大阪大学
OSAKA UNIVERSITY

IRSP2023

Solid-phase bonding process using nanostructured surface for power devices in automotive

24th April, 2023

Hiroshi Nishikawa

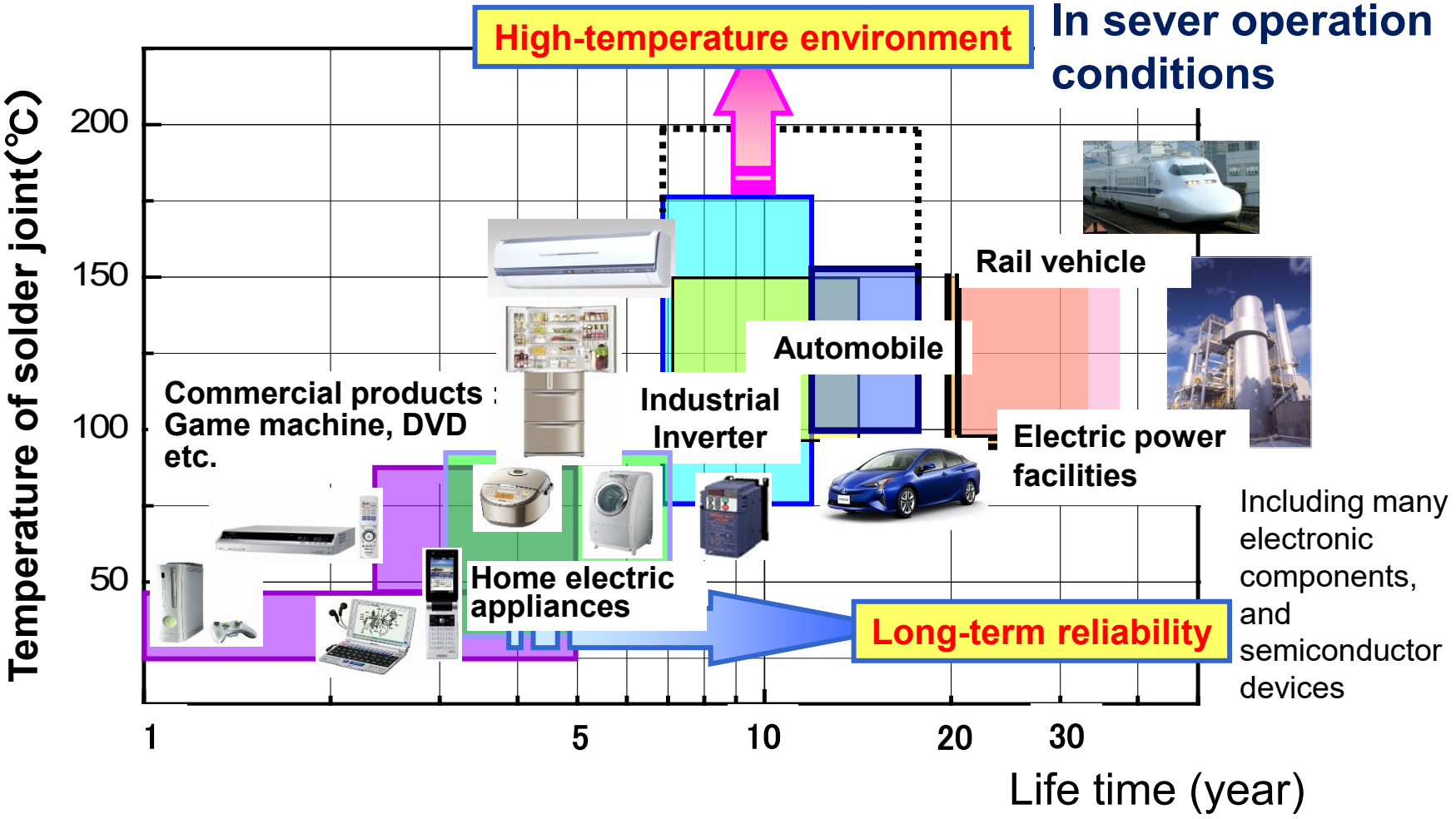
Professor

Joining and Welding Research Institute (JWRI)

Osaka University

Resent trends
in Micro Joining Process and Interconnection

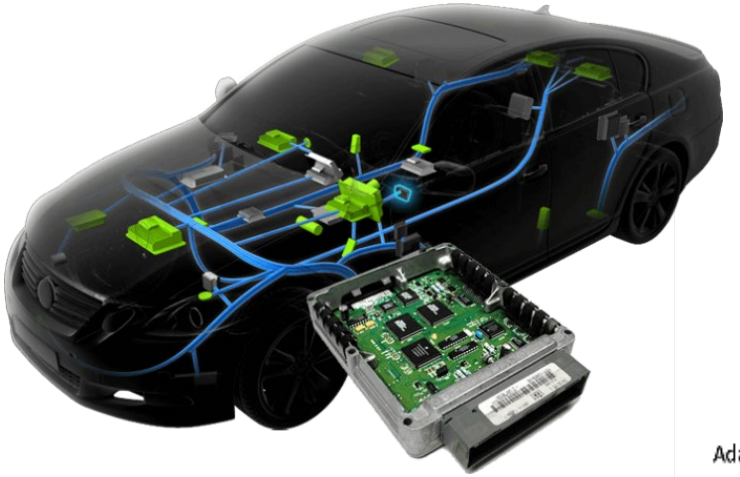
Temperature of joint in operation



High-temperature bonding becomes a key technology

Electronic devices on vehicle

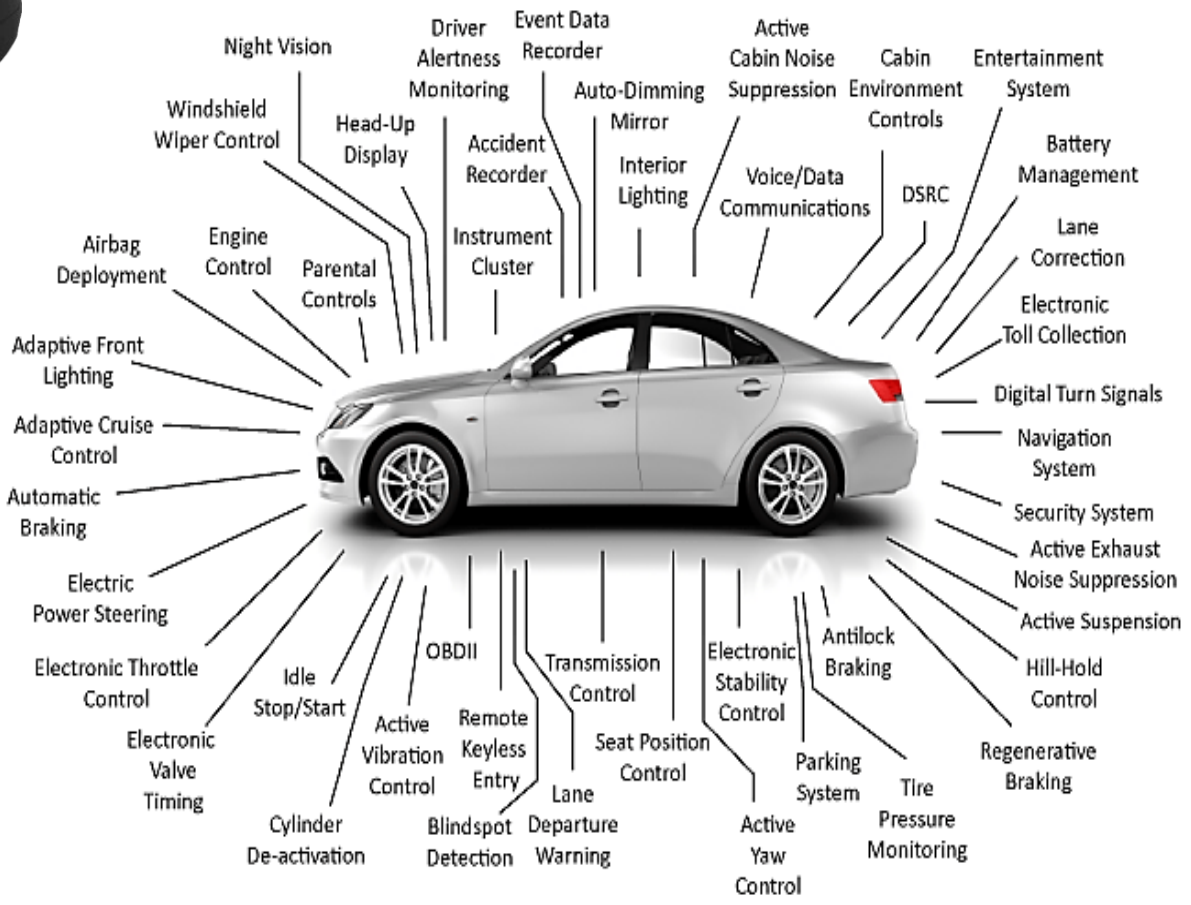
Electronic Control Unit is one of the most important electronic devices



ECU:
Electronic Control Unit
for engine, brake, wiper

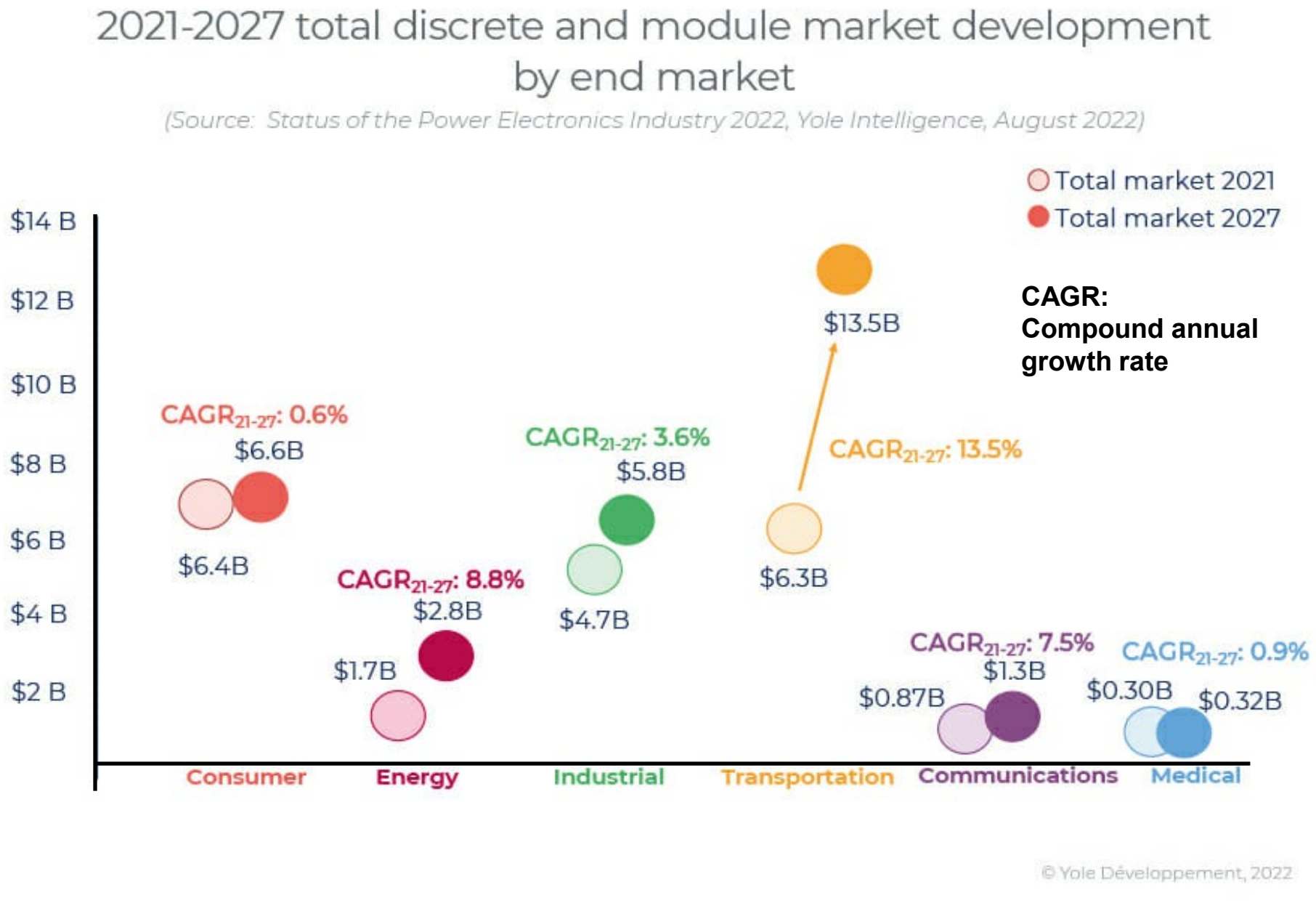
More than 20 years ago, vehicles were mostly seen as mechanical systems

Automotive Innovation Driven by Electronics



Source: https://autotechdrive.com/electronic-control-unit/

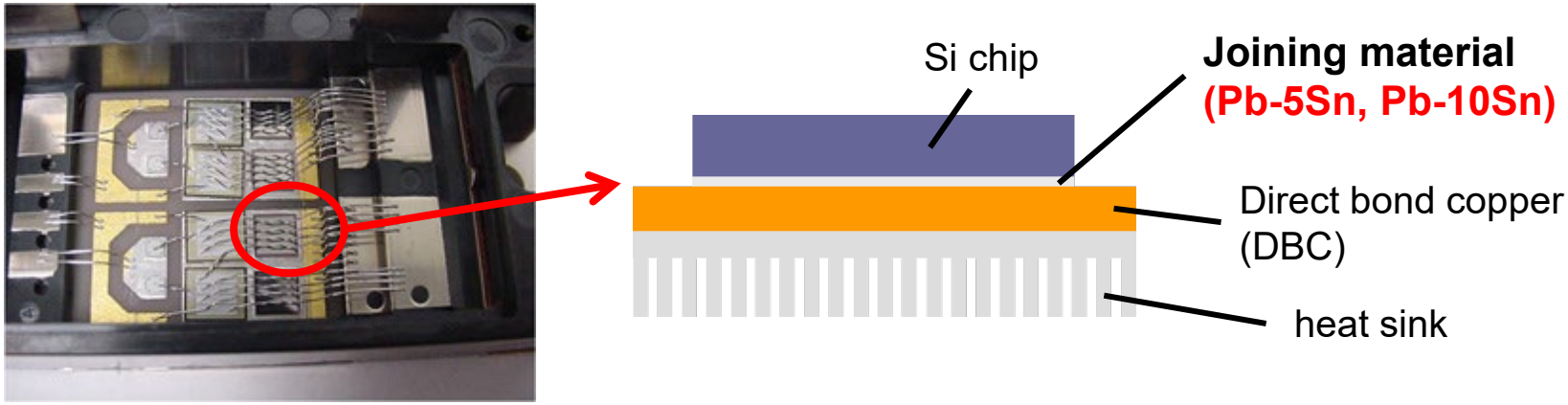
Expected global market of power devices



CAGR: Compound annual growth rate

Power device packaging

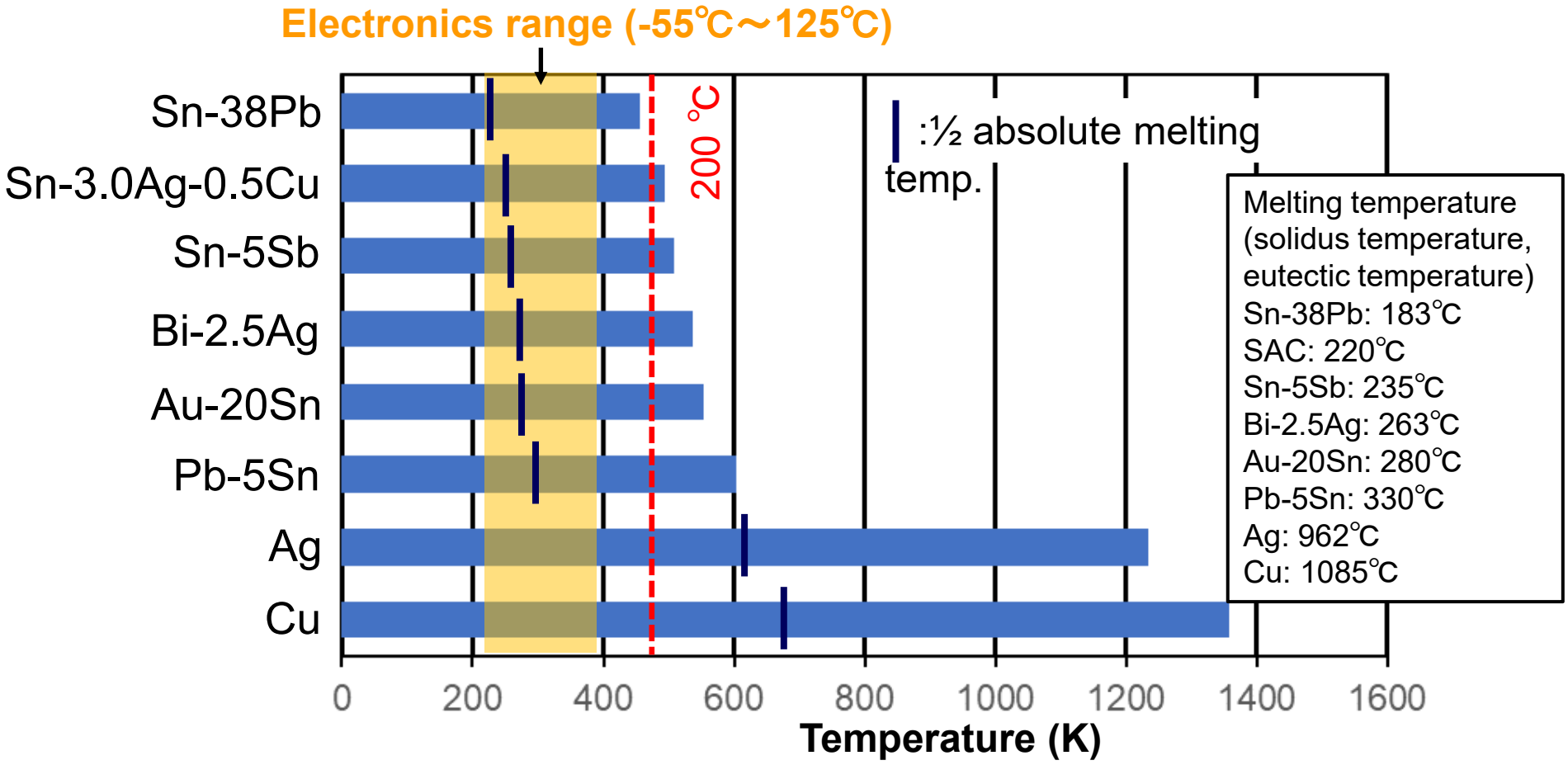
- Power device packaging for the automobile electronics



- Pb-free joining method for the high temperature application in the literature

Joining method	
High temperature soldering	• Zn-based alloy
	• Au-based alloy
	• Bi-based alloy
Transient liquid phase bonding (TLP)	
Bonding using nanomaterials	• Metal nanoparticles

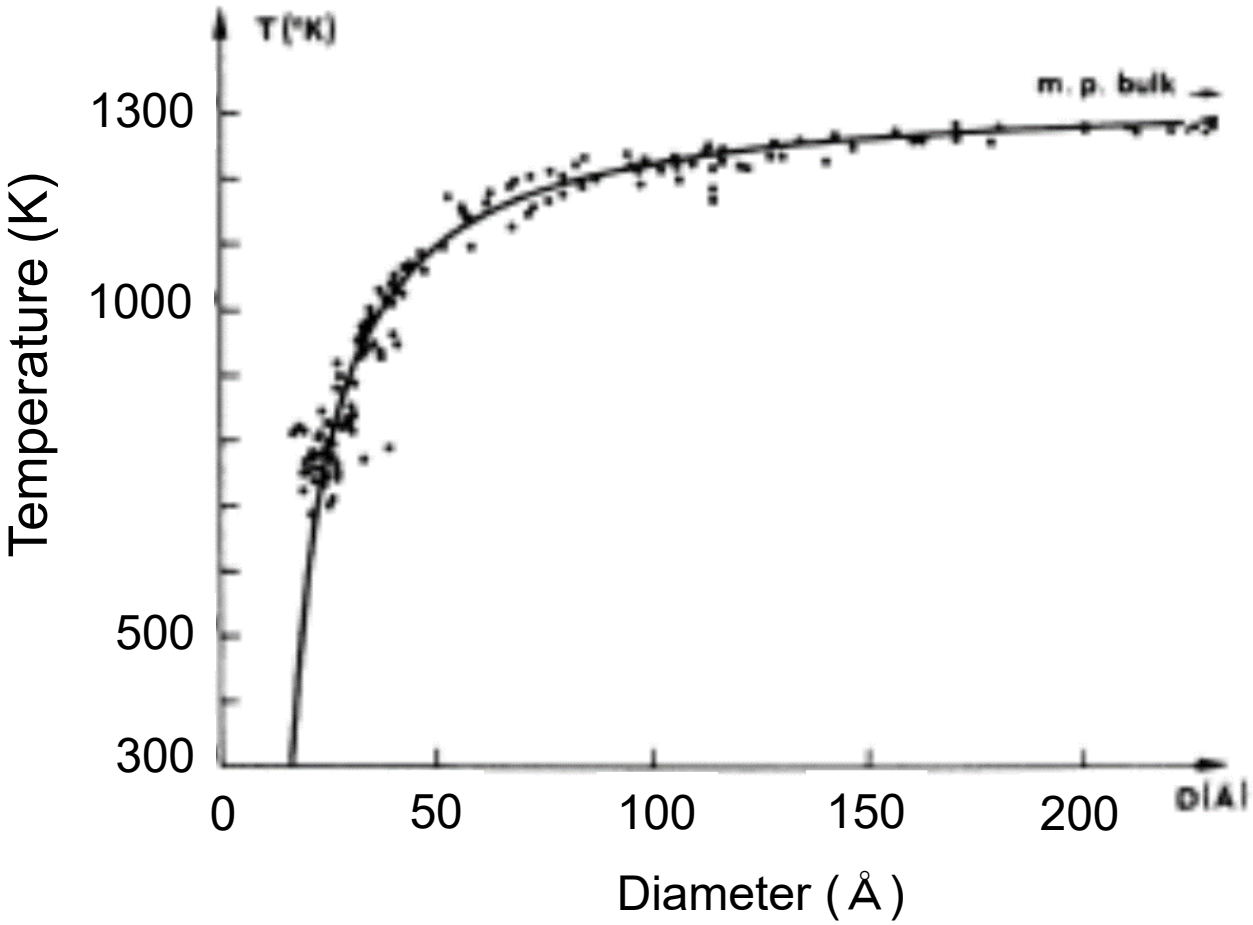
Homologous temperature of alloys and metals



Recrystallization temperature: $0.3 \sim 0.5 T_m$ (K)

Temperature of creep: $0.35\ T_m$ (K)

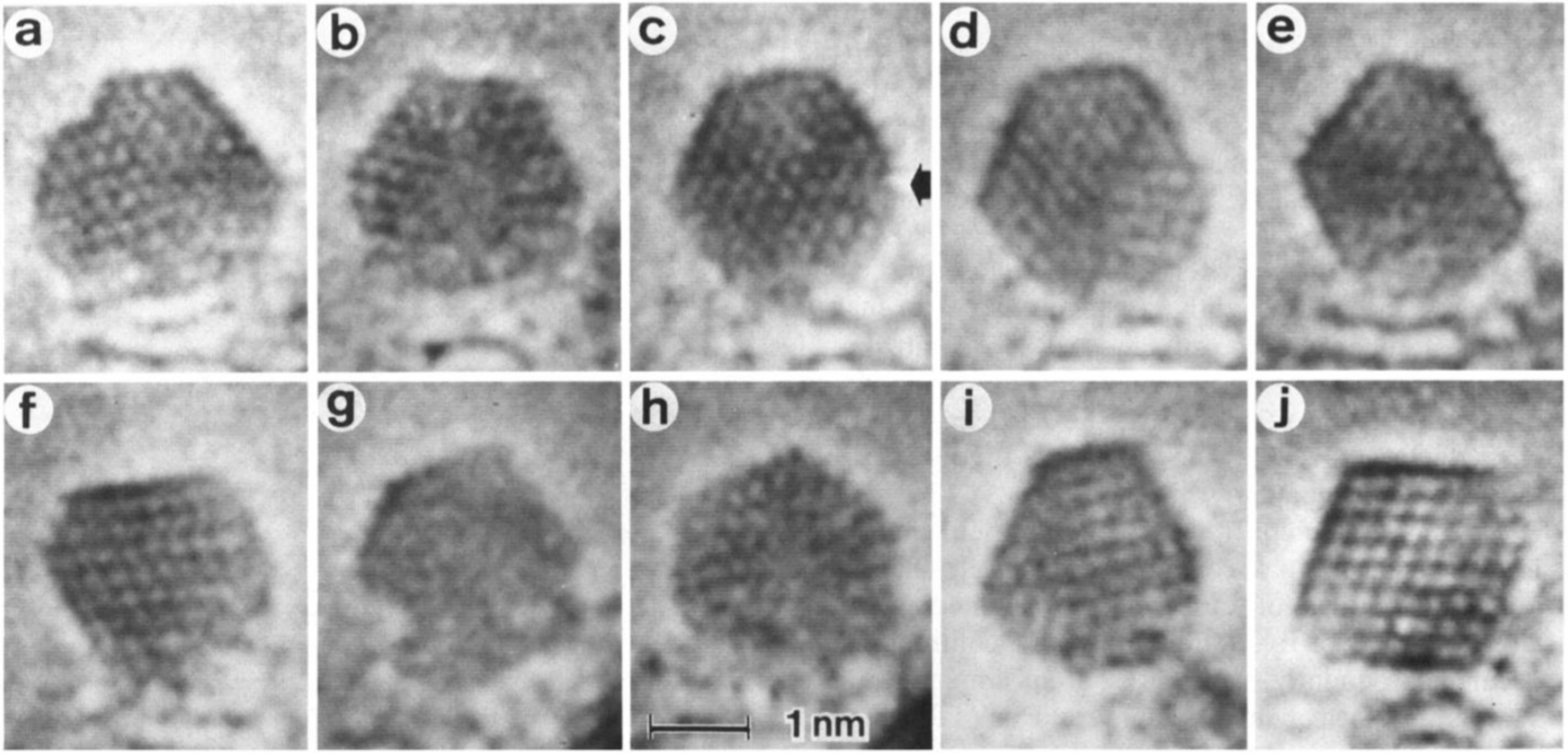
Size effect on melting temperature of Au particles



Ph. Buffat and J-P Borel: Size effect of the melting temperature of gold particles, *Phys. Rev. A*, Vol. 13 (1976), 2287-2298

Behavior of ultrafine gold particles

Change of morphologies and internal structures of ultrafine gold particles



Constantly changed approximately every few tenths of a second

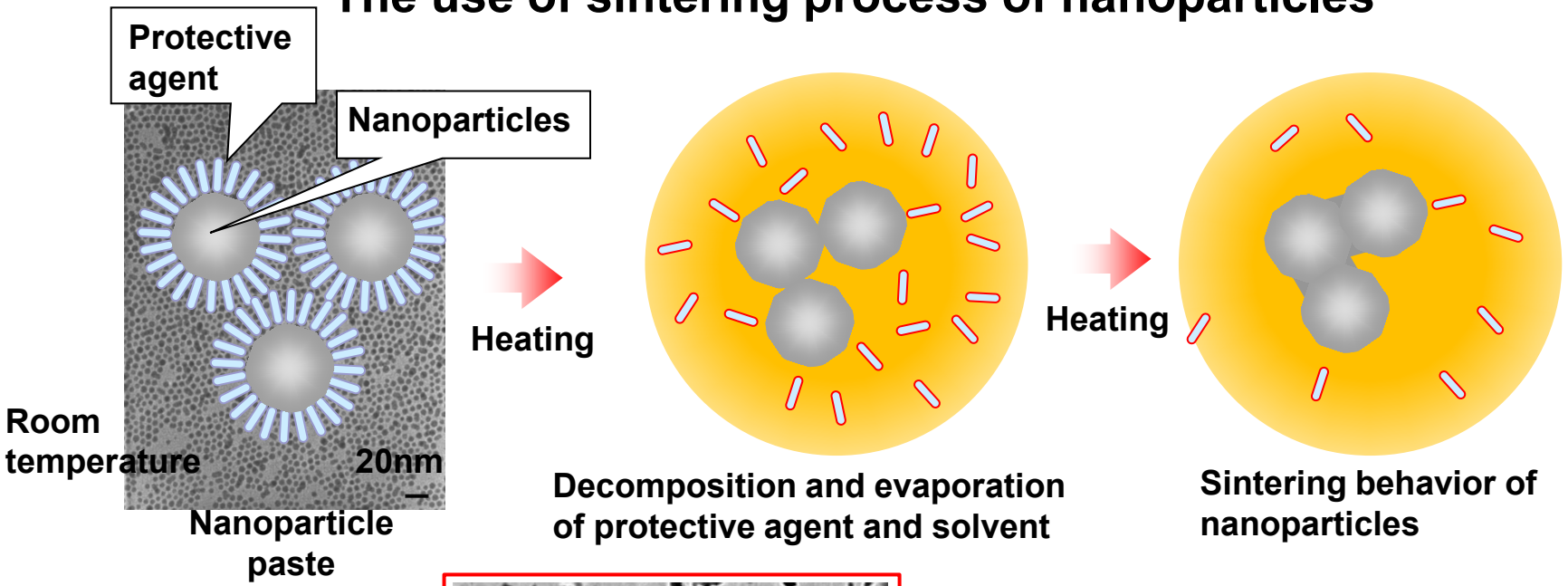
S. Iijima and T. Ichihashi: Structural Instability of Ultrafine Particles of Metals, *Phys. Rev. Lett.*, Vol. 56 (1986), 616-619.

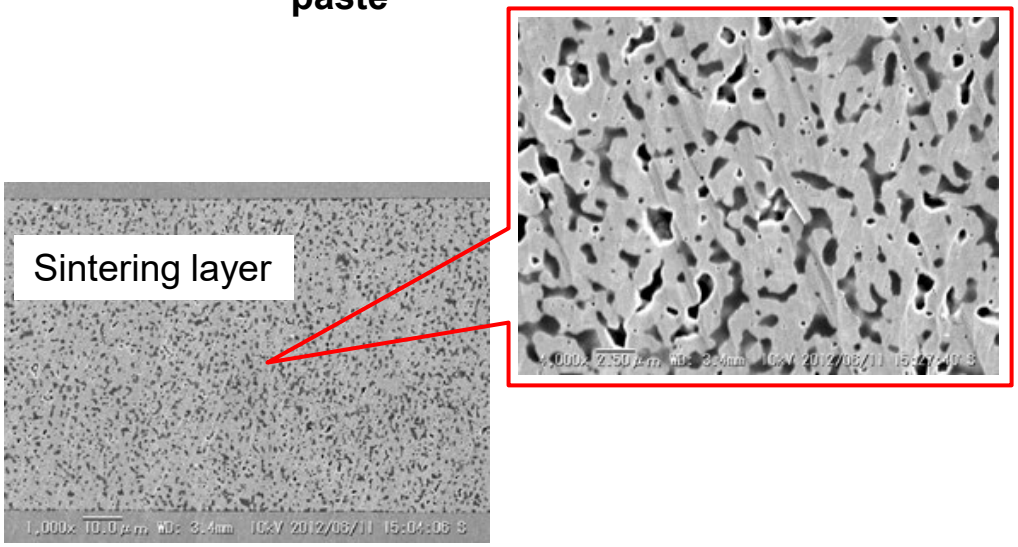
Liquid-like behavior of Au grain boundary

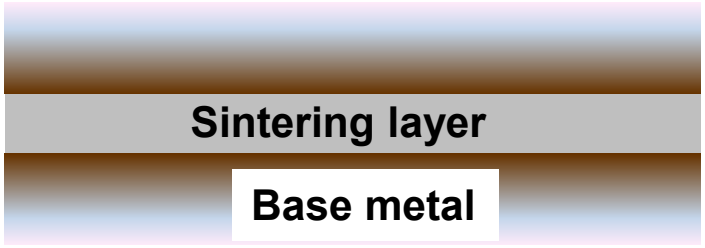
G. Casillas, A. Ponce, J. Jesús V.-Salazar and M. José-Yacamán: Direct observation of liquid-like behavior of a single Au grain boundary, Nanoscale, Vol. 5 (2013), 6333-6337.

Bonding process using nanoparticles

The use of sintering process of nanoparticles







Ag nanoparticles

Melting point of sintering layer > **Process temp.**

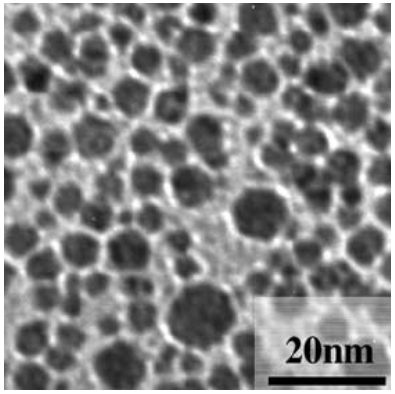
960 ℃ 300 ℃

Much lower temperature !!

Bonding process using nanoparticles

Nanoparticle paste

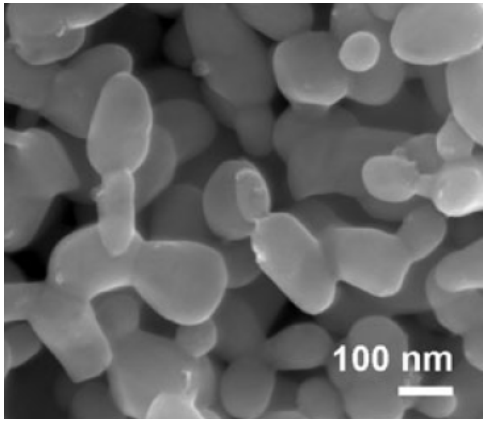
- ✓ High specific surface area → low temperature bonding
- ✓ **Solvent and organic substances are required**
- ✓ Residual organic materials → unexpected large void / gap volume change



E. Ide et al., *Acta Mater.*, **53** (2005) 2385

New bonding materials proposed from our lab.

- ✓ Stable state
- ✓ Removal or minimum amount of solvent and organic substance
- ✓ High specific surface area like nanoparticle
- ✓ Low-temperature solid-phase bonding



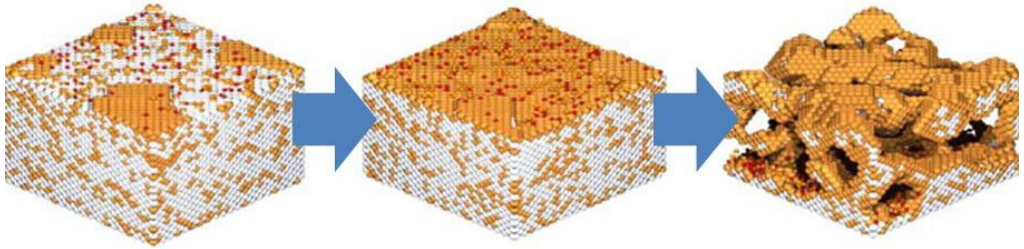
Nanoporous metal

Dealloying as Nano-processing tool of metals

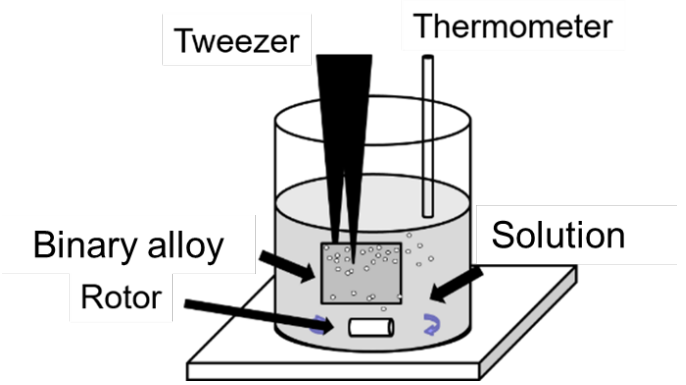
Dealloying is a kind of corrosion process

Selective dissolution of less noble element

Nature Vol.410, 2001, p450



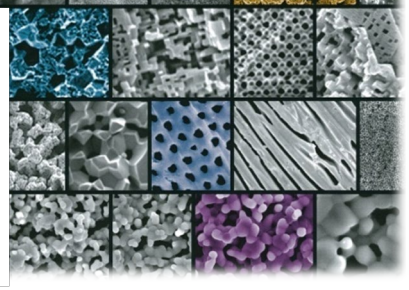
S. A. Policastro et al., *J. Electrochem. Soc.*, **157** (2010) C328



(Source: MRS Bulletin Vol.34, Aug., '09)

Recently, dealloying proved to be very effective in generating new types of porous metals

Useful in energy, environment, and biomedical applications.



(*Guest Editor,* J. Erlebacher)

Many crystalline alloys have been investigated.
(Ag-Au, Ni-Au, Al-Au, Zn-Cu, Mn-Cu, Ag-Au, Cu-Pd, tec.,)

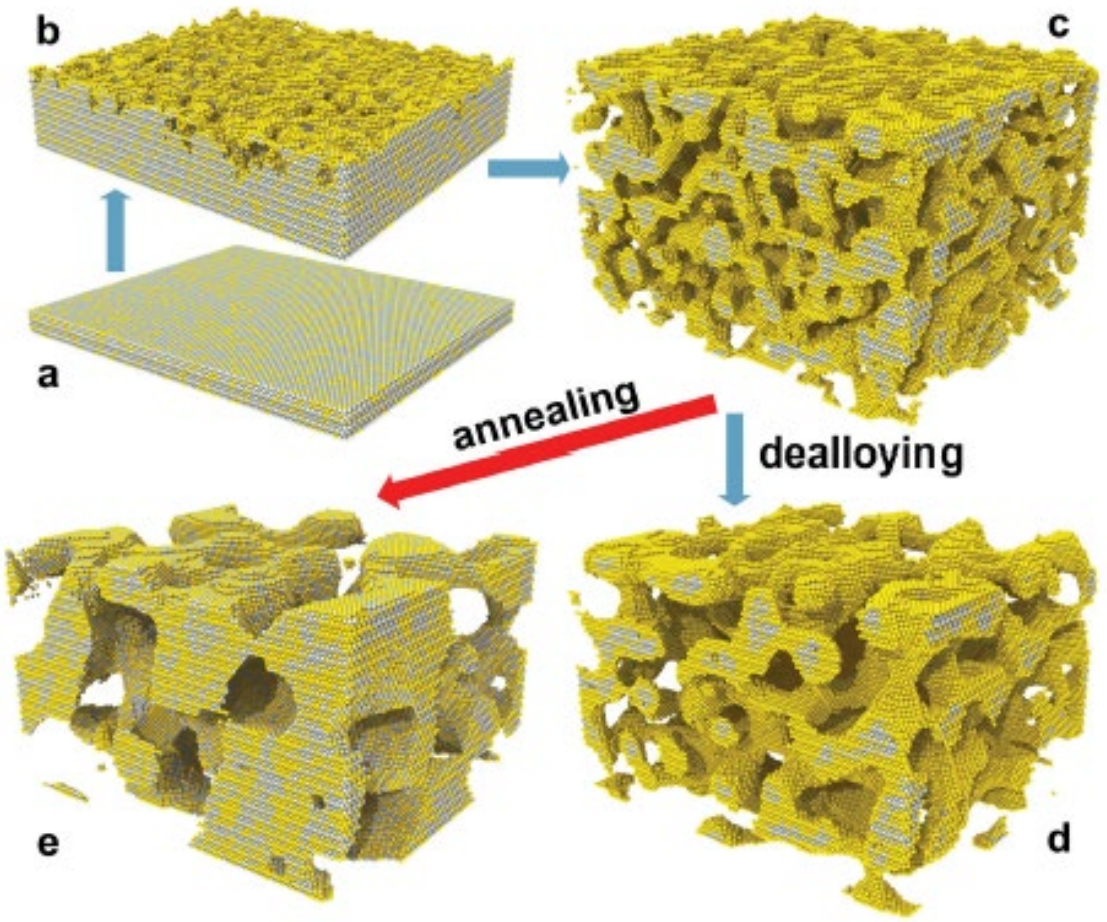
Formation process of nanoporous by dealloying

- Selectively dissolving Ag from an Ag-Au solid solution via controlled corrosion
- Ag dissolution and Au surface diffusion

By Kinetic Monte Carlo (KMC) simulation

At 300 K

$Ag_{75}Au_{25}$ (fcc)
100 × 100 atoms
90 {111} layers thick



Covered by a single atomic monolayer of Au

Curvature-driven coarsening by surface diffusion

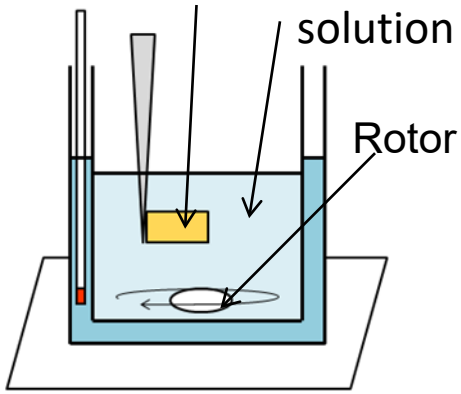
Ag which was exposed at the surface during coarsening has been dissolved

Tobias Krekeler, Anastasia V. Straber, Matthias Graf, Ke Wang, Christian Hartig, Martin Ritter and Jorg Weissmuller: “Silver-rich clusters in nanoporous gold”, *Materials Research Letters*, **5** (2017) 314-321

Au Nanoporous for bonding material

Synthesis method

Au-Ag alloy

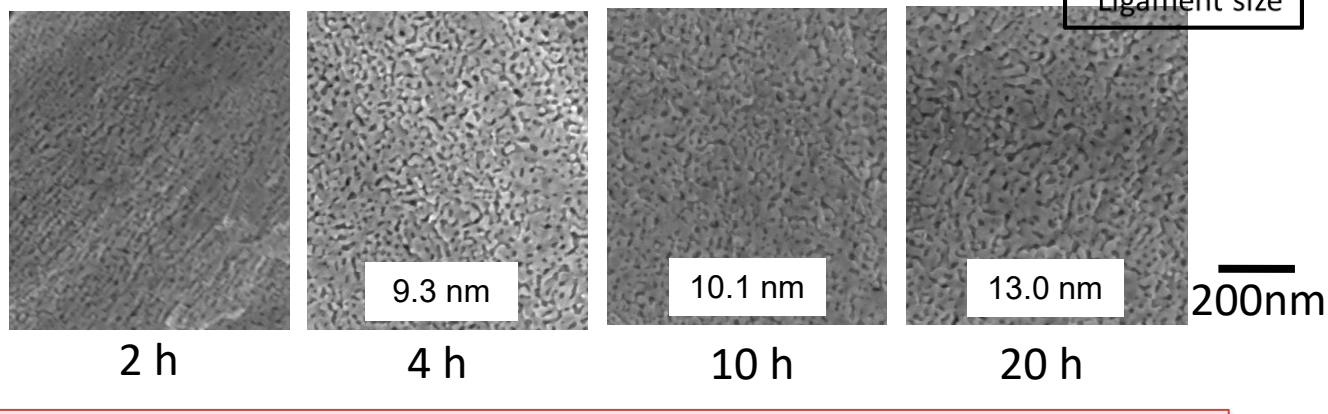


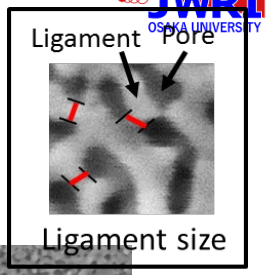
Temp.: 25 ℃

Precursor alloy:
Au-50mass% Ag

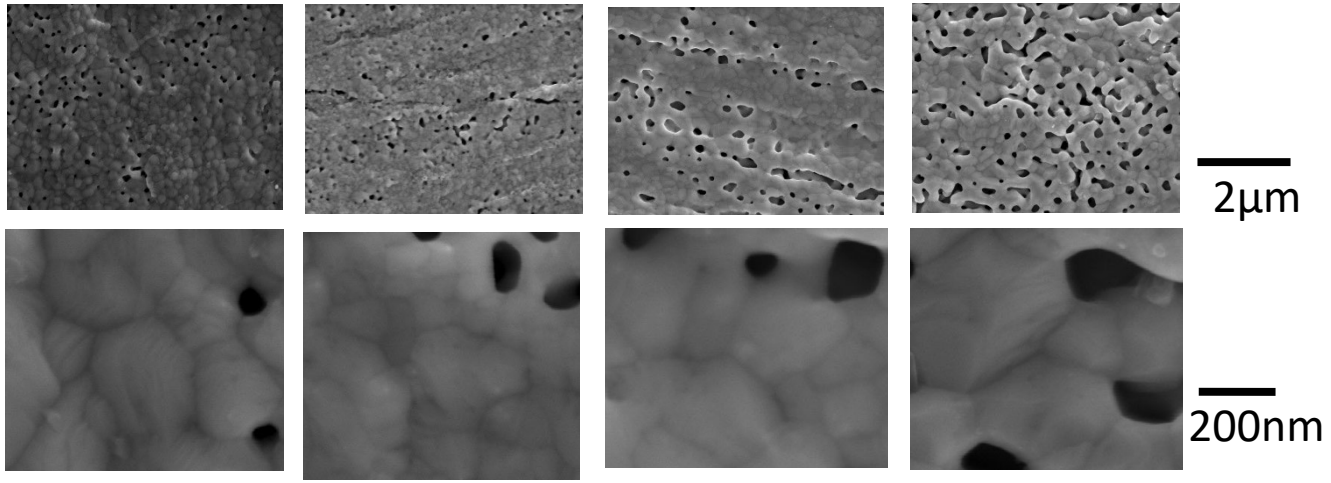
Thickness:
100μm

After dealloying into 60%HNO_3 at 25 ℃





After heating at 350 ℃ for 30 min under N_2 atmosphere

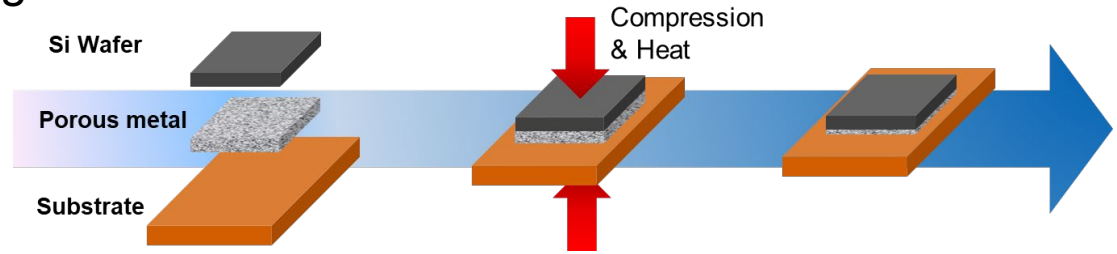


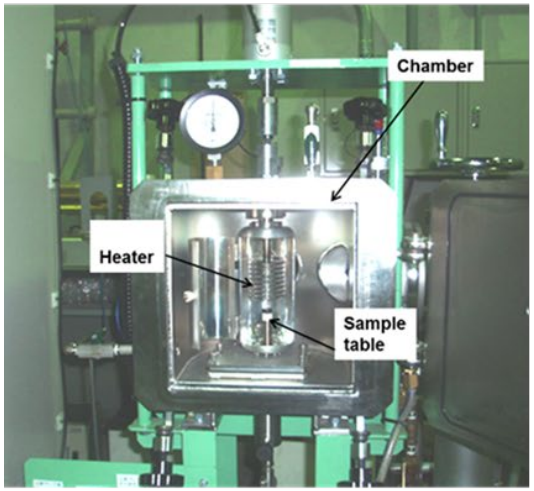
K. Matsunaga, M-S. Kim, H. Nishikawa, M. Saito and J. Mizuno: “Effect of Au nanoporous structure on bonding strength”, *Proc. of ICEP-IAAC 2015*, 830-833 (2015)

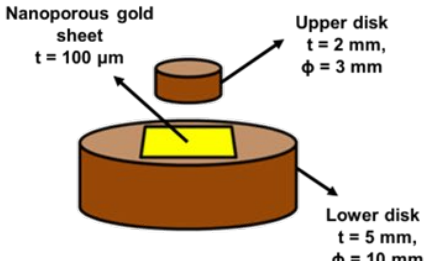
Proposal and feature of nanoporous bonding (NPB)

We suggest nanoporous bonding (NPB) method, as a die-attach bonding method for the high-temperature electronics packaging.

➢ without solvent and organic substances to overcome drawbacks of nanoparticle pastes



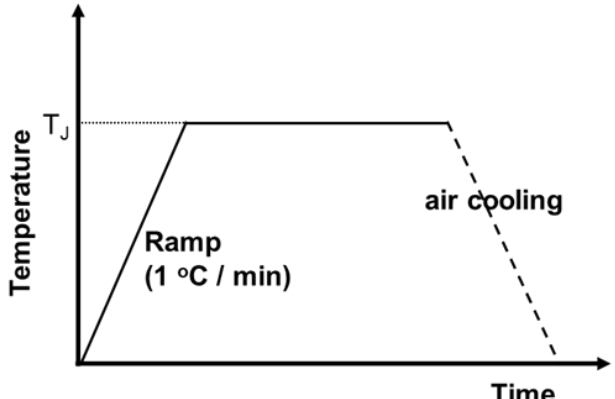




✓ **Test specimen** : Oxygen-free Cu disk

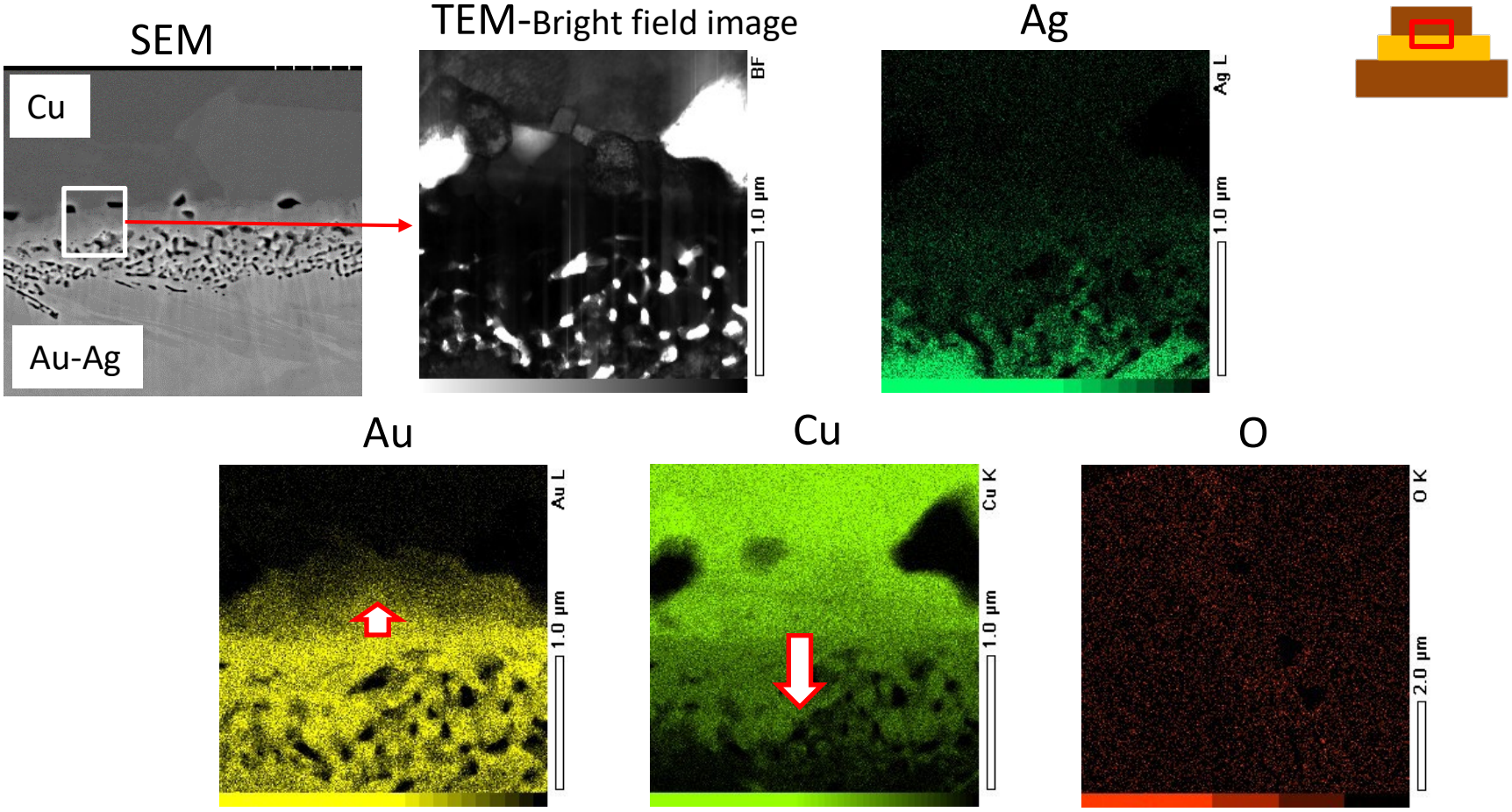
✓ **Conditions of NPB process**

- Temperature : 250, 300, or 350 °C
- Time: 30 min
- Applied pressure : 20 MPa
- Atmosphere : N_2



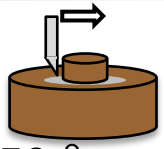
Interface between Cu and Au nanoporous

Dealloying time: 1 h,
NPB process: Temp. 350 ℃, Time 30 min, Applied pressure 20 MPa, N_2



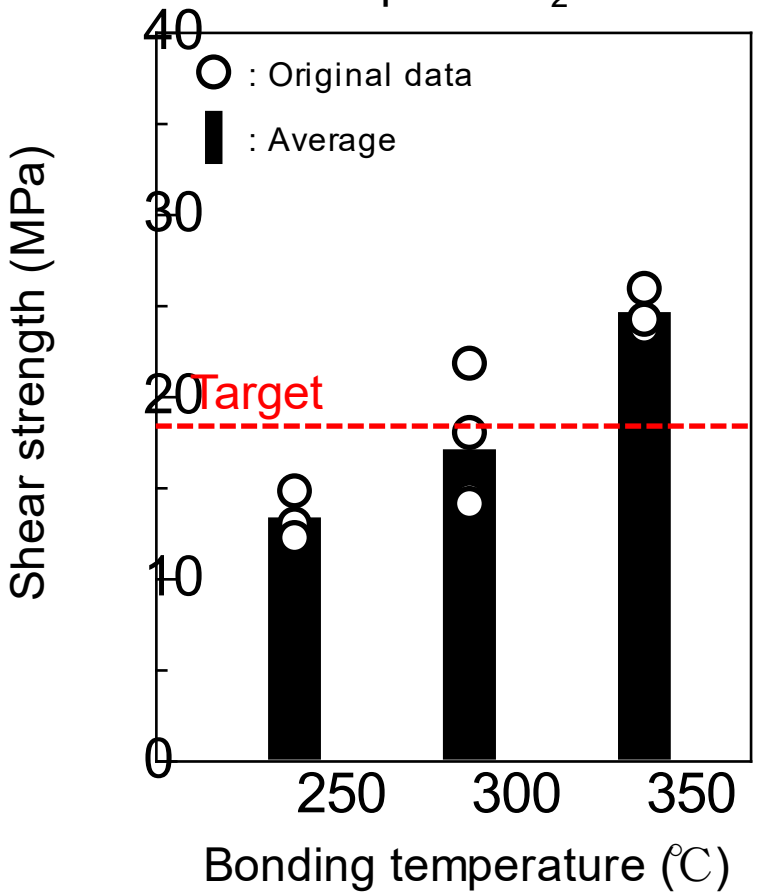
K. Matsunaga, M-S. Kim, H. Nishikawa, M. Saito and J. Mizuno: “Effect of Au nanoporous structure on bonding strength”, *Proc. of ICEP-IAAC 2015*, 830-833 (2015)

Shear strength of NPB joints

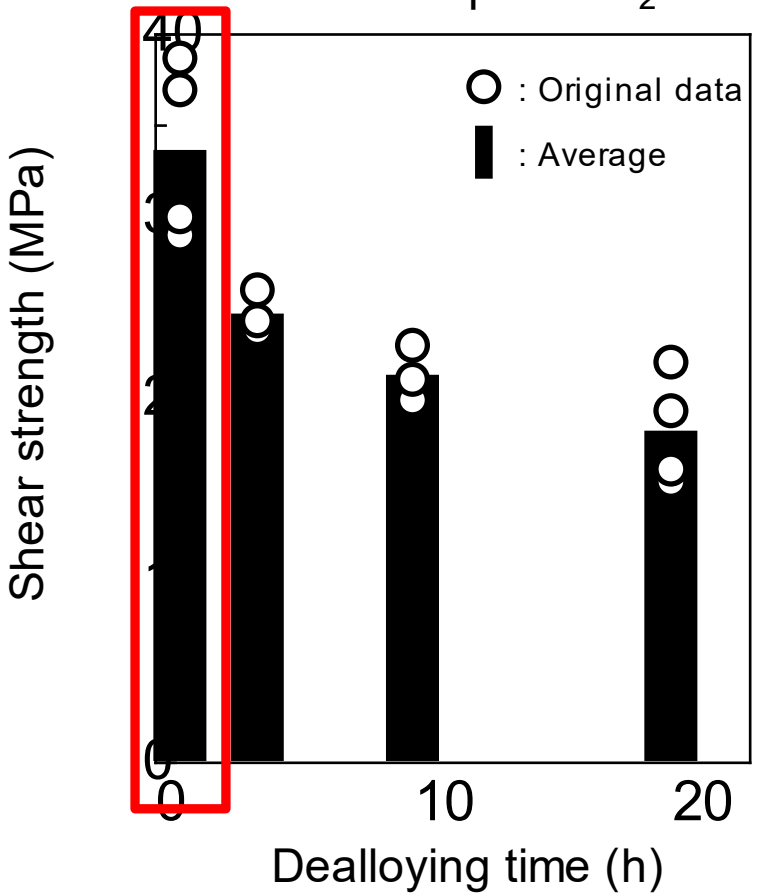


Cu-to-Cu joint

Dealloying time: 4 h,
NPB process: Time 30 min
Applied pressure 20 MPa
Atmosphere N_2



NPB process: Temp. 350 ℃
Time 30 min
Applied pressure 20 MPa
Atmosphere N_2

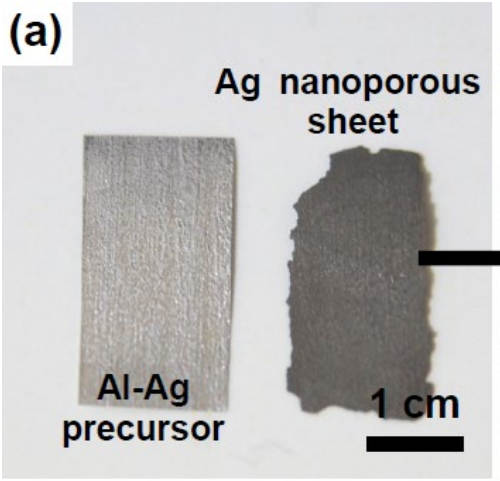


K. Matsunaga, M-S. Kim, H. Nishikawa, M. Saito and J. Mizuno: “Effect of Au nanoporous structure on bonding strength”, *Proc. of ICEP-IAAC 2015*, 830-833 (2015)

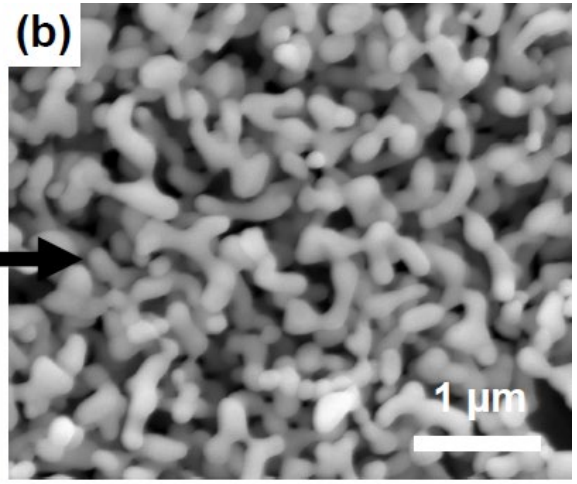
Fabrication of Ag nanoporous sheet

- ✓ fabrication of melt spun Al-20at%Ag precursor (t = 90~100 μm)
- ✓ dealloying with 2M HCl solution at 75 °C for 3 h

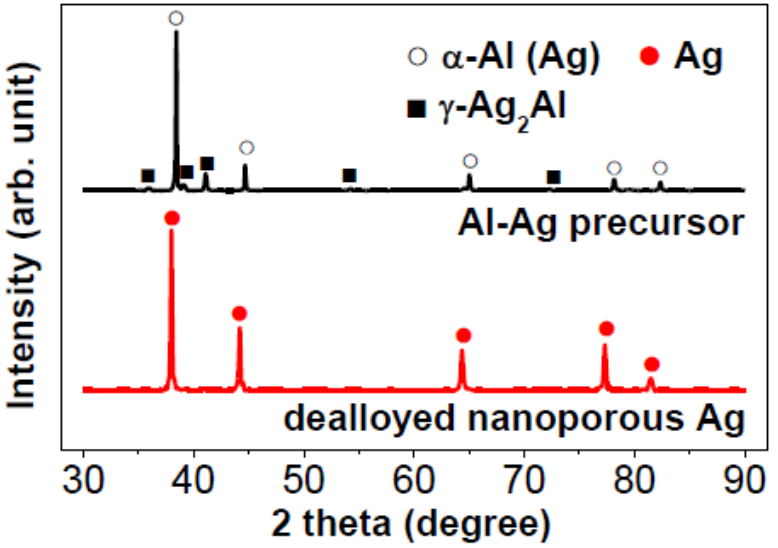
Optical image



SEM SE image



XRD results



➢ The ligament size of about 110 nm of Ag nanoporous sheet was successfully fabricated.

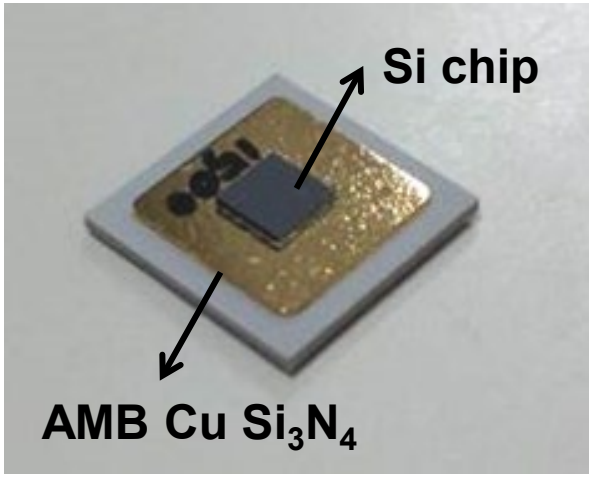
Sample and temperature profile of joining process

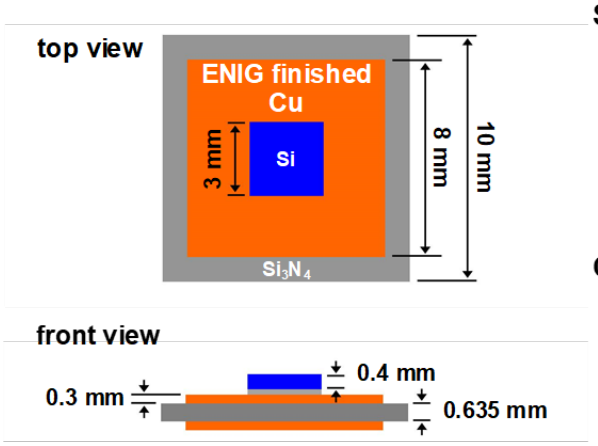
✓ Test specimen

- Si chip (3 mm x 3 mm) with backside metallization of Ti/Ni/Au
- active metal brazed Cu Si_3N_4 substrate with ENIG surface finish

✓ Conditions of joining process

- temperature : 300 °C
- applied pressure : 20 MPa
- atmosphere : N_2





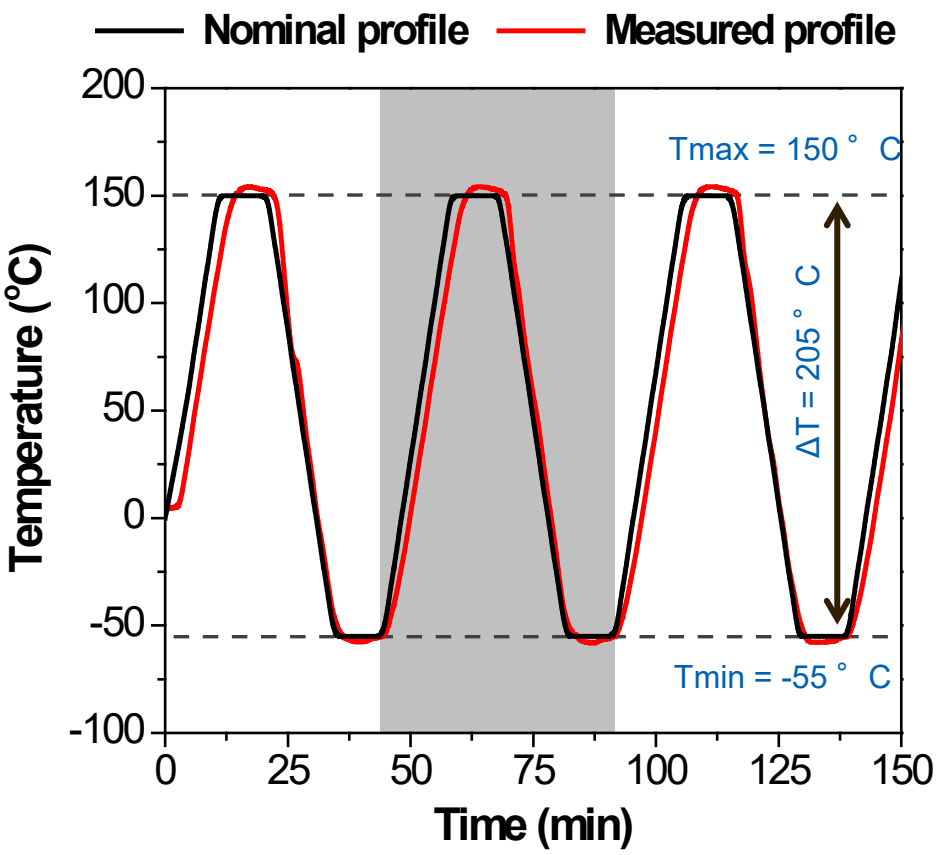
Si backside metallization

Si 400 µm
Ti 100 nm
Ni(P) 2 µm
Au 50 nm

Cu surface finish

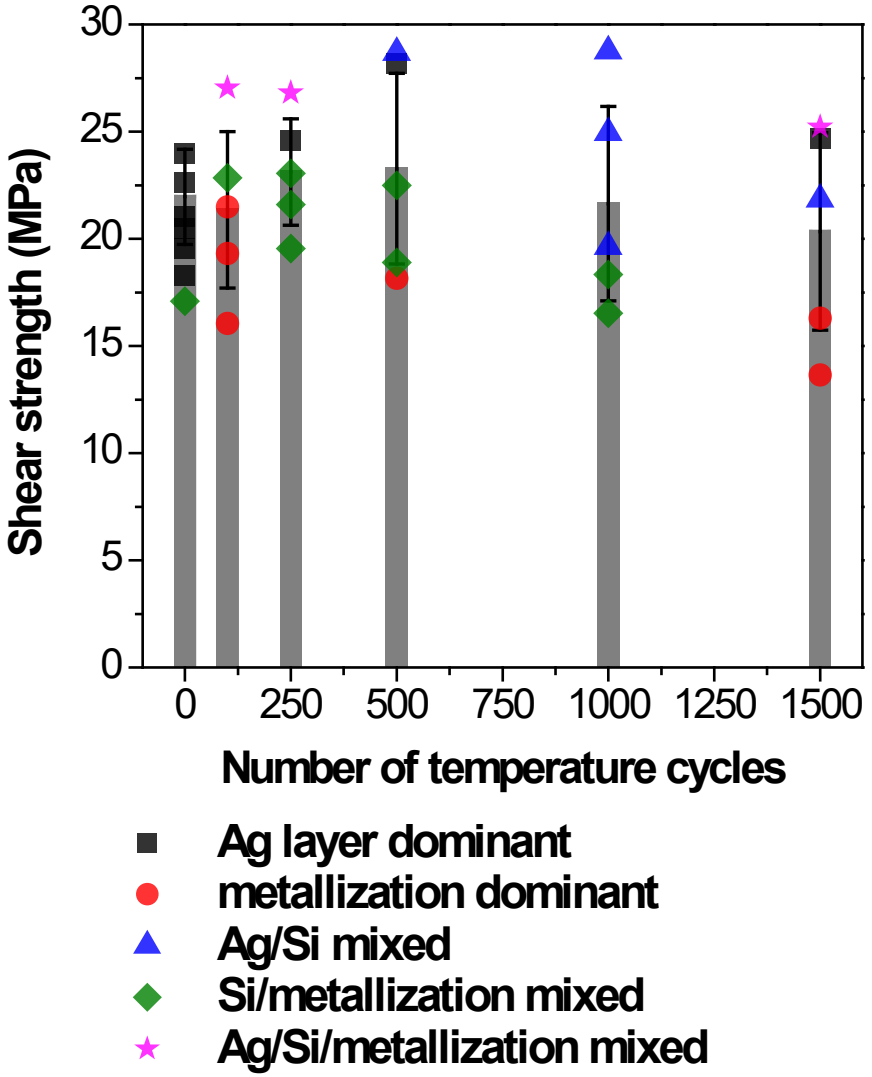
Au 50 nm
Ni(P) 2 µm
Cu 300 µm

Temperature cycling conditions



- Temperature cycling test according to JEDEC standard (JESD22-A104E)
- Temperature fluctuation from -55 ° C to 150 ° C
- Soaking time at T_{max} and T_{min} 10 min
- Heating and Cooling rate 15 ° C/min
- Number of cycles up to 1500 cycles

Change of shear strength of Ag NPB after TC



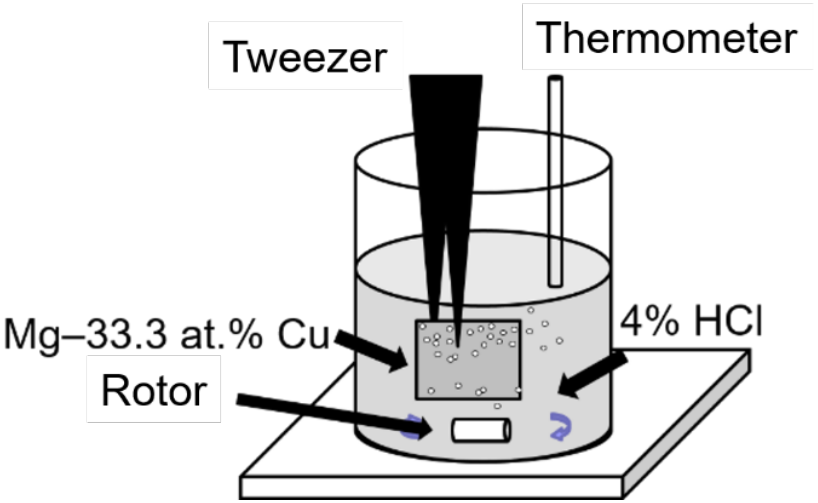
- Initlal shear strength
  - 22 MPa

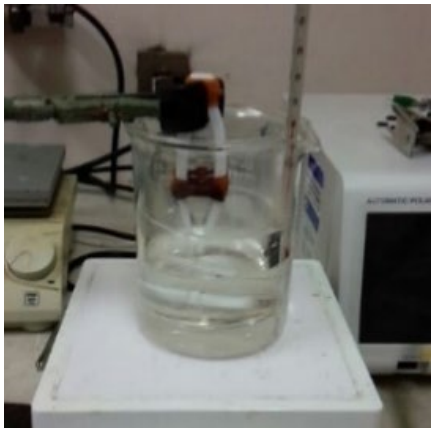
- Ag layer
- Ag/Si mixed
- Ag/Si/metallization mixed
  - Show comparatively higher values

- Metallization dominant
- Si/metallization mixed
  - Show comparatively lower values

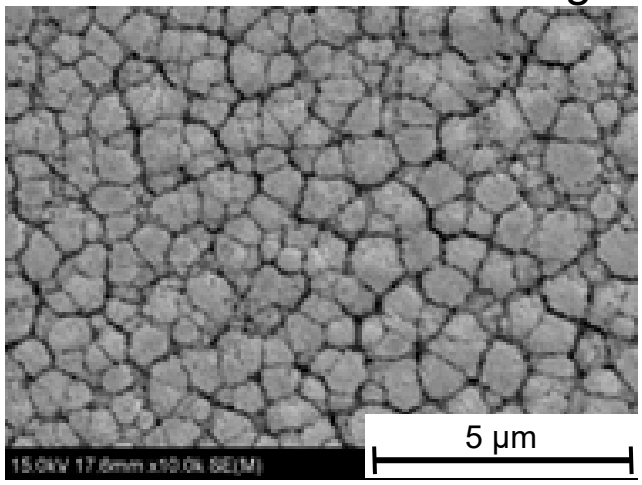
Formation of Cu nanoporous sheet

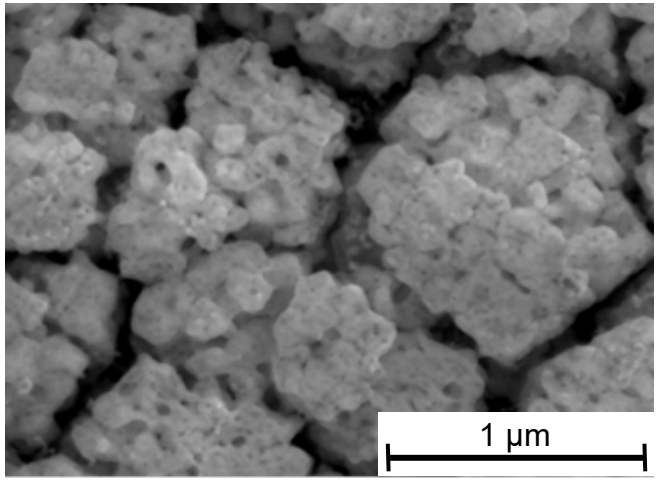
Precursor
・Mg–33.3 at.%Cu
（Thickness: 100 μm）
・4% HCl





SEM images of Cu nanoporous sheet

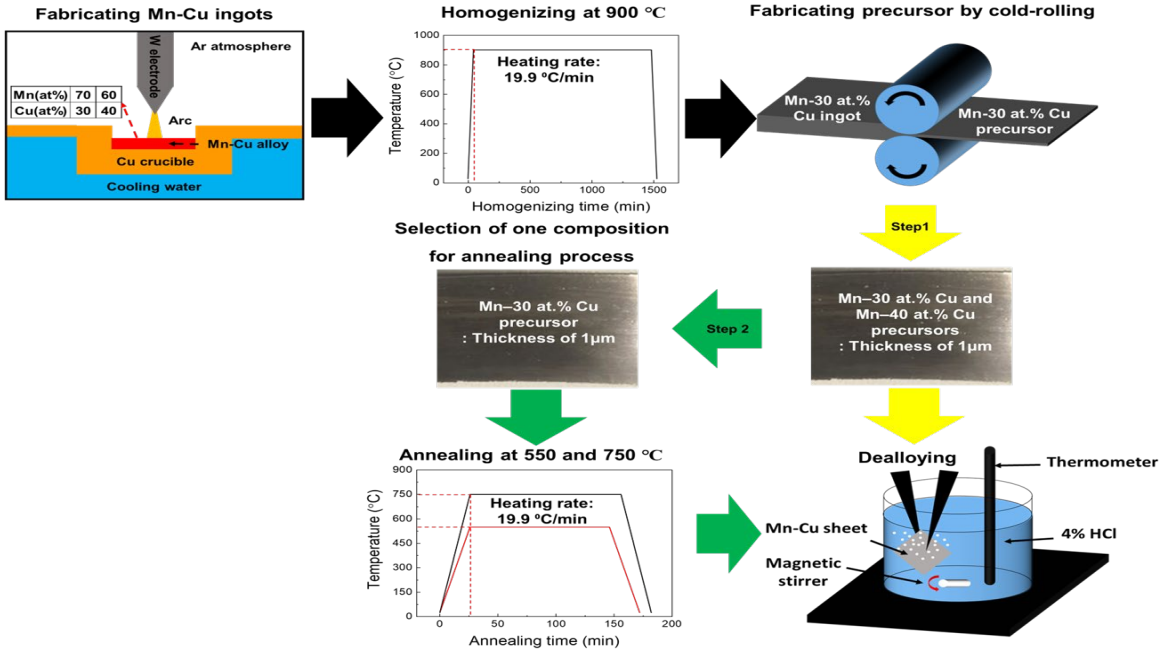


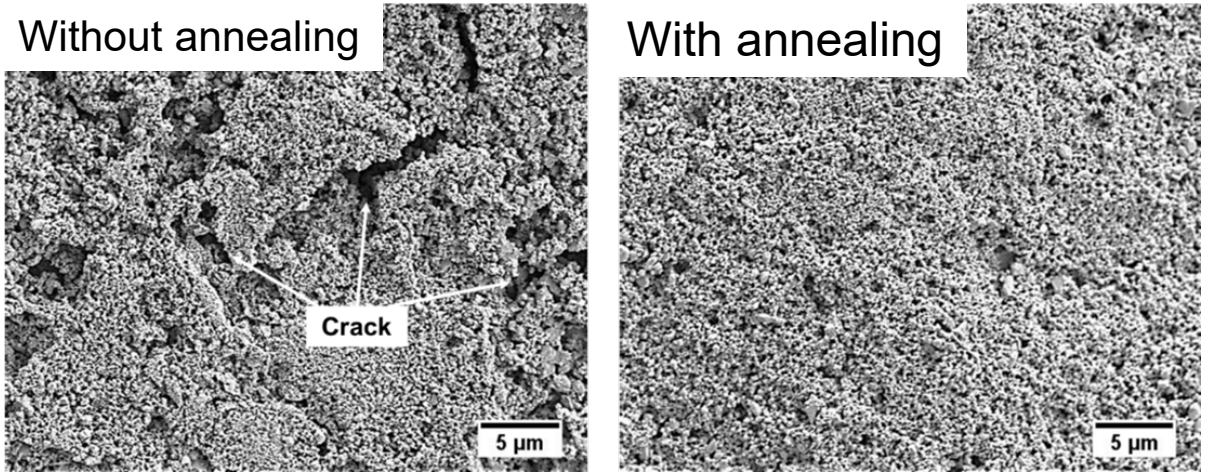


S. Koga, H. Nishikawa, M. Saito, J. Mizuno: Fabrication of Nanoporous Cu Sheet and Application to Bonding for High-Temperature Applications, *J. Electronic Materials*, **49** (2020), 2151-2158.

Formation of Cu nanoporous sheet

Precursor
- Mn–30 at.%Cu
(Thickness: 100 μm)
- 4% HCl



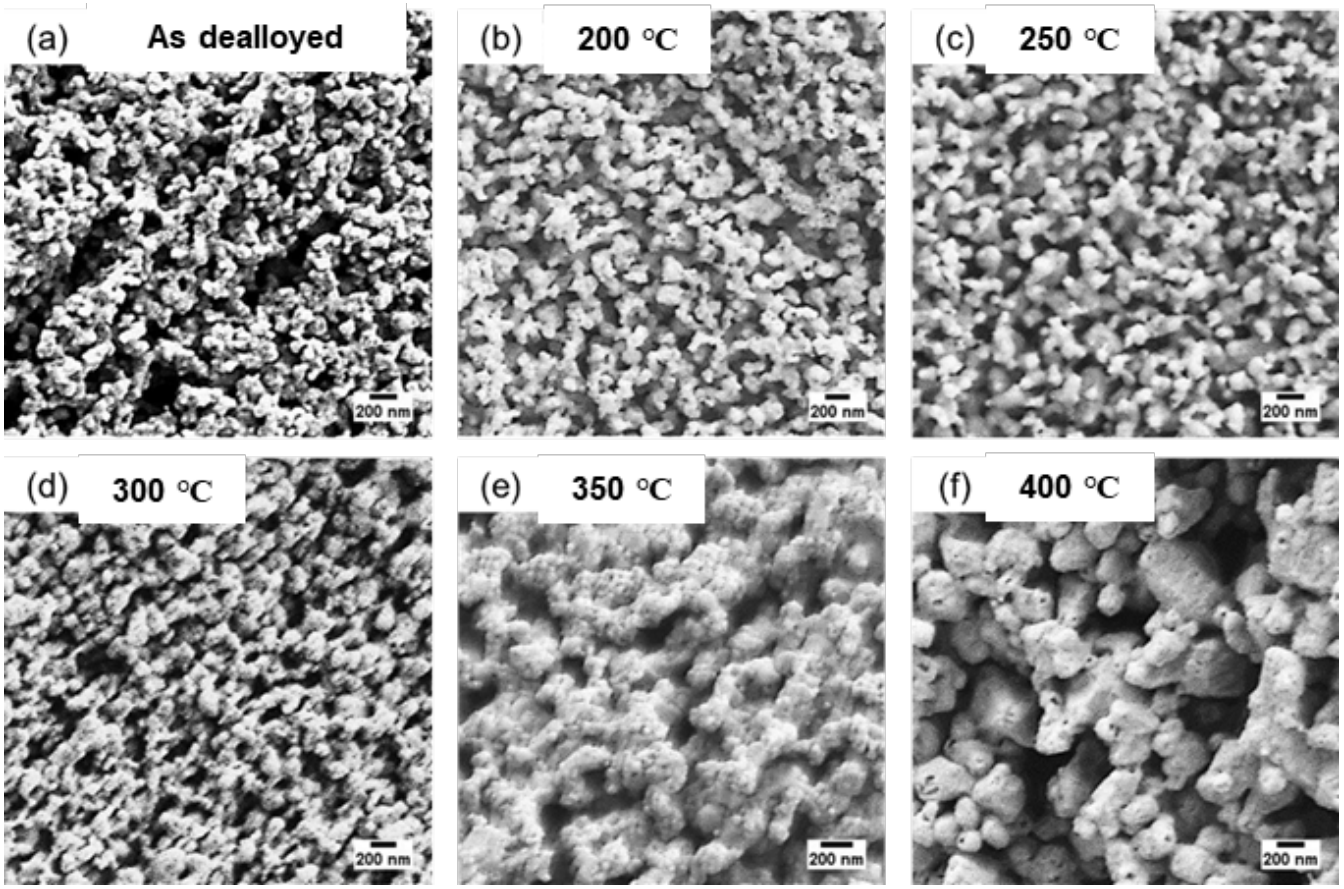


B. Park, D-L. Han, M. Saito, J. Mizuno, H. Nishikawa: Fabrication and characterization of nanoporous copper through chemical dealloying of cold-rolled Mn–Cu alloy, *J. porous materials*, 28 (2021), 1823-1836

Grain growth of Cu nanoporous structure during heating

Precursor
- Mn–30 at.%Cu
(Thickness: 100 μm)
- 4% HCl
- With annealing

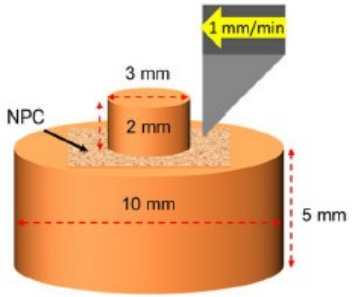
Hearting test
- 10 min
- N_2 atmosphere



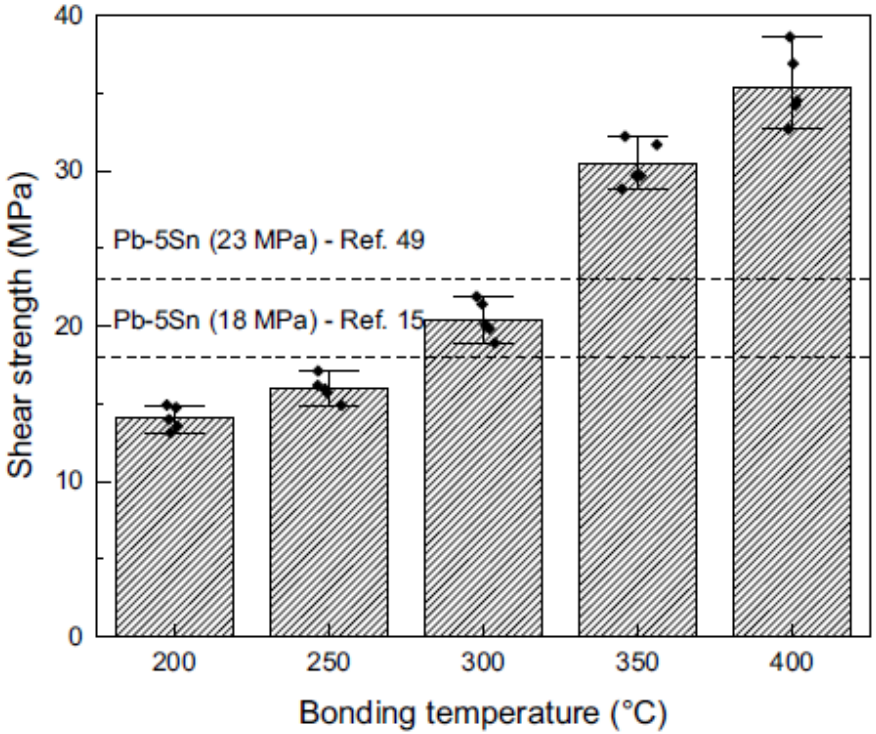
B. Park, D-L. Han, M. Saito, J. Mizuno, H. Nishikawa: Effect of various parameters on the shear strength of solid-state nanoporous Cu bonding in Cu–Cu disks for power device packaging, *J. Electronic Materials*, 51 (2022), 3851-3862.

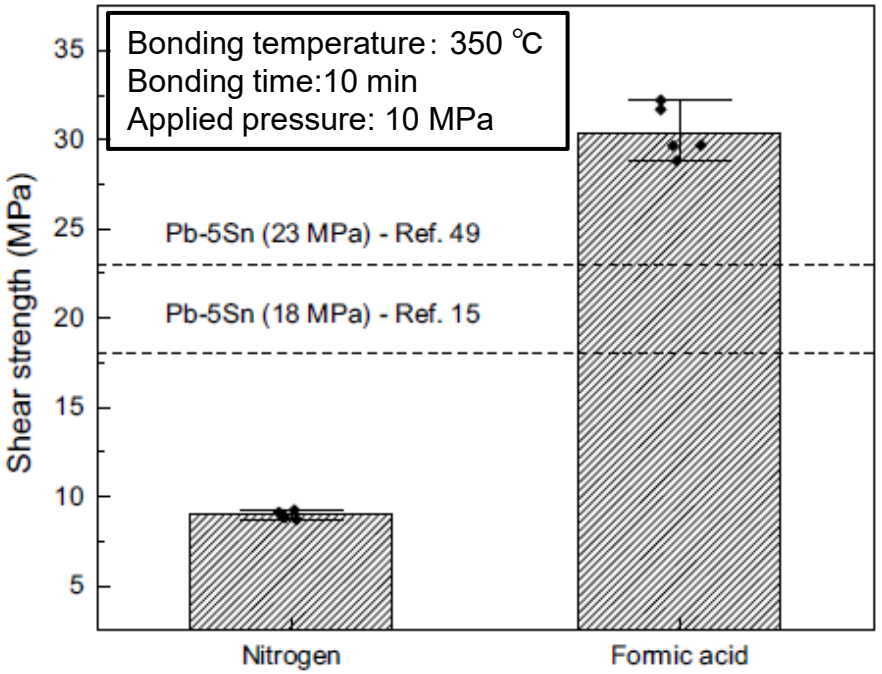
Shear strength of joints using Cu nanoporous sheet

Bonding experiments
- Oxygen-free Cu disc
- Thermo-compression bonding
  Applied pressure: 10 MPa
  Bonding time: 10 min
  Formic acid atmosphere



Bonding using NPC

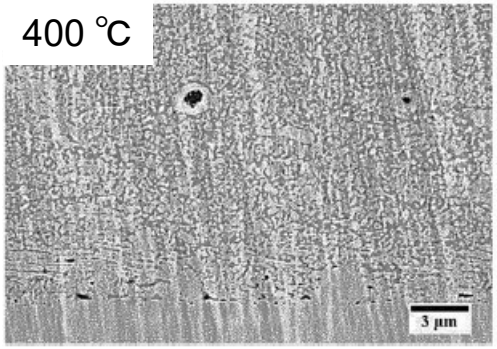


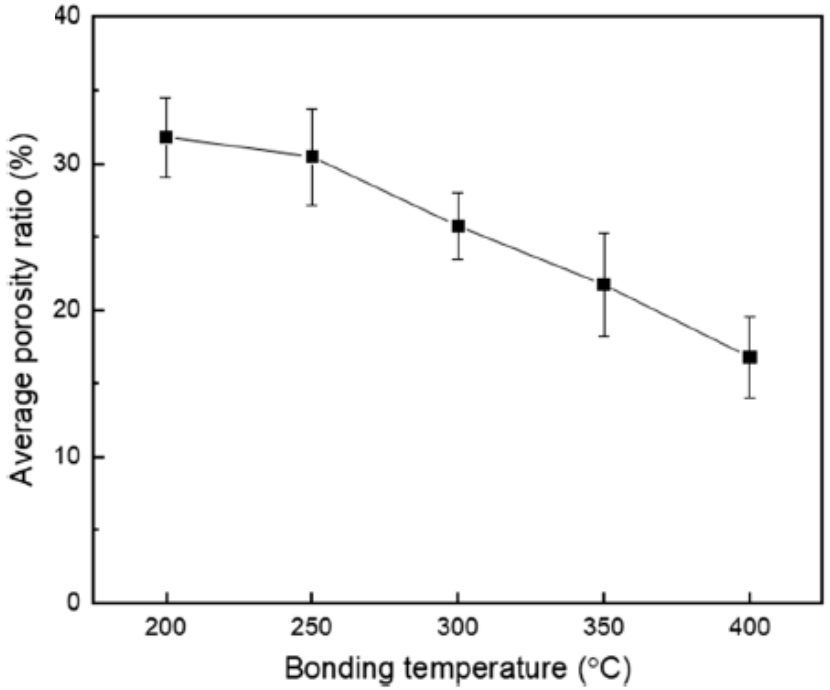


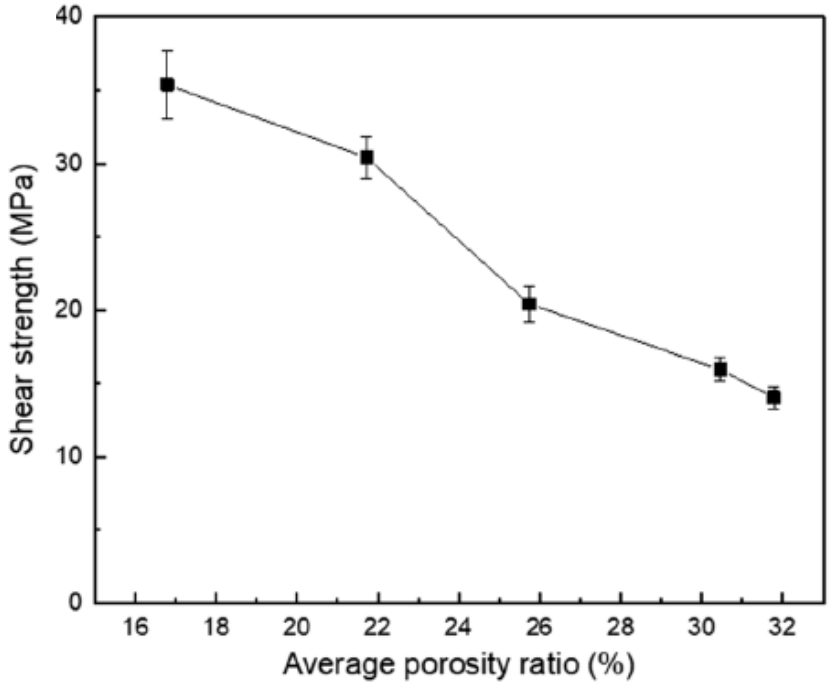
B. Park, D-L. Han, M. Saito, J. Mizuno, H. Nishikawa: Effect of various parameters on the shear strength of solid-state nanoporous Cu bonding in Cu–Cu disks for power device packaging, *J. Electronic Materials*, 51 (2022), 3851-3862.

Relationship between porosity and shear strength

Bonding experiments
- Oxygen-free Cu disc
- Thermo-compression bonding
  Applied pressure: 10 MPa
  Bonding time: 10 min
  Formic acid atmosphere







B. Park, D-L. Han, M. Saito, J. Mizuno, H. Nishikawa: Effect of various parameters on the shear strength of solid-state nanoporous Cu bonding in Cu–Cu disks for power device packaging, *J. Electronic Materials*, 51 (2022), 3851-3862.

Summary

To establish bonding materials and processes as a low-temperature solid-phase bonding technology, a feasibility study has been conducted to determine whether a nanoporous sheet can be used as an insert material.

- ✓ There was an interesting effect of nanoporous-structure generated by the dealloying process on the sintering property of the sheet.
- ✓ The Cu-to-Cu disc joint using the Au nanoporous sheet made with a dealloying time of 1 h at 25 ℃ had the highest shear strength over 30 MPa in the case of bonding temperature at 350 ℃.
- ✓ The Cu-to-Cu disc joint using the Cu nanoporous sheet had the shear strength over 30 MPa under formic acid atmosphere.

Joints using the nanoporous sheet can be achieved with sufficient joint strength and this NPB method is expected to be an alternative to high-Pb-containing solder