
Sn L	45458	95.90	92.72
トータル		100.00	100.00





元素 線名	カウント	元素 重量%	原子%
Cu K	14588	29.91	44.34
Ag L	141	0.36	0.32
Sn L	26126	69.73	55.35
トータル		100.00	100.00

By courtesy of Nagoya-University

There must be concerns
when we use Sn rich component
as a joint material

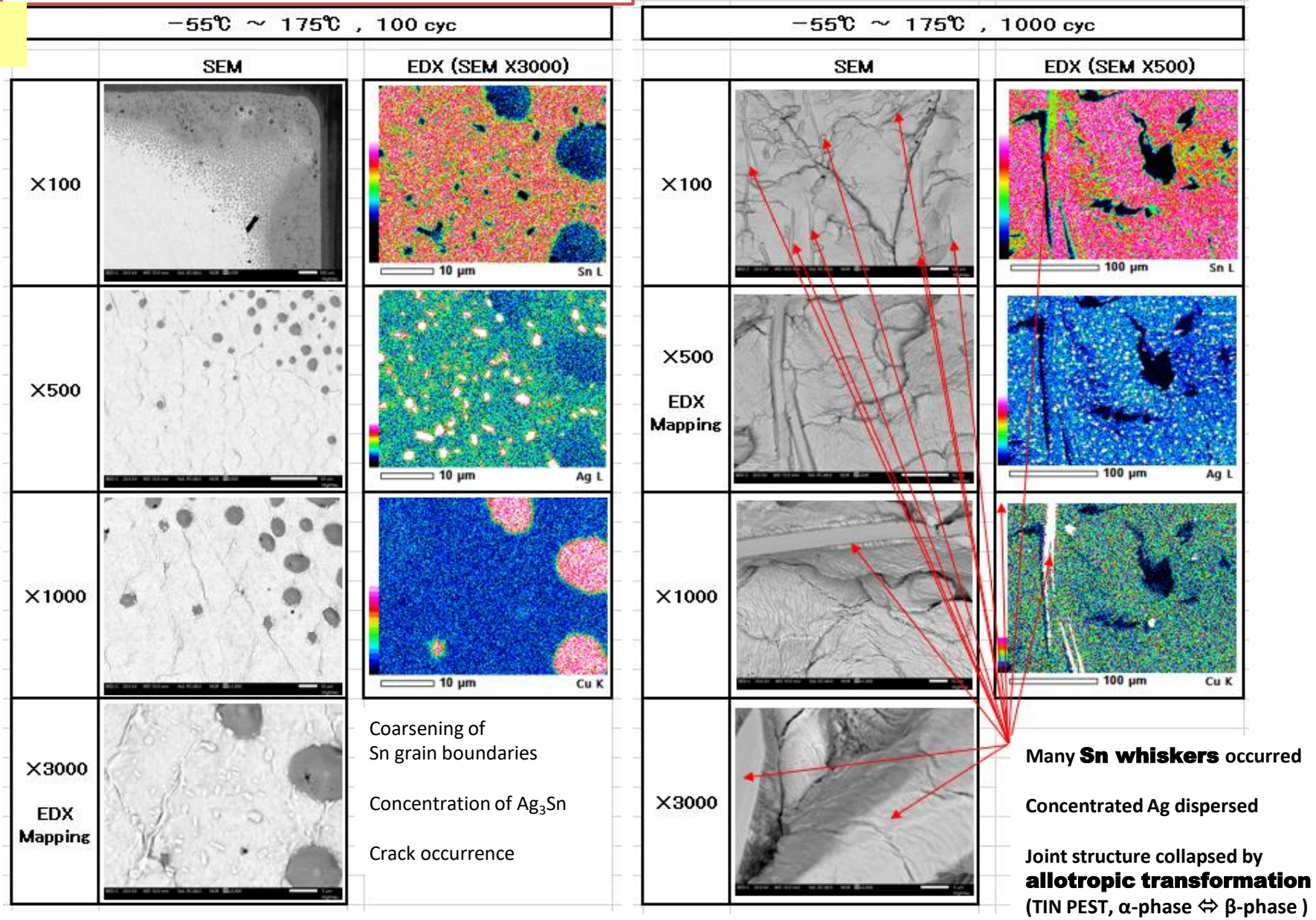
⇒ **Whisker**
⇒ **Tin Pest (allotropic transformation)**
⇒ **Re-melting temperature**

Fig.6

SAC305 after TCT 100-1,000 cycles

TCT effect for SAC305 paste

⇒ Whisker
⇒ Tin pest



Coarsening of
Sn grain boundaries

Concentration of Ag_3Sn

Crack occurrence

Many **Sn whiskers** occurred

Concentrated Ag dispersed

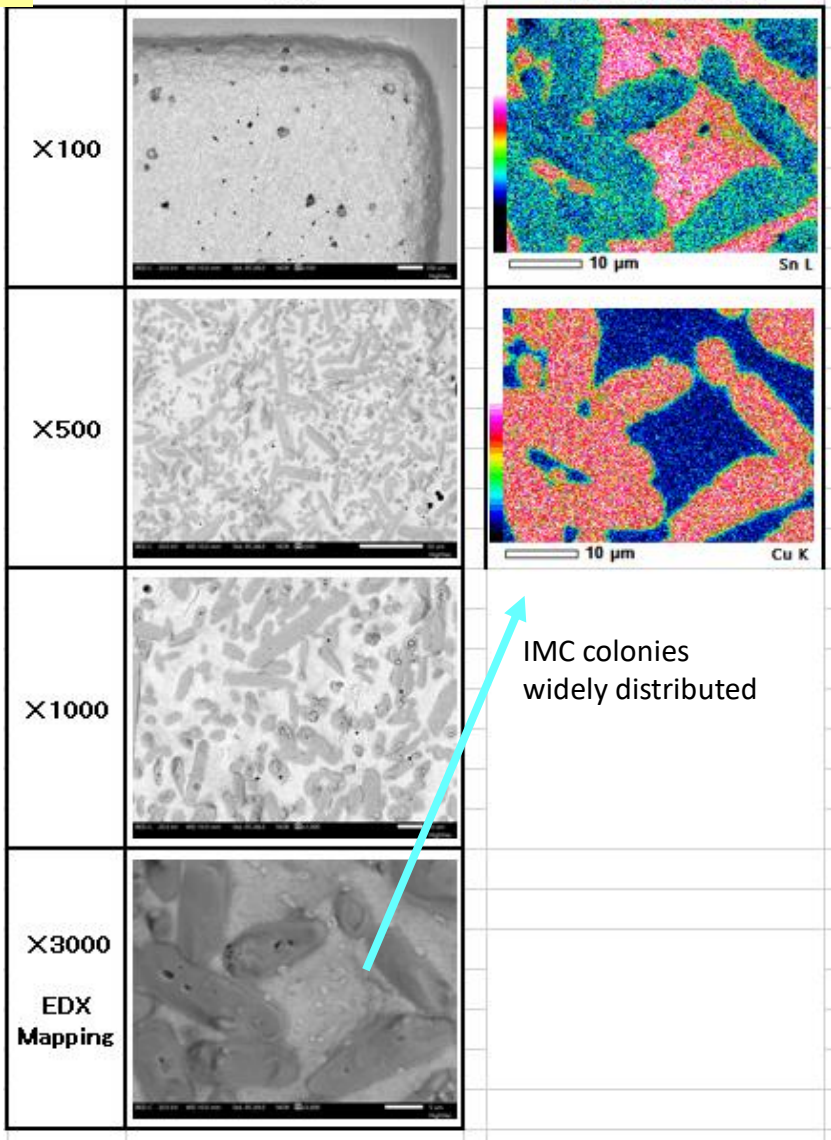
Joint structure collapsed by
allotropic transformation
(TIN PEST, α-phase ⇔ β-phase)

Fig.10

IMCC paste after TCT 100-1,000cycles

⇒ Whisker
⇒ Tin pest

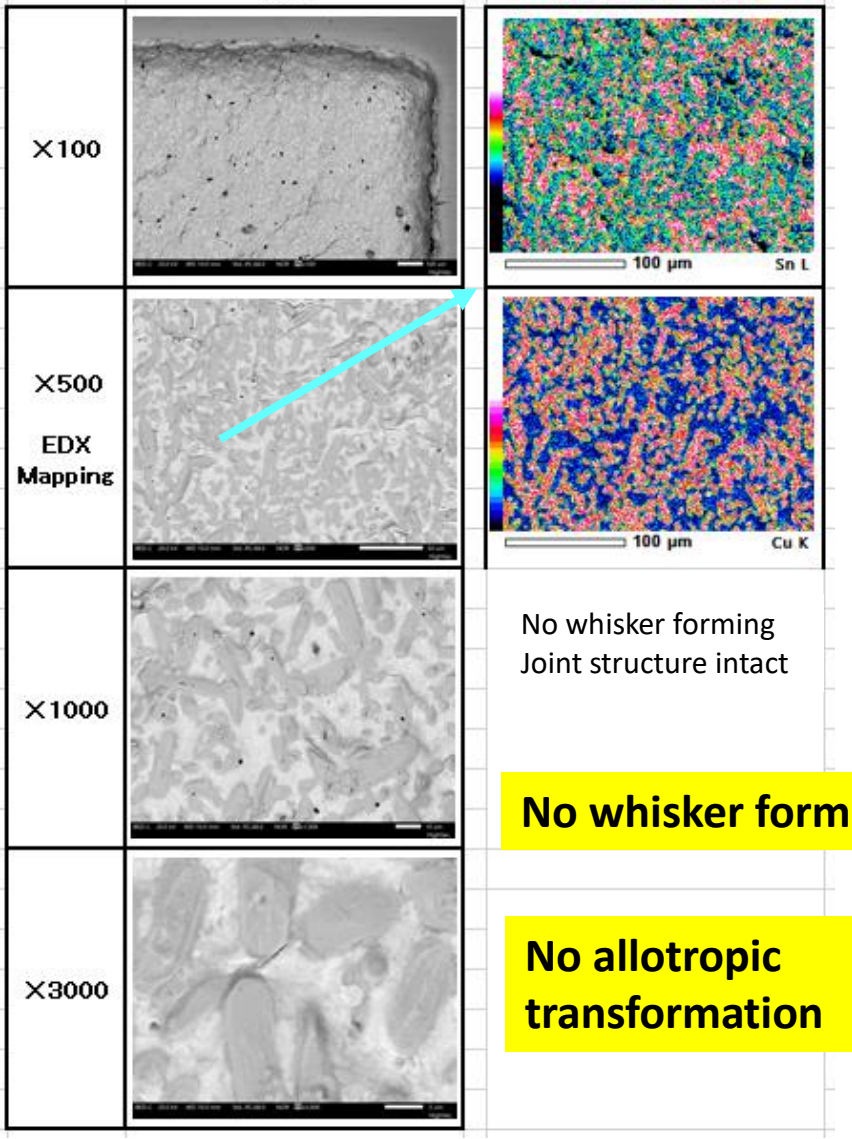
−55℃ ～ 175℃ , 100 cyc



IMC colonies widely distributed

TCT effect for IMCC paste

−55℃ ～ 175℃ , 1000 cyc



No whisker forming
Joint structure intact

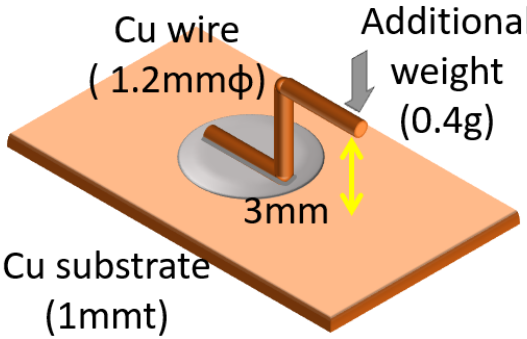
No whisker forming

No allotropic transformation

Fig.10

⇒ **Re-melting temperature**

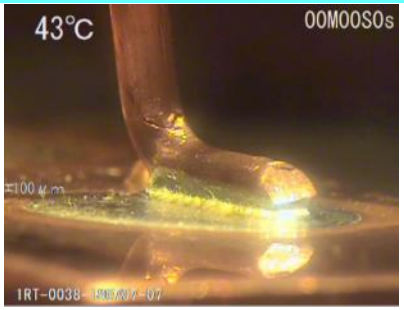
Re-melting point temperature confirmation

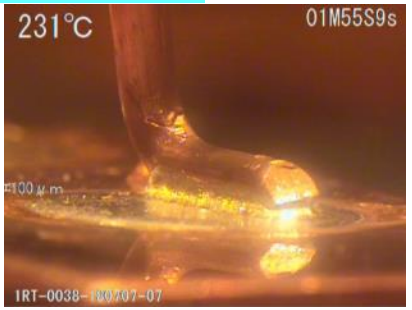


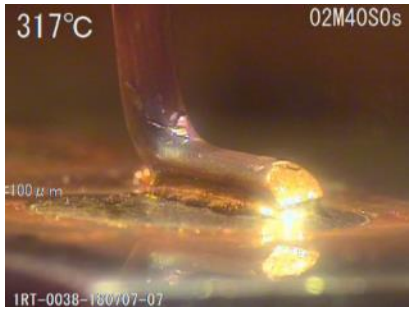
First reflow temperature (˚C) **T1**

Re-melting point temperature (˚C) **T2**

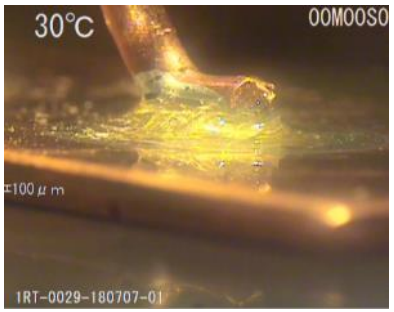
IMCC paste (IMC source only)

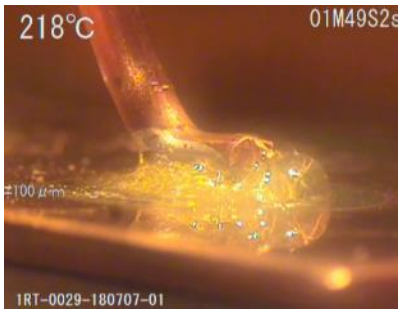


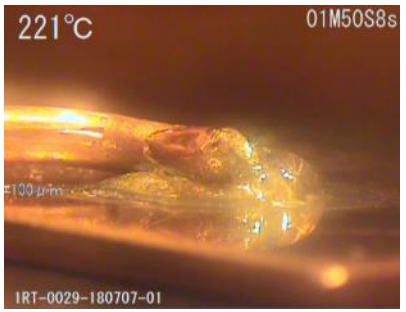




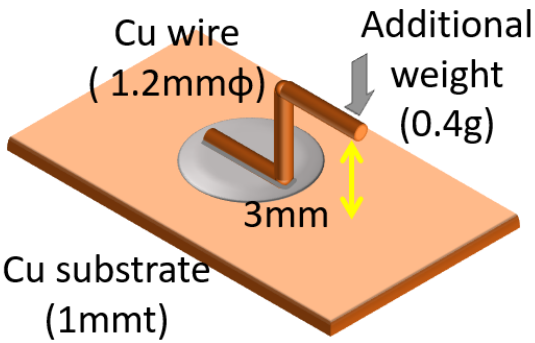
SAC305







⇒ **Re-melting temperature**



Re-melting point temperature

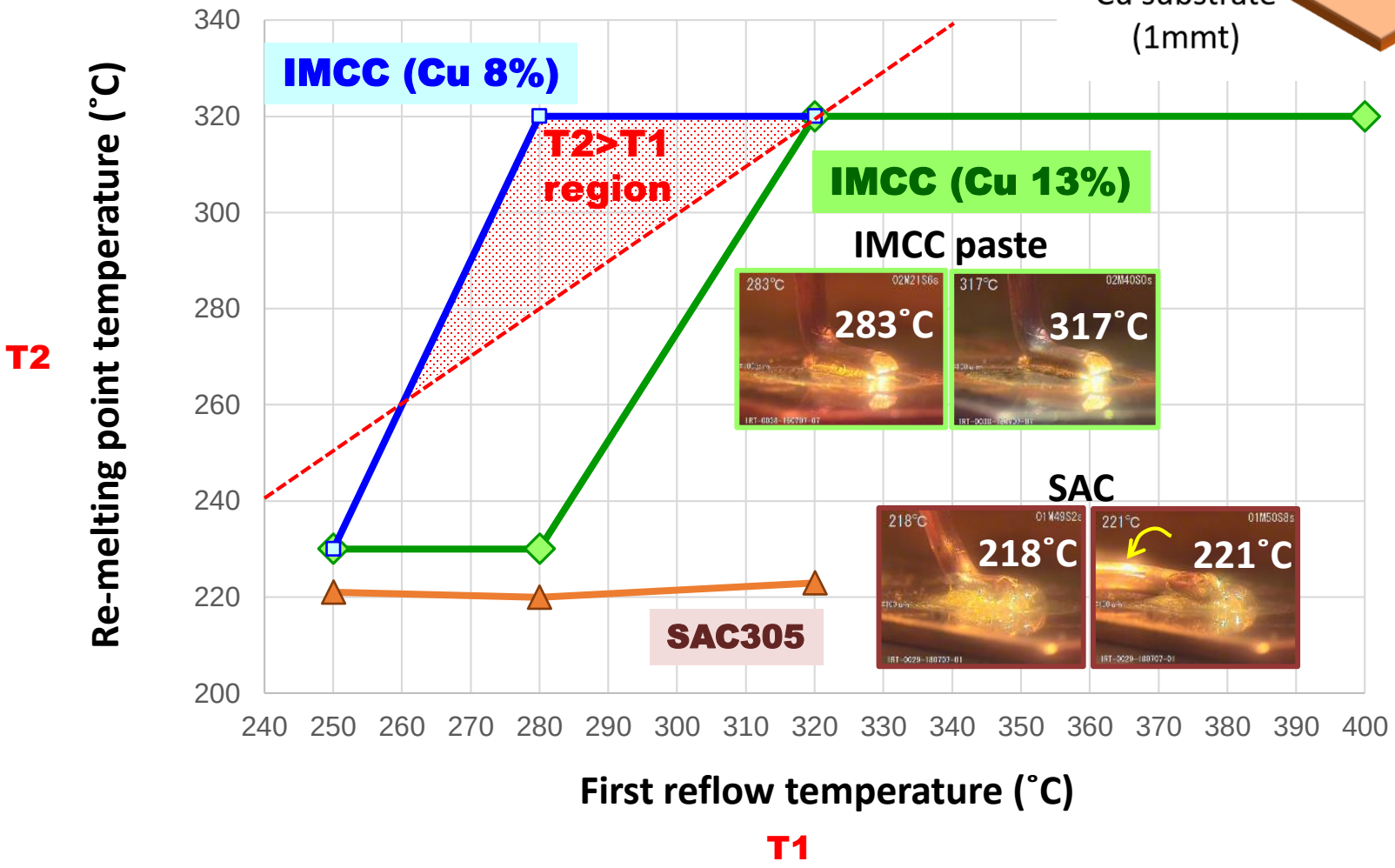
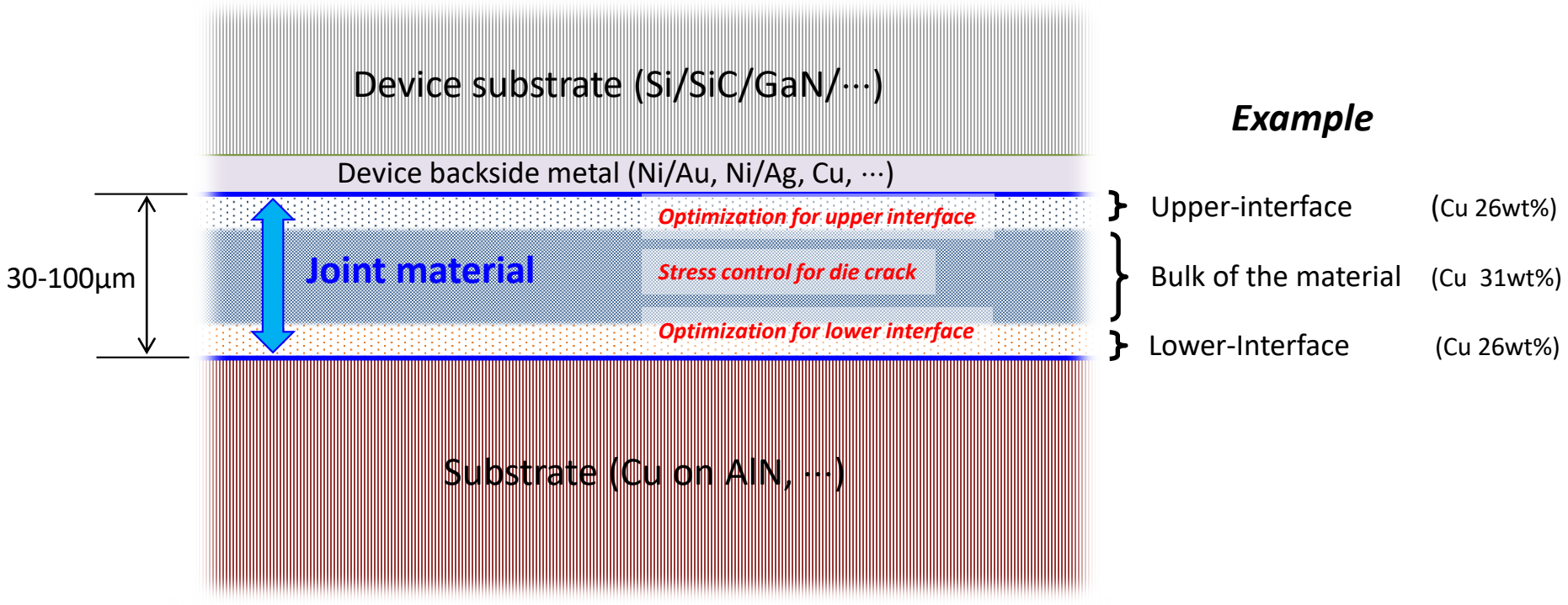


Fig.13

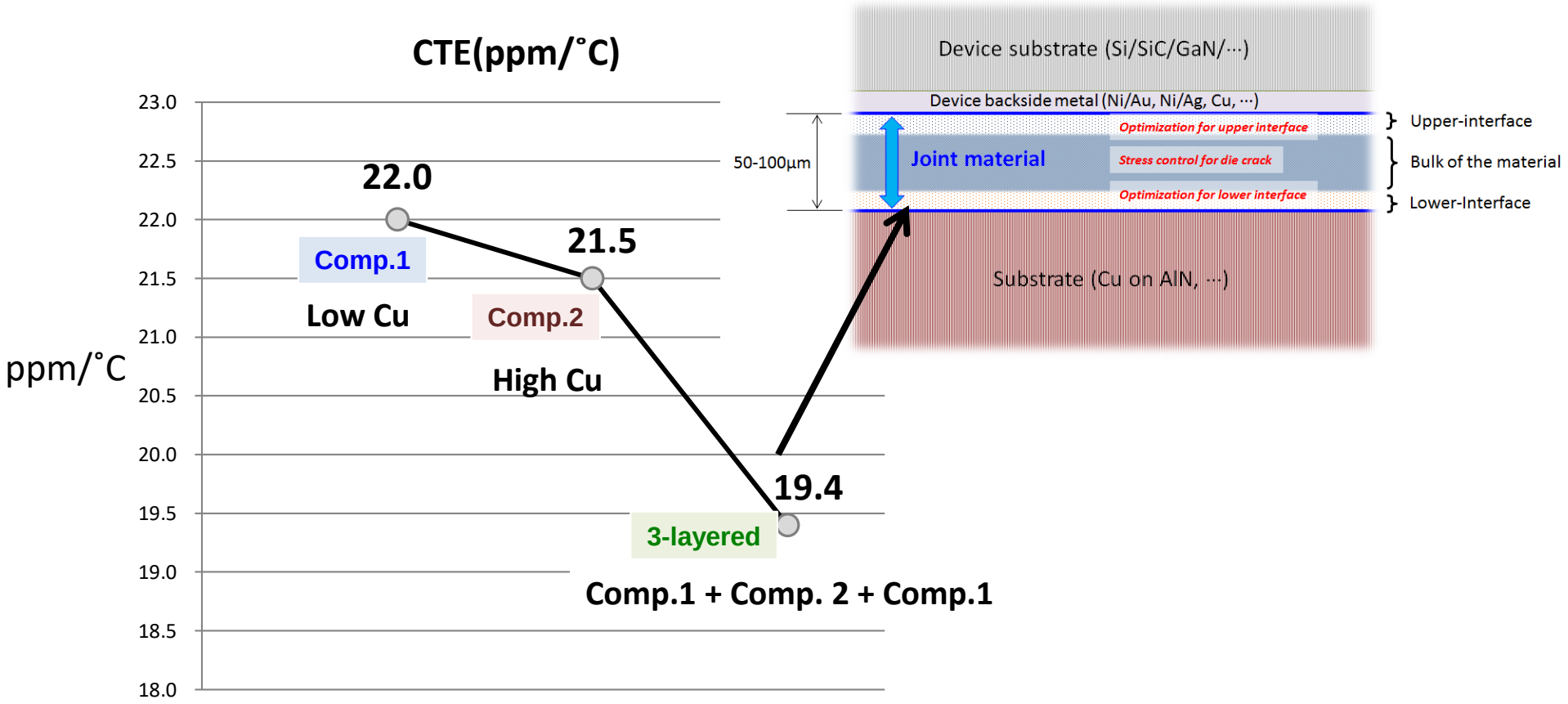
Optimization of the material's Cu distribution and thickness



To determine the composition of each layer, optimization for three areas is required

Fig.12

3-layered structure indicated minimum CTE after sintering

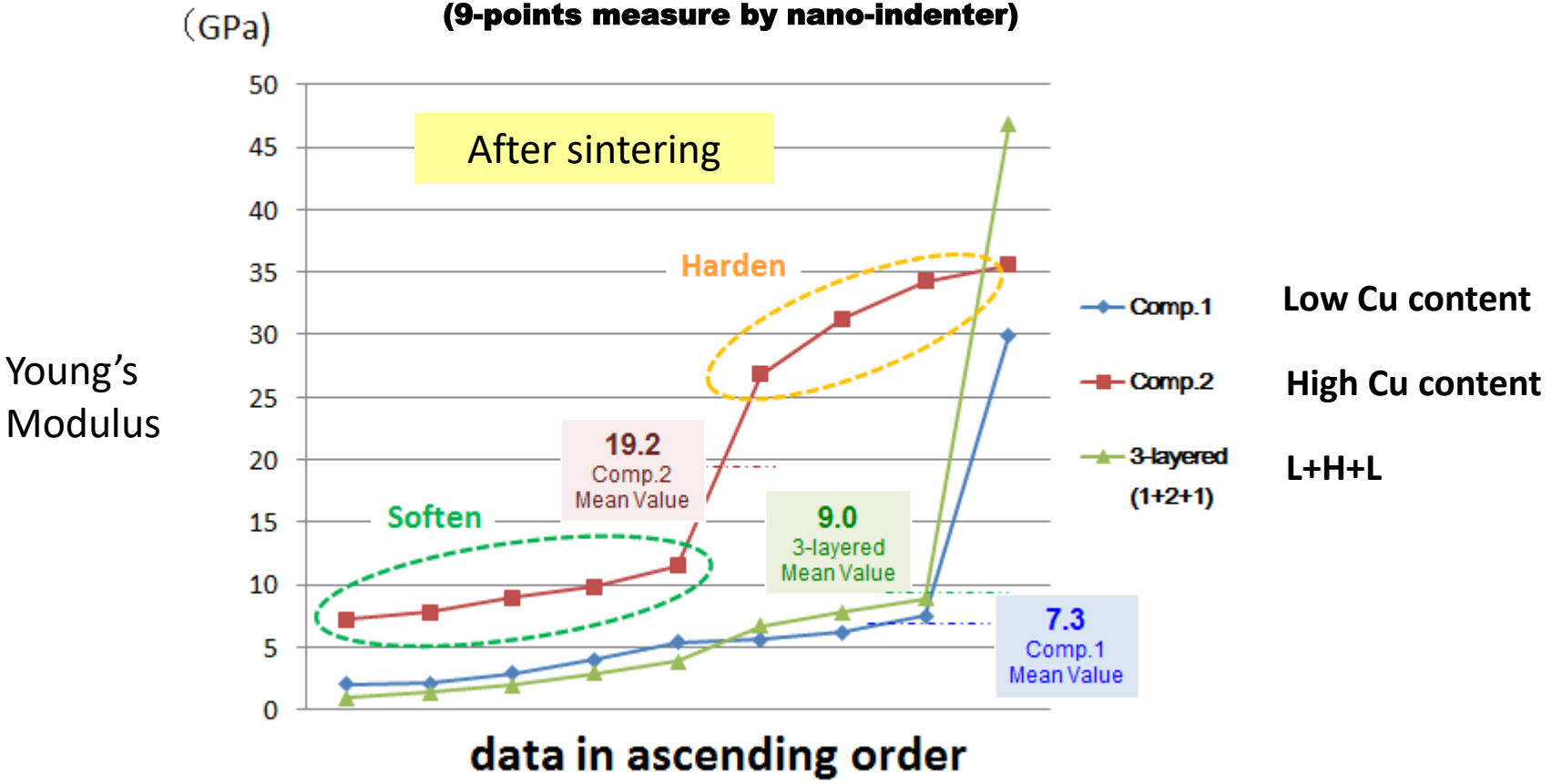


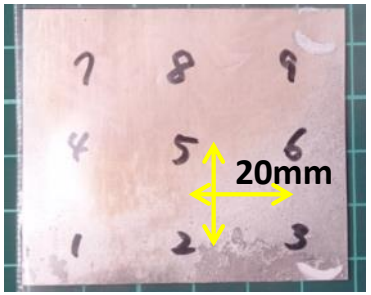
Temperature range for CTE measure: 20-60˚C

Fig.16

Young's modulus after sintering

(9-points measure by nano-indenter)





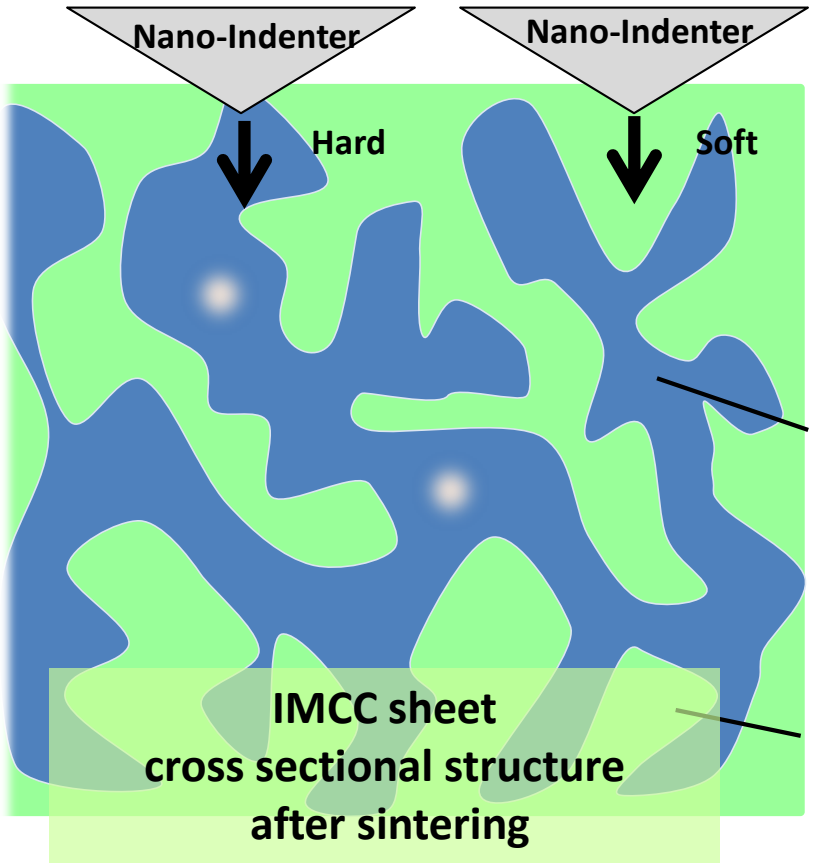
Composition-1			Composition-2			3-Layered (1+2+1)		
2.09	2.03	4.00	11.48	7.19	26.84	46.82	0.91	6.69
6.16	29.95	2.91	8.98	34.29	9.81	1.98	8.88	1.34
5.59	7.53	5.36	7.80	31.29	35.54	7.81	2.88	3.85

Hit hard region

Hit soft region

Fig.14

Young's Modulus Data dispersion affected by location



Sample and measure points

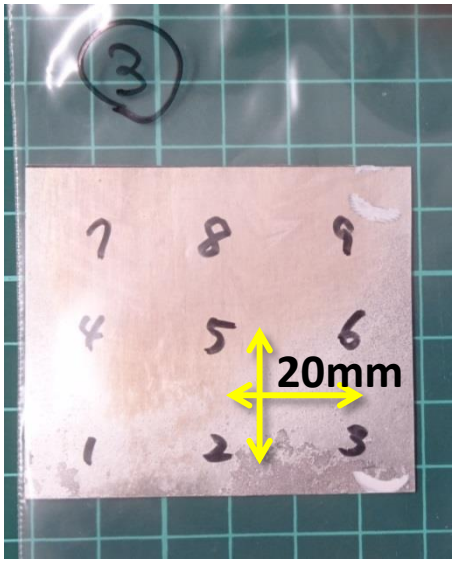
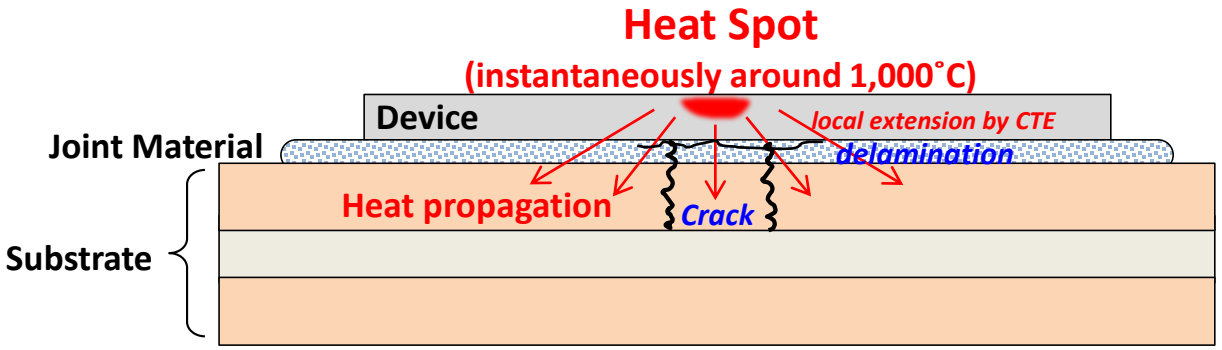


Fig.15

Crack/Delamination by Heat Spot of Power Device

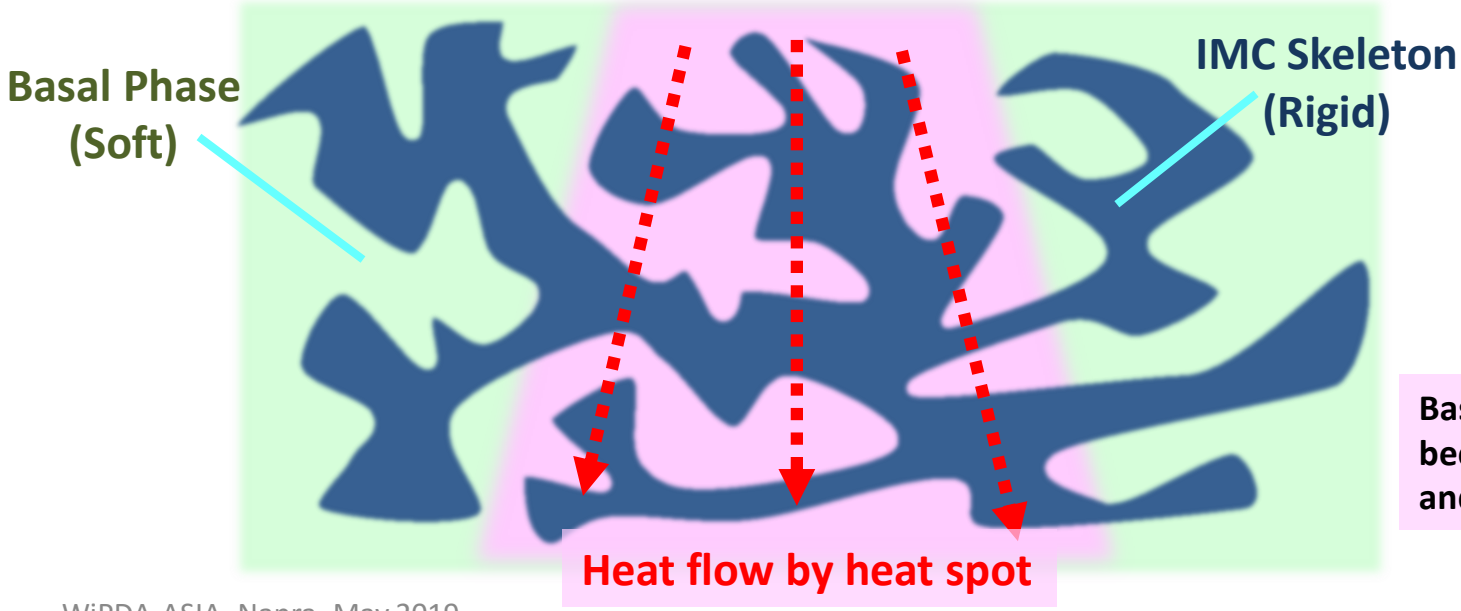


If the joint material is too rigid, the existence of heat spot results delamination and vertical crack

(Power Cycling Test failure mode)

[Countermeasure]

Soft region around IMC skeleton relieves local stress



Basal phase region becomes soft by heat and relieves stress

Estimated Mechanical Properties of IMCC (after sintering)

	Estimation	By several database*					
	Cu 26wt%	Cu	Sn	Ni	Cu_6Sn_5	Cu_3Sn	SAC305
Young's Modulus (GPa)	10～40	117	41	213	85.56	108.3	31
							41.6
			53				55
CTE (ppm/K)	19～21	17.1	23	12.9	16.3	19	21
			22.3				21.7
Electrical Resistivity (μΩ·cm)	12～15	1.7	11.5	7.8	17.5	8.93	11.4
			12.2				11
Thermal Conductivity (W/m·K)	40～50	398	67	90.5	34.1	70.4	62
			65.7				55

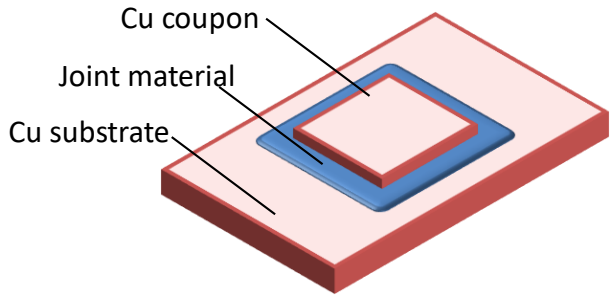
* http://www.geocities.jp/sato5fu/staticmechaprop.htm

Table-1

We have confirmed good stability of the joint material itself and also the Cu-interfaces by Thermal Cycling Test (-40 °C ~ +200 °C)

Case-1

Cu coupon – Joint material – Cu substrate



Joint material stays stable after 1,000cycle Thermal Cycling Test (-40°C ~ +200°C)

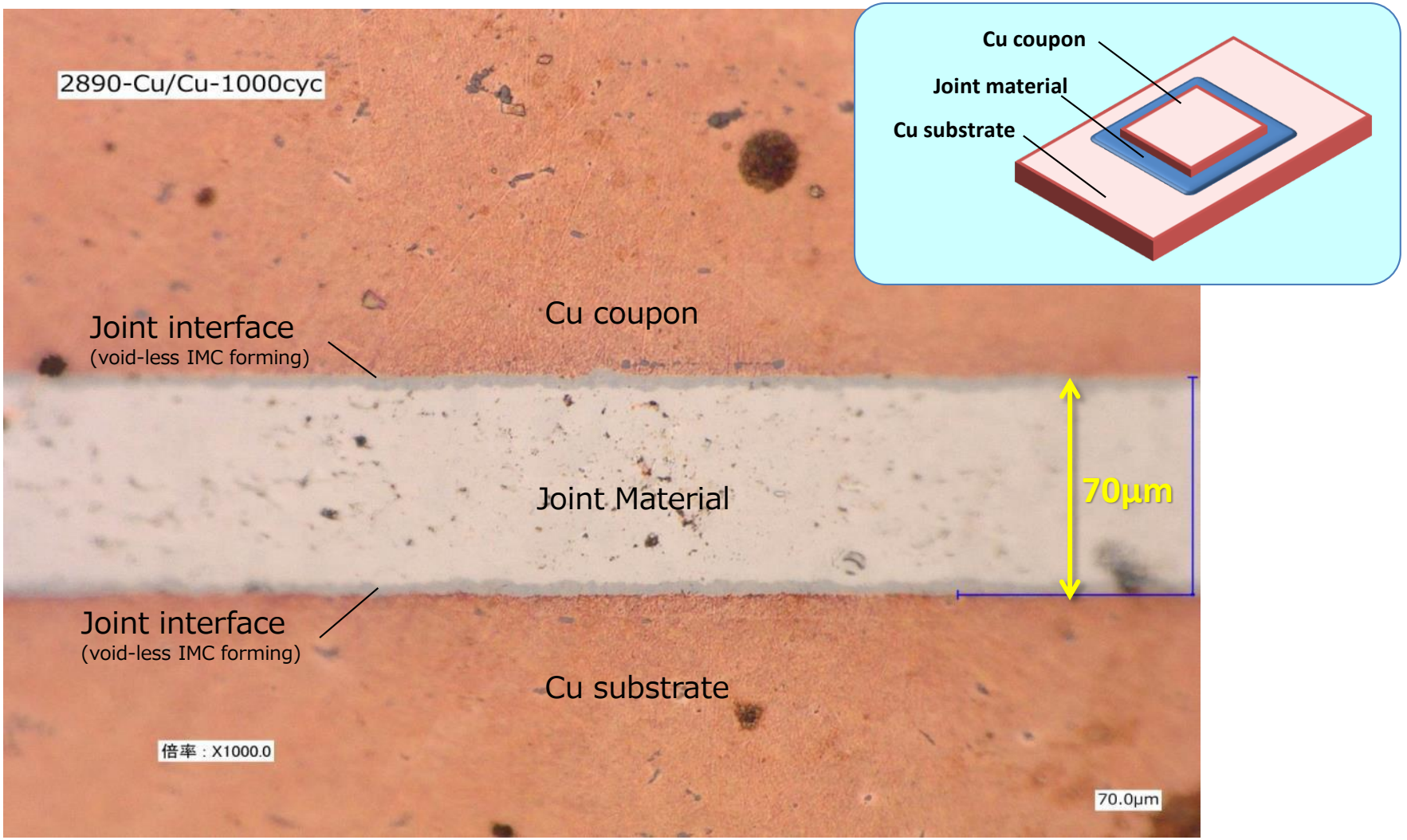
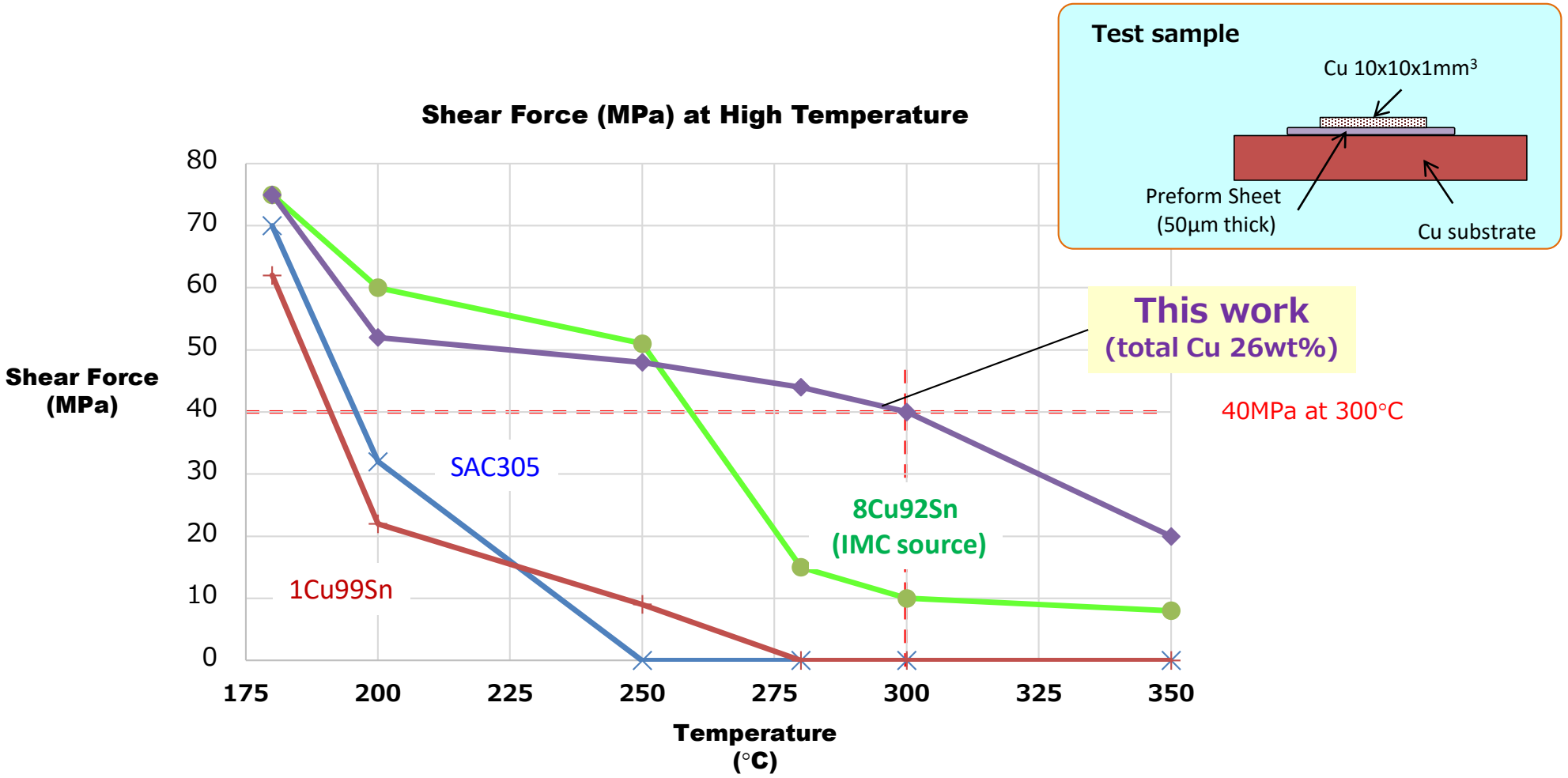


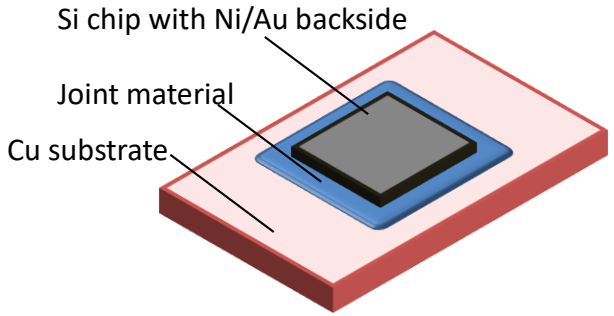
Fig.17

IMCC sheet Shear strength example

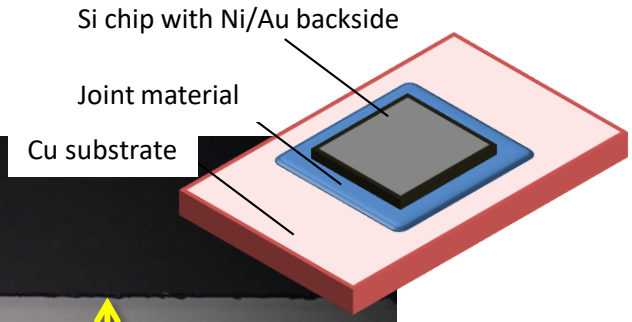


Case-2

Si（Ni/Au backside terminal) – Joint material – Cu substrate



Evaluation of Si/Ni/Au – Cu structure By TCT 50cycle (-40 °C ~ +200 °C)



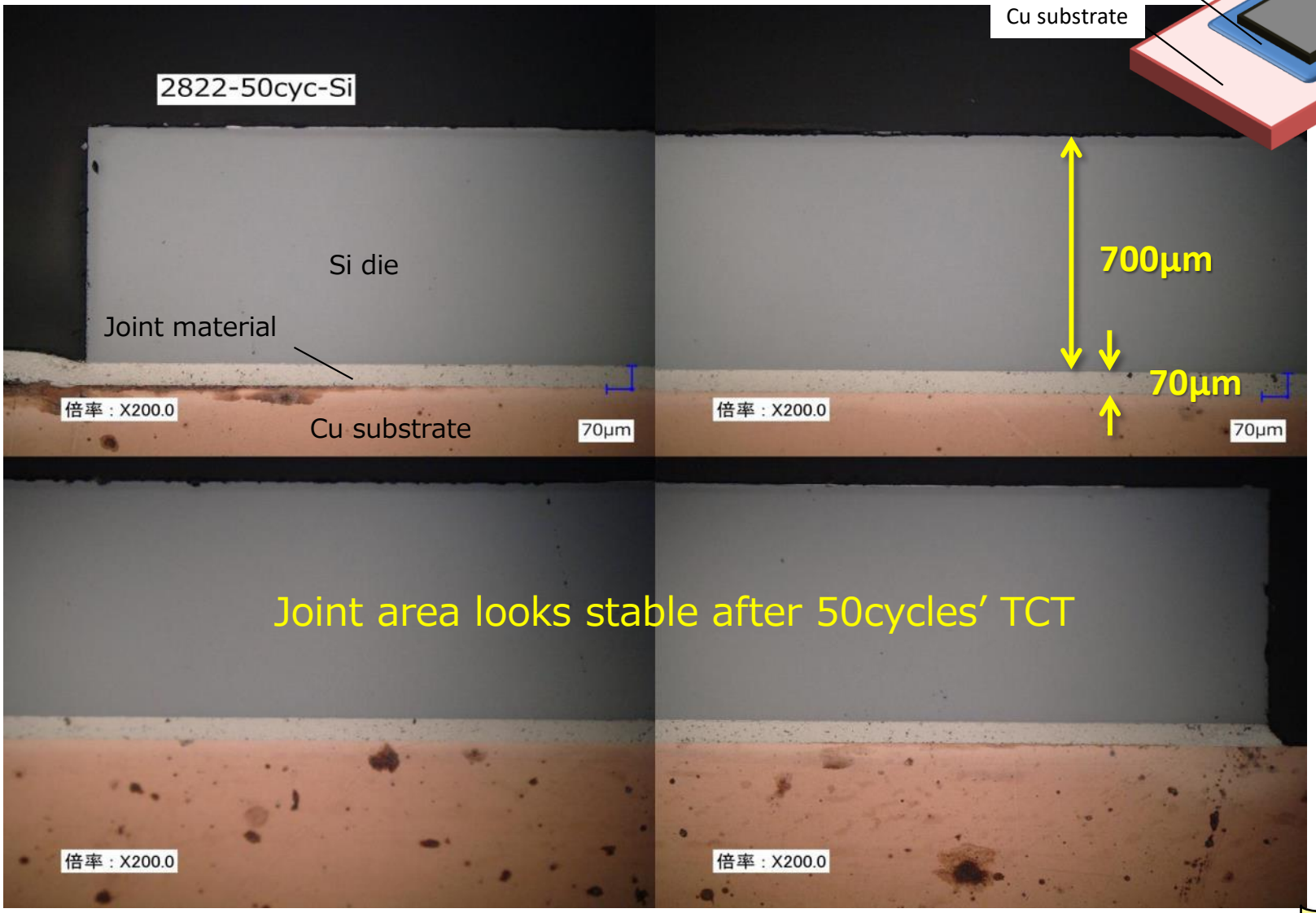
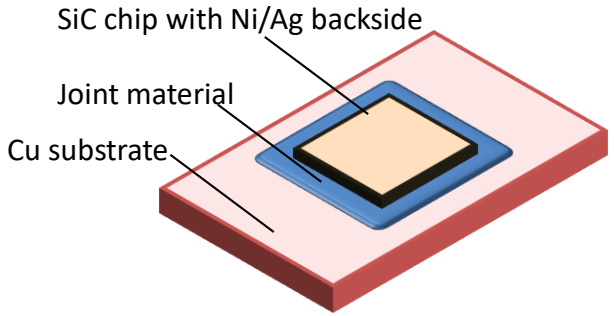


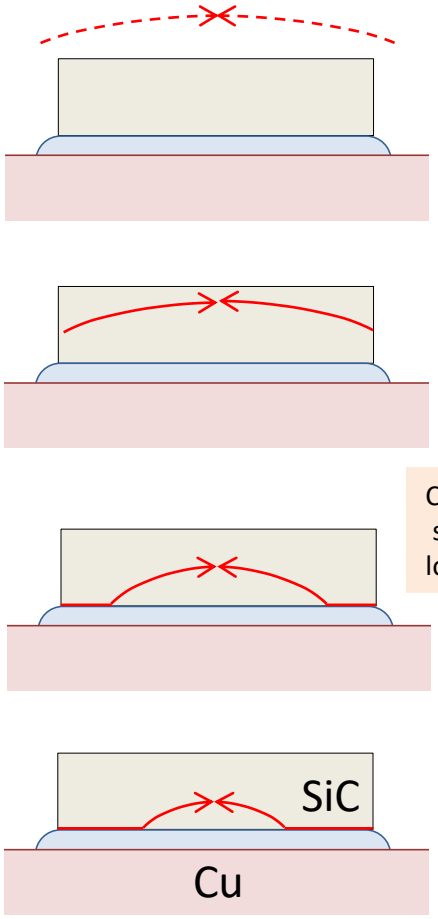
Fig.18

Case-3

SiC (Ni/Ag backside terminal) – Joint material – Cu substrate



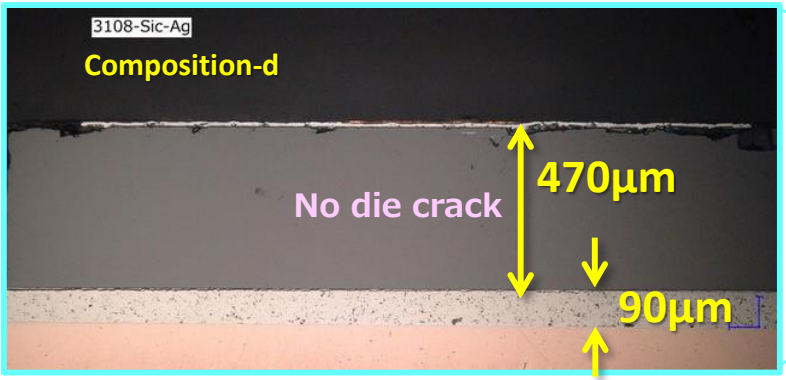
SiC attached onto Cu substrate with TCT 50cycles (-40~+200°C)

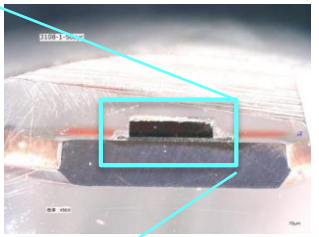


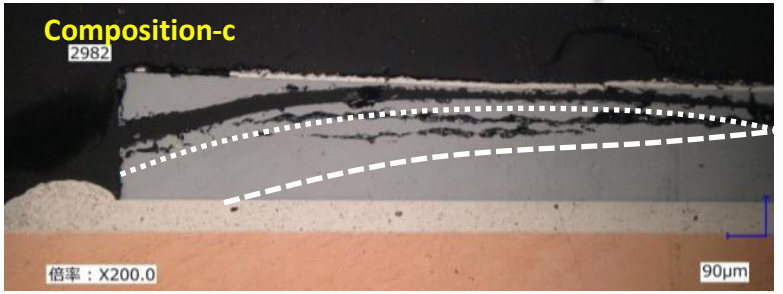
Stress Low

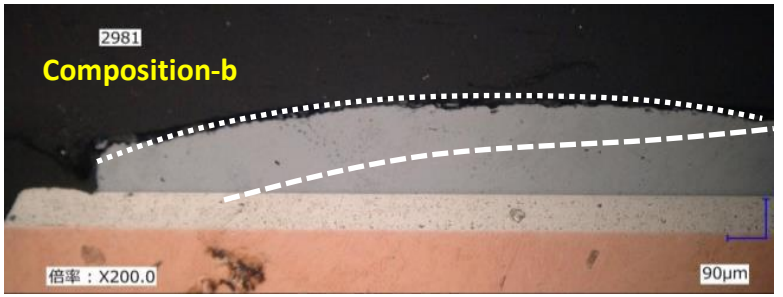
Crack position shifted by lowering stress

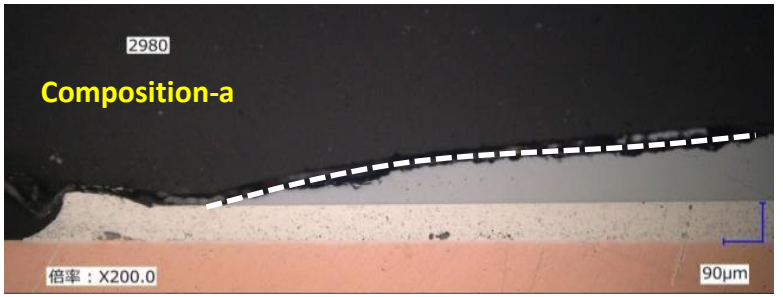
Stress High











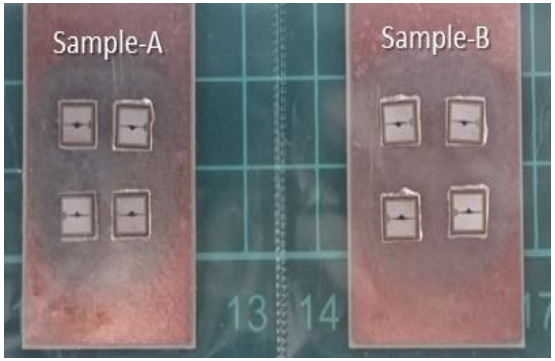
Physical properties can be adjustable by customers' system

Fig.19

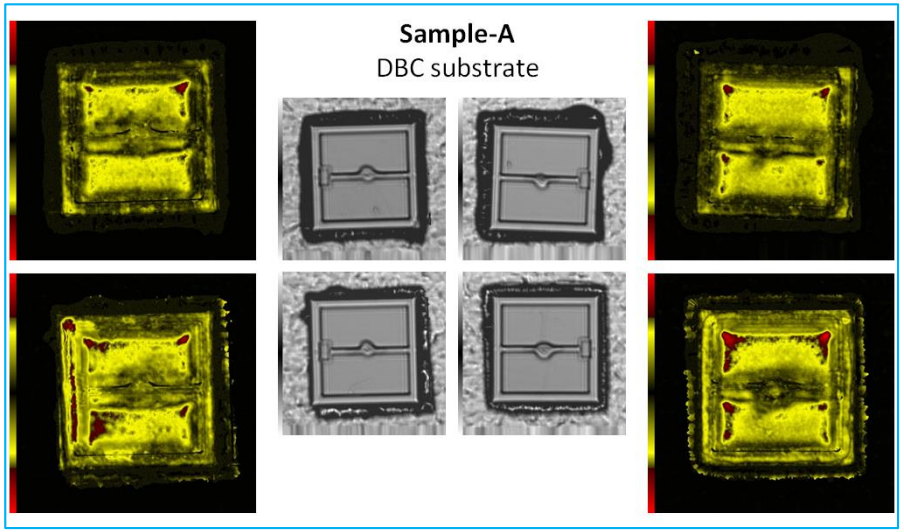
sheet

Joint SiC chips on DBC substrate

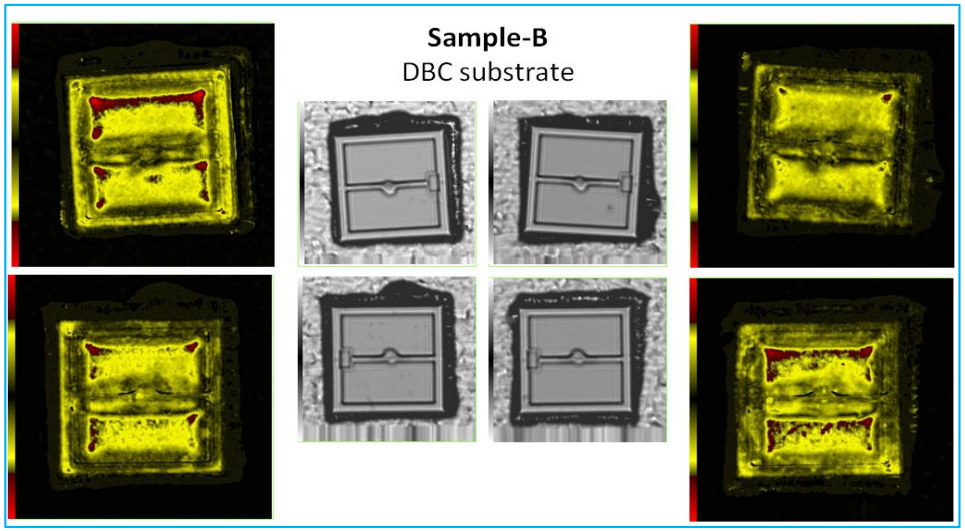
(just after sintering)



SAT images



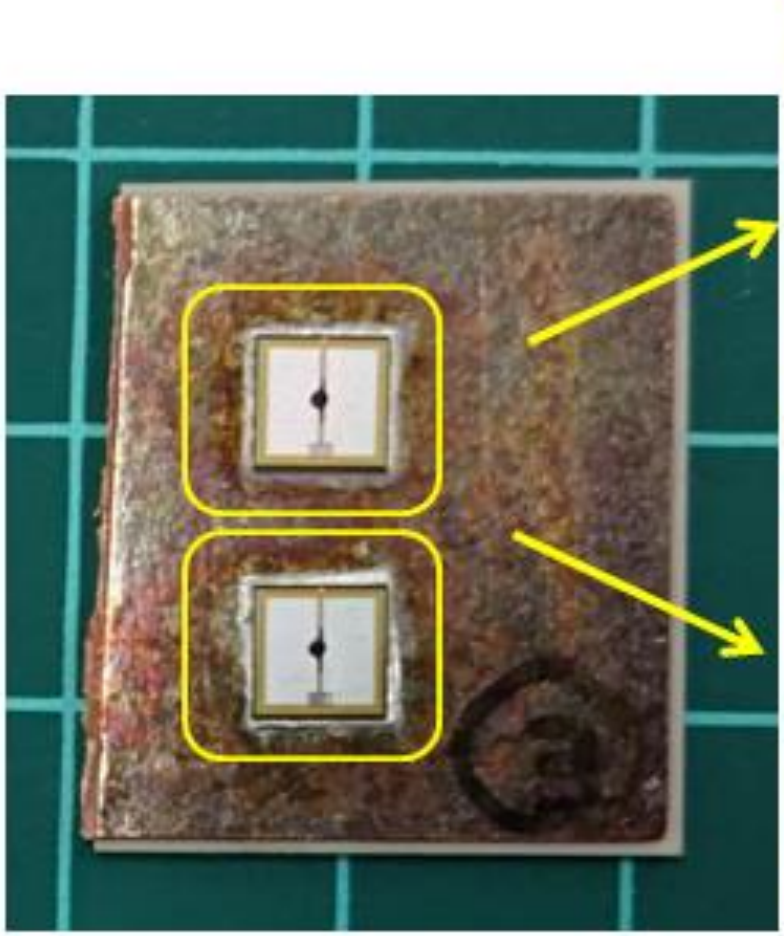
SAT images



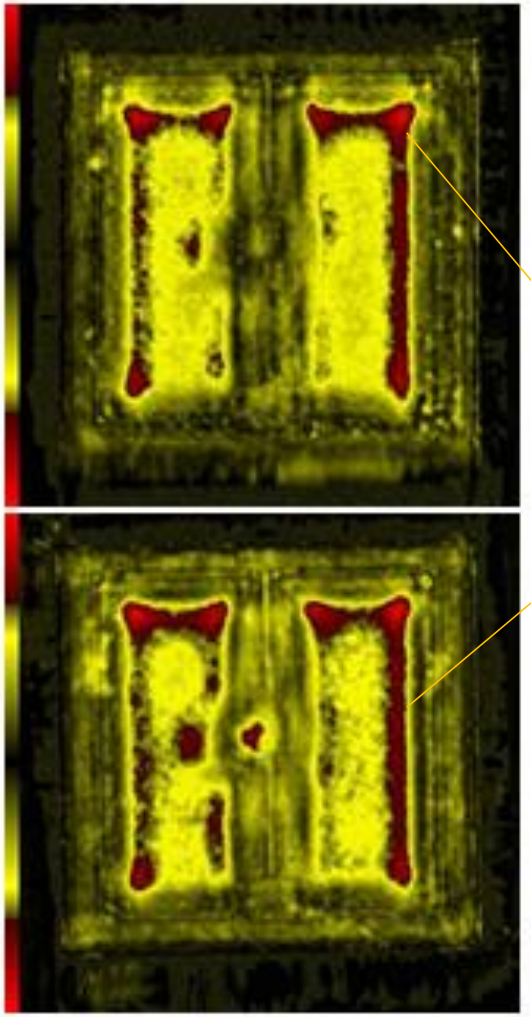
sheet

Joint SiC chips on DBC substrate

(after TCT 50cycles)



Joint areas are stable and no voids



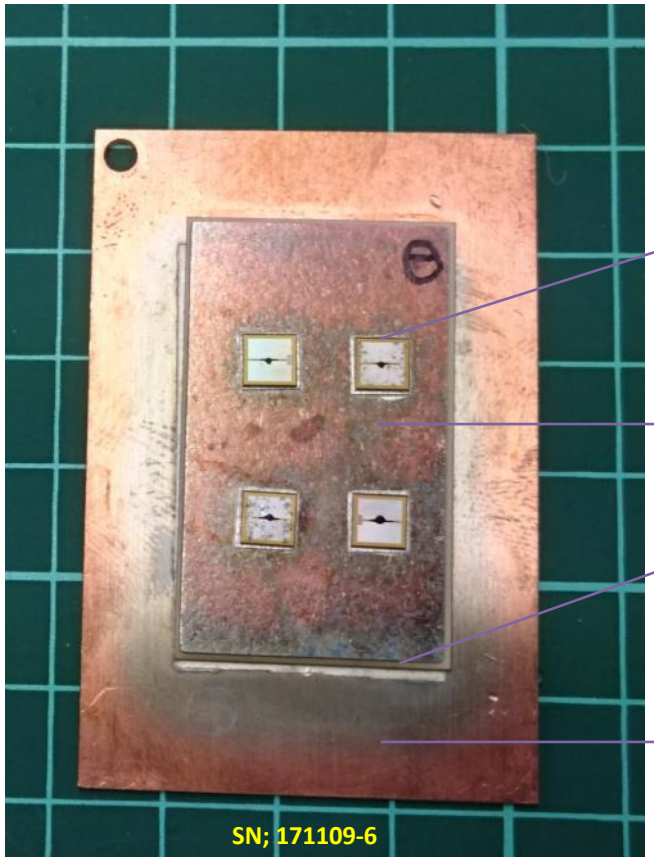
thin die warpage affected joint uniformity

Fig.20

Joint samples on Cu substrate
(just after sintering)

sheet

SiC



Joint material
(sheet, 100μmt)

DBC substrate
(1.32mmt)

Joint material
(sheet, 100μmt)

Cu substrate
(1mmt)

IGBT

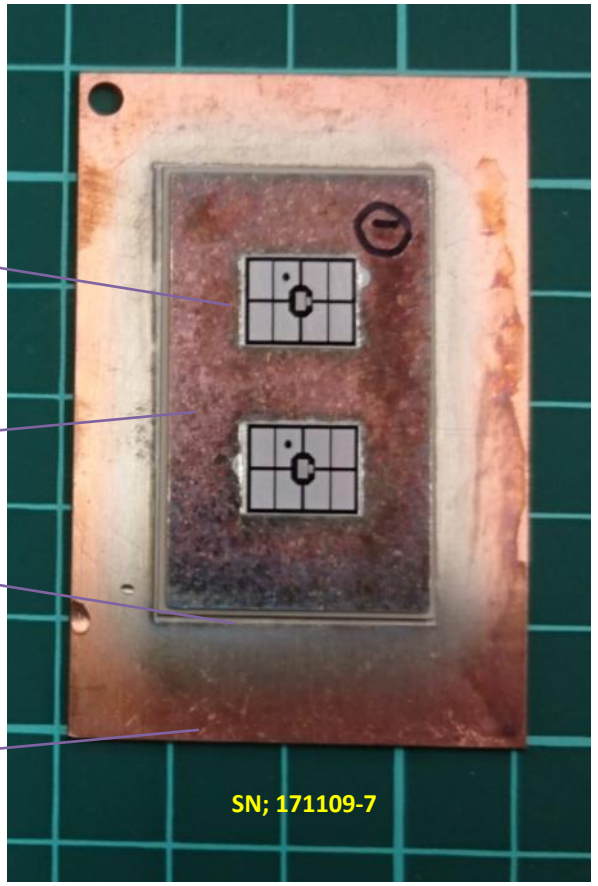


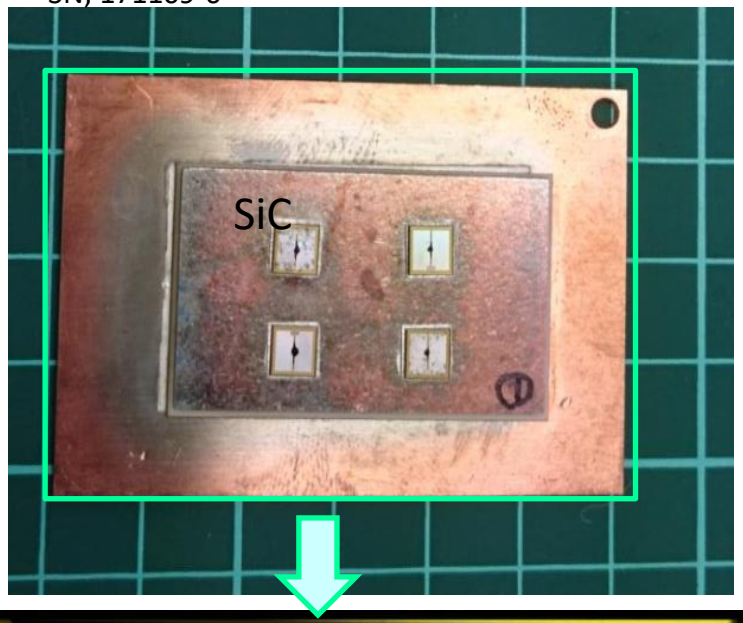
Fig.21

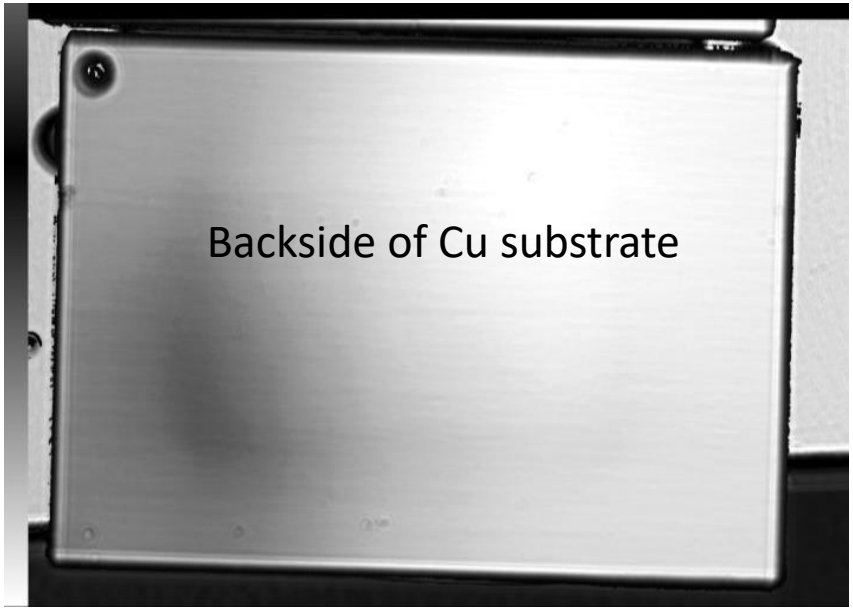
SAT observation of DBC and Cu substrate from backside

(just after sintering)

sheet

SN; 171109-6





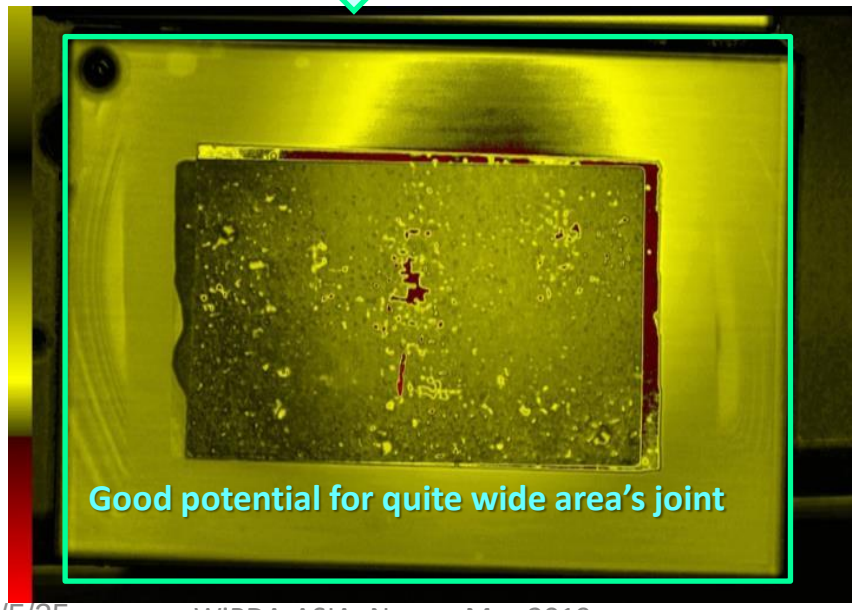


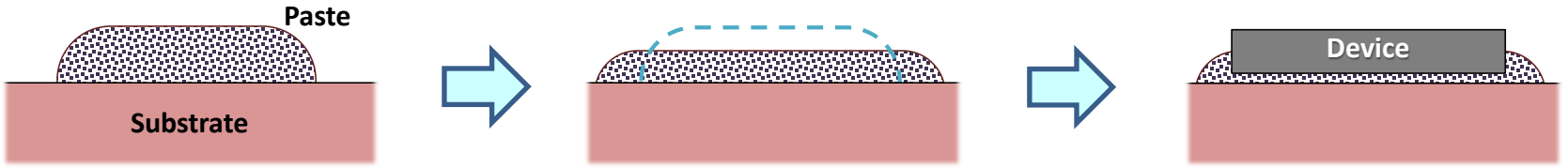
Fig.22

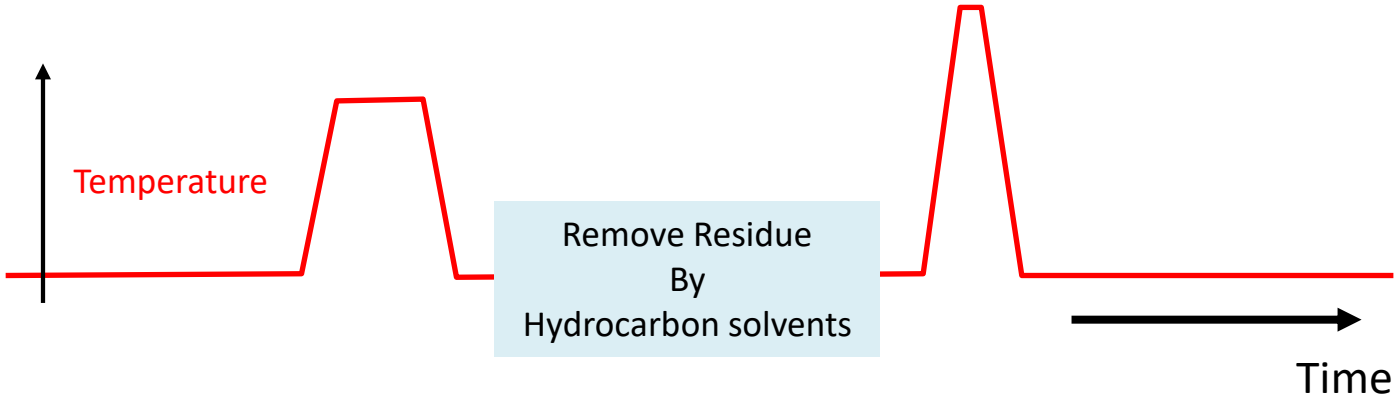
Two step sintering for IMCC paste

Put the paste
onto substrate

Evaporate volatiles
Pre-sintering
Clear residue

Put device
Main sintering





Two steps sintering for large die

Pre-sintering
200˚C x 3min.
(N_2)

Cu substrate (15mm×20mm×1010 μm)

Main-sintering
260˚C x 60-90sec.
(Formic Acid or N_2)

0.05MPa*

Ni/Au back metal

Si die (9mm×12mm×370μm)

Cu substrate (15mm×20mm× 1010μm)

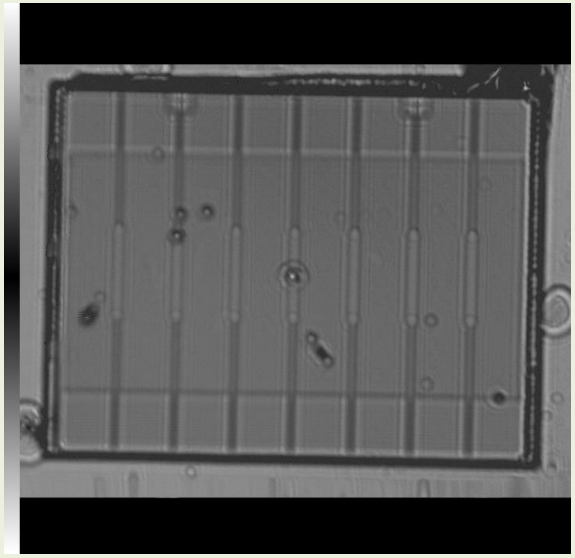
* 0.5kgf/1.08cm^2=0.46kgf/cm^2=0.05MPa

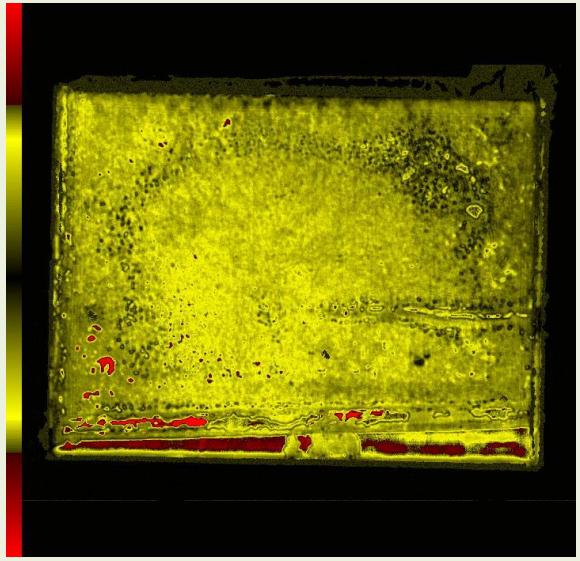
Fig.23

Two steps sintering for large die (well controlled voids)

Main Sintering 260°C 90sec. (N_2)

with de-compression (30sec)

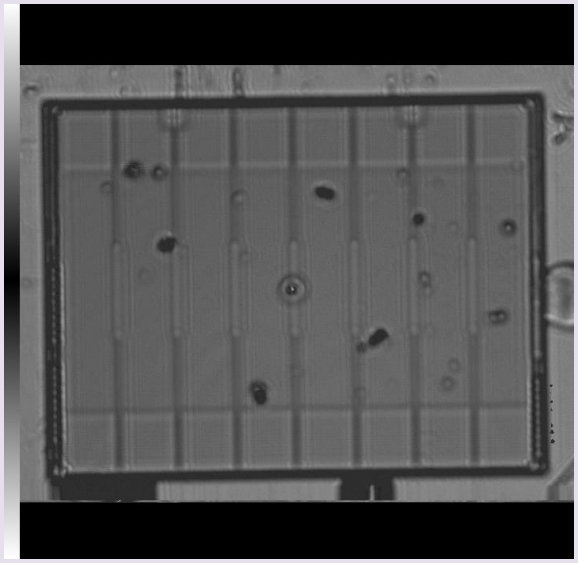


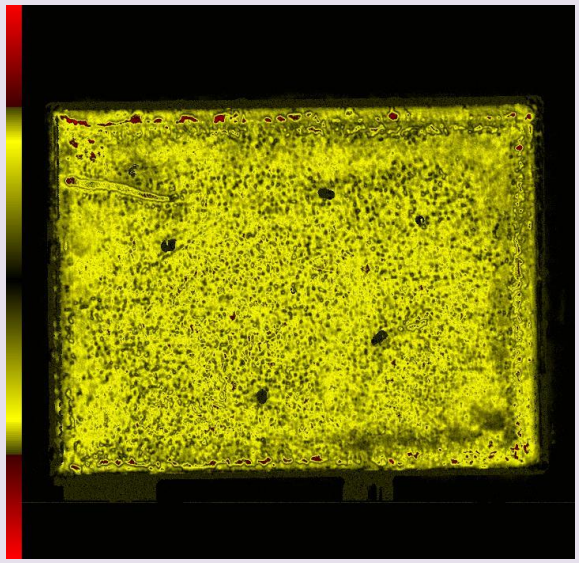


Joint thickness

43-46um

Main Sintering 260°C 60sec. (Formic Acid)





38-42μm

Fig.23

Conclusion and the next steps

We have developed Cu-Sn based joint material for high-temperature usage

Controlled Cu-Sn IMC forming resulted IMC skeleton surrounded by Sn rich base phase area by using pre-included IMC colonies in IMC source particles

The skeleton structure provides robust joint strength

- Shear strength; 40MPa at 300˚C
- TCT 1,000cycles pass (-40 to +200 ˚C) ; Cu-Cu Test piece
- Wide area joint capable such as 25mmx40mm DBC on Bulk Cu

We are ready for mass production of the joint material (sheet and paste).

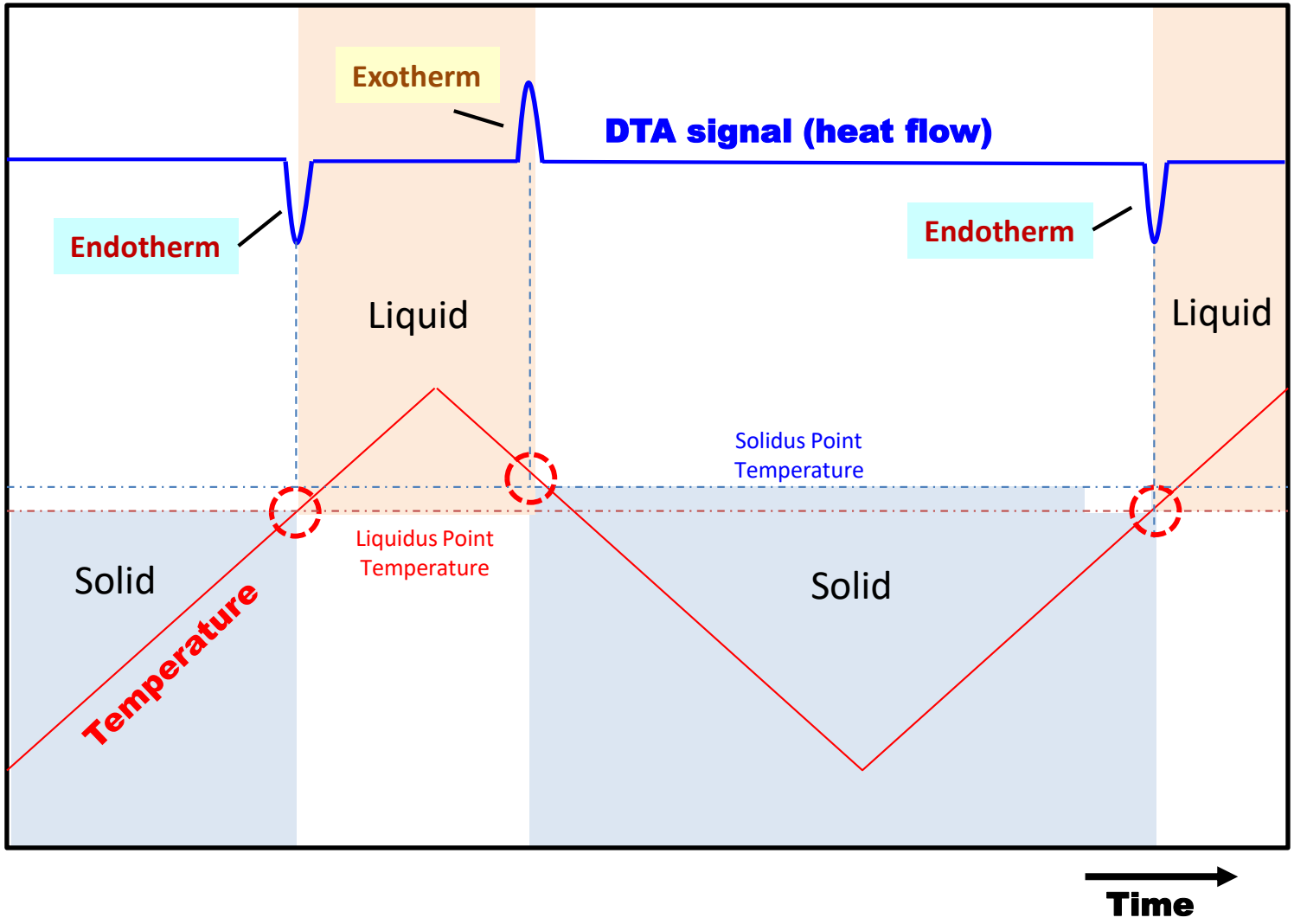
We are confirming wide adoptability of the material

- Sensor encapsulation, Via fill, RDL forming, Bumping, etc.

Thank you!

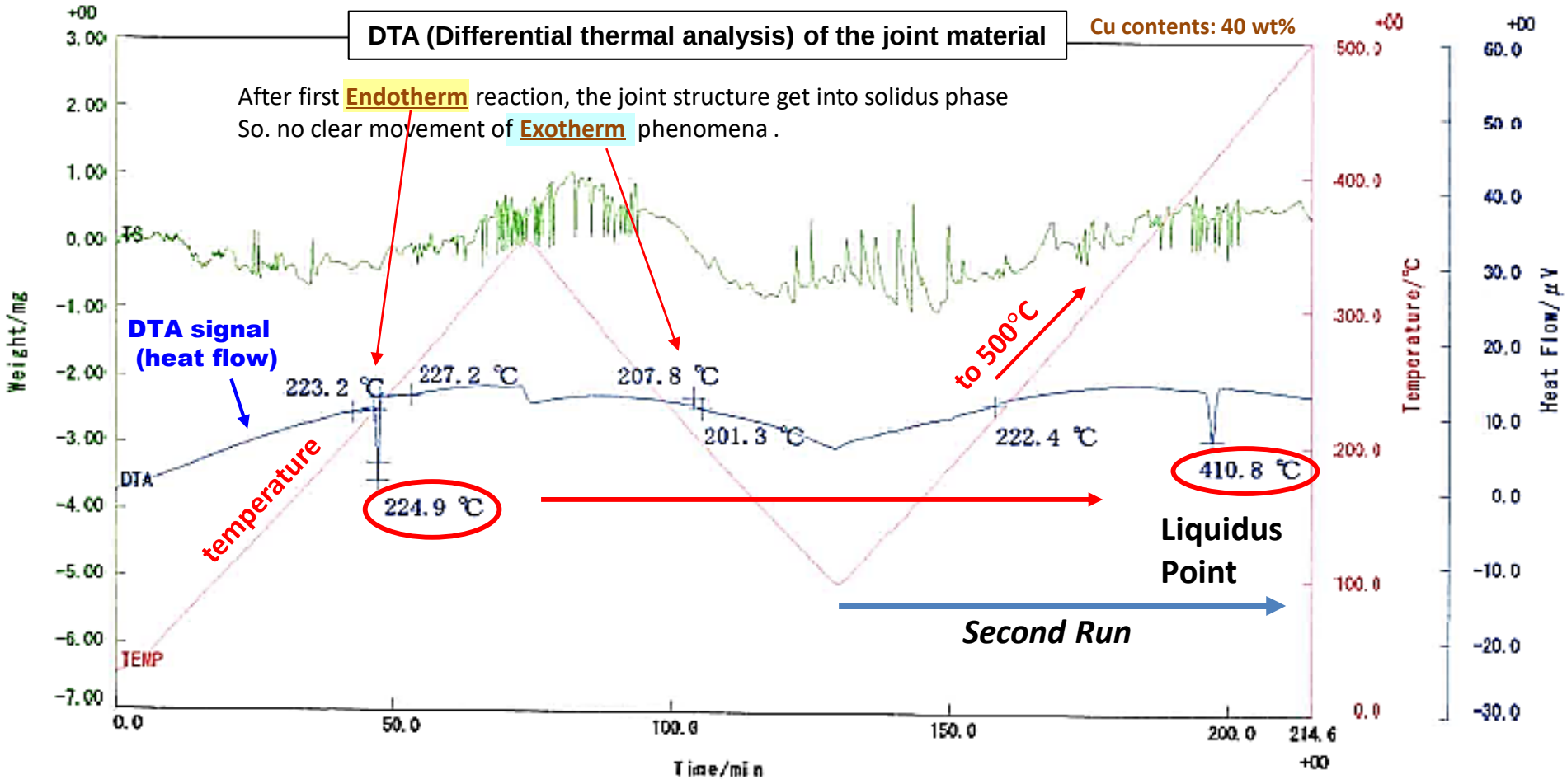
Appendix

Typical behavior of solder by Differential Thermal Analysis (DTA)



⇒ **Re-melting temperature**

Interaction between Cu sources and IMC sources in joint sheet



- Lower sintering temperature
- Higher operational temperature

Comparison of Joint Materials

	Temperature In Use (Sintering)	Compression	Reliability beyond 200° C	Resistivity	Material Availability	Issue	Joint Structure Stability	Usage beyond 200° C
SAC	125℃ (260℃)	Not required	Not Applicable	11μΩ·cm	Good	Low melting point	Not Applicable	Not Applicable
Sn-Sb	175℃ (250℃)	Not required	Unstable in TCT	20-40μΩ·cm	RoHS	Toxic Poor for TCT	Not Applicable	Faire
Sintering Cu	200℃ (250℃)	30MPa	Require Fillet	17μΩ·cm	Good	High Cost by nano particle H_2 Reduction High Pressure	Not Saturate	Fair
Sintering Ag	200℃ (280℃)	30-50MPa	Crack by Power Cycling Test Oxidation/Sulfurization	8-9μΩ·cm	Poor	High Cost by nano particle High pressure/Temperature	Not saturate	Fair
Ag paste	150℃ (150℃	Not required	Not applicable	400μΩ·cm	Good	High resistivity Low temperature usage	NO	NO
Cu-Sn IMC	250℃ (280℃)	0-1MPa	Stable by saturated Cu-Sn IMC skeleton structure	12μΩ·cm	Good	Optimization for objects	Saturate	Good

Lower Cost than existing materials and solutions

High Temperature Operation by Low Temperature Processing

Power device die attach

Power CMOS, IGBT, SiC, GaN, LED

Metal encapsulation

Sensor Packaging for IoT

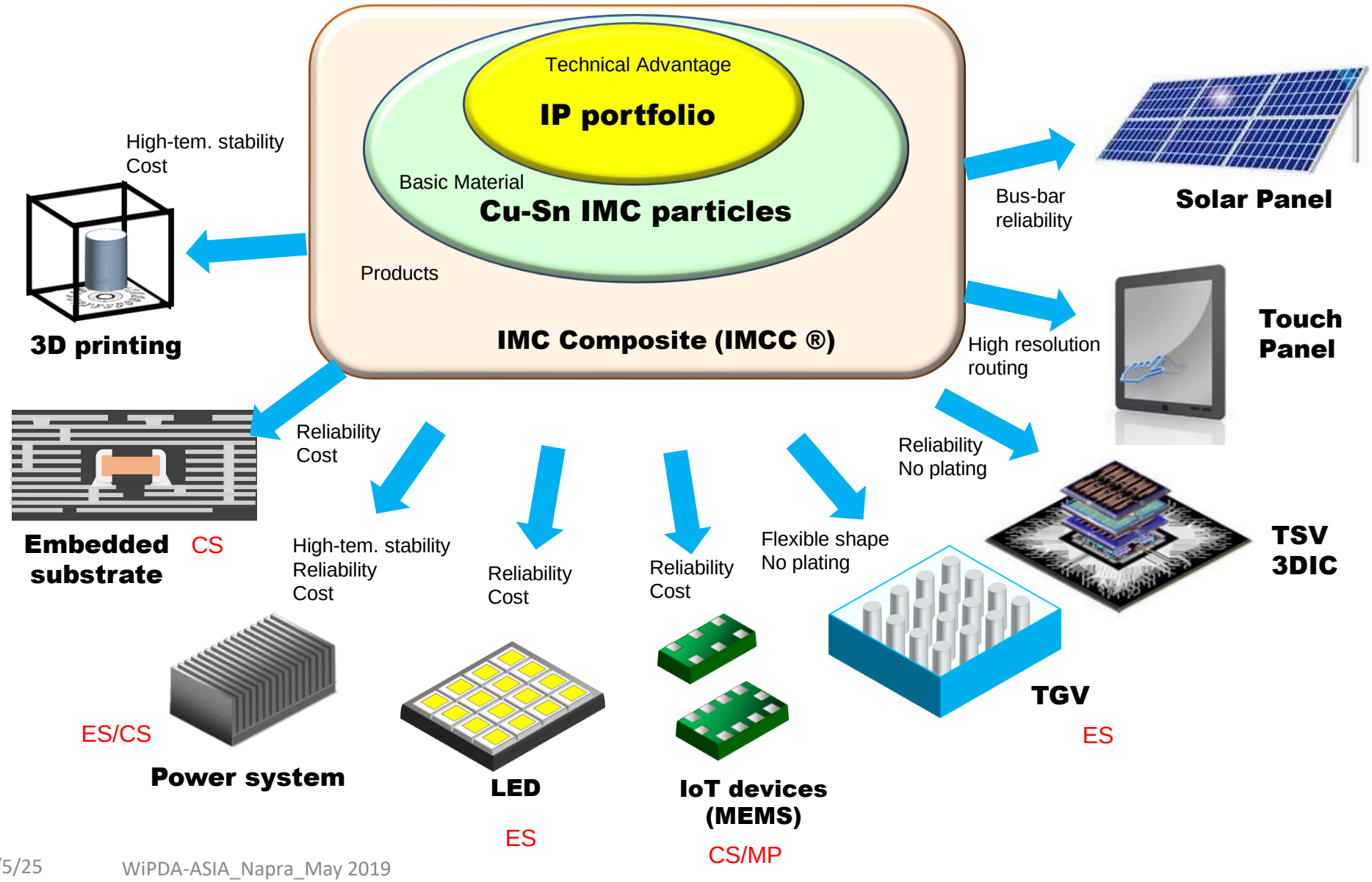
Fine Pattern Filling

Interposer

TSV/TGV/TQV

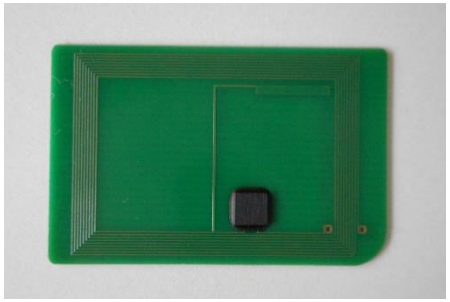
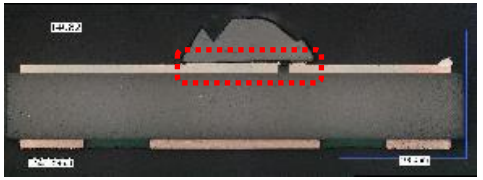
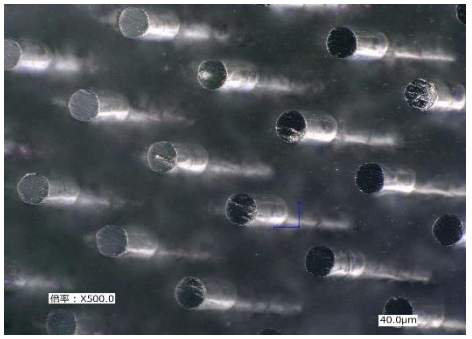
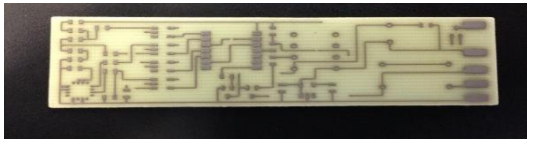
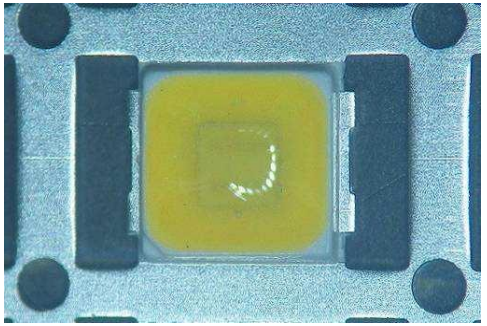
RDL on glass panel or wafer backside

Core Technology of Napra



IMCC
- paste (w/, w/o resin)
- sheet

IMCC pastes for interconnect

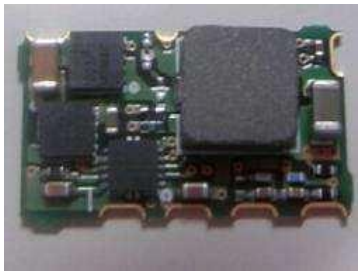
paste with resin	paste without resin	
 RFID	 LED	 TGV
 Substrate for automotive	 LED	

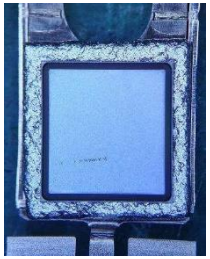
IMCC

- paste (w/, w/o resin)
- sheet

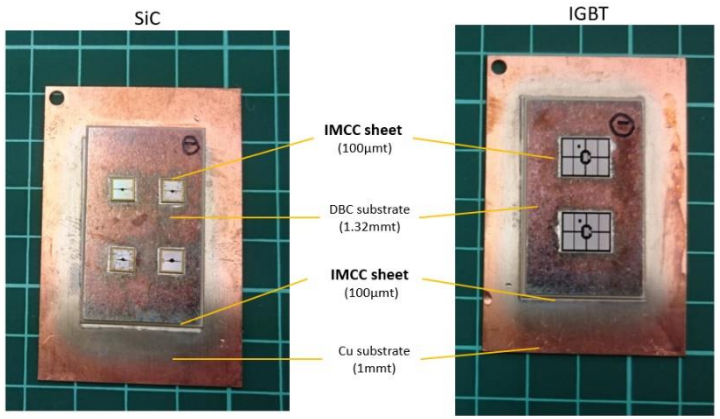
IMCC sheet

die attachment



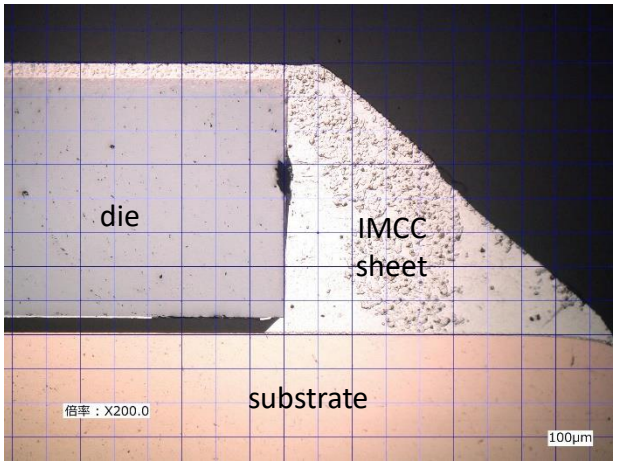


Power Module



die/heat-sink attachment

metal capsulation



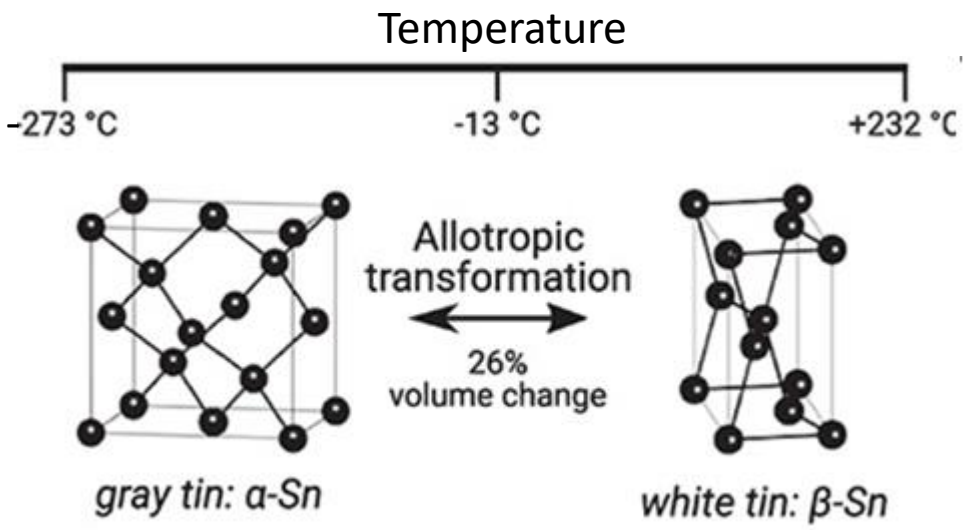
Tin Pest (Wikipedia)

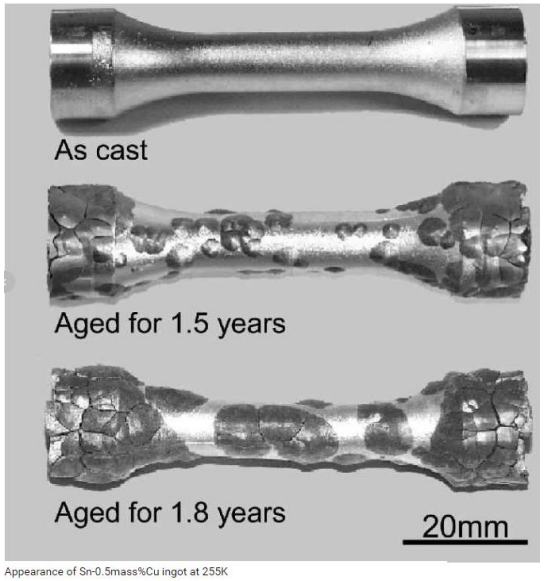
Tin pest is an autocatalytic, **allotropic transformation** of the element tin, which causes deterioration of tin objects at low temperatures. Tin pest has also been called tin disease, tin blight, tin leprosy or tin leprosy.

Allotropic transformation (Wikipedia)

At 13.2˚C and below, pure tin transforms from the silvery, ductile metallic allotrope of β-form white tin to the brittle, nonmetallic, α-form grey tin with a diamond cubic structure. The transformation is slow to initiate due to a high activation energy but the presence of germanium (or crystal structures of similar form and size) or very low temperatures of roughly −30 ˚C aids the initiation. There is also a large volume increase of about 26% associated with the phase change to the nonmetallic low temperature allotrope. This frequently makes tin objects (like buttons) decompose into powder during the transformation, hence the name tin pest.

The decomposition will catalyze itself, which is why the reaction speeds up once it starts; the mere presence of tin pest leads to more tin pest. Tin objects at low temperatures will simply disintegrate.





Sn-0.5Cu Aging (conventional **Tin Pest** example)

https://www.researchgate.net/figure/Appearance-of-Sn-05massCu-ingot-at-255K_fig1_42796240