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Materials Science and Technology

Nanojoining technologies for miniaturized assemblies

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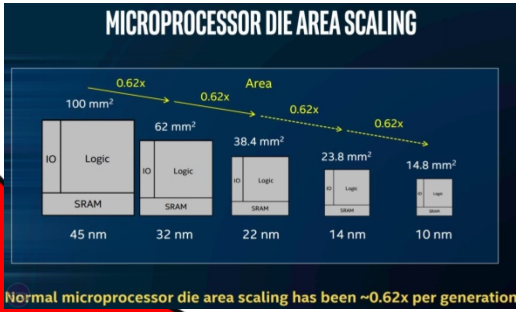
SWISS PHOTONICS

Overview

1. Nanojoining: a new scientific field and technology
2. Joining of nanomaterials
   - Cold welding, femto-/picolaser welding
3. Joining with nanomaterials
   - Nanoparticles (NPs)
     - Sintering with nanoparticle pastes
     - (Passivated) nanoparticles for Transient Liquid Phase bonding
   - Nanomultilayers (NMLs)
     - Reactive joining with nanomultilayers
     - Selective, low-temperature bonding with nanomultilayers
4. Outlook

Microelectronics and photonics: a drive for joining technology

Miniaturisation…


MICROPROCESSOR DIE AREA SCALING

Normal microprocessor die area scaling has been ~0.62x per generation

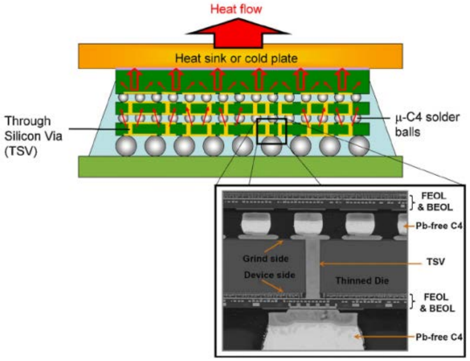
Source: Intel

Requirements on joining process:

- Fast, “cold”, high-precision, “clean”
- High packaging density
- Hybrid integration, various materials
- Sustainable

Diversification…

… and 3D Integration



Source: A.I. Moore and L. Shi, Materials Today, 2014

Joint assembly:

- Ever-smaller dimensions
- Improved performance
- High reliability
- Thermal management

ITRS Roadmap 2015:

”It is the ***interconnection*** *of the components in the IC, in the package,…where the* ***future limitations*** *reside”*

Nanojoining: a key enabling technology

Interconnecting (nano)materials and miniaturized components

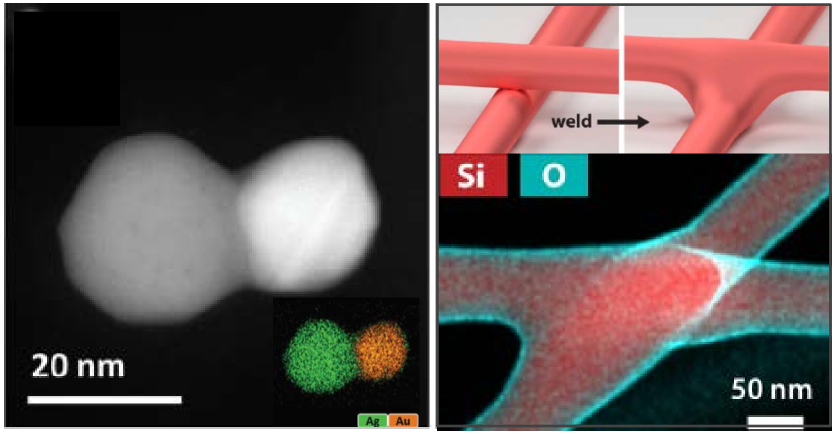
- Creating functional interfaces with a control down to the atomic scale
- Exploiting nano-effects for joining technology

Joining <u>of</u> nano-materials

- ➢ *Joining of nano-objects*
- ➢ *Integration of nano-materials*
- ➢ *Assembly of nano-scale devices*

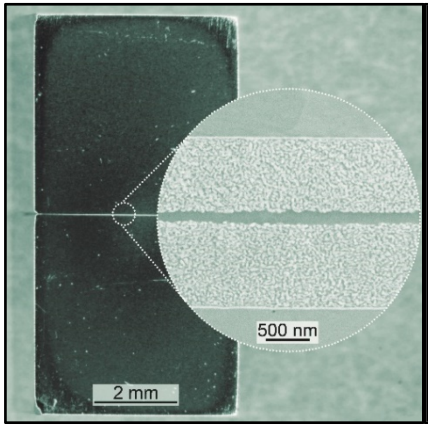
Joining <u>with</u> nano-materials

- ➢ *Nanoparticle pastes*
- ➢ *Nano-brazing fillers*
- ➢ *Reactive nanomultilayers*



Nanojoining of nanoparticles and nanowires

Sources: X.Xu et al, Nanoscale, 2018; T.A. Celano, et al., Nano Lett., 2016



Joint with Cu-W nanofiller ***Reactive nanofoil ignition***

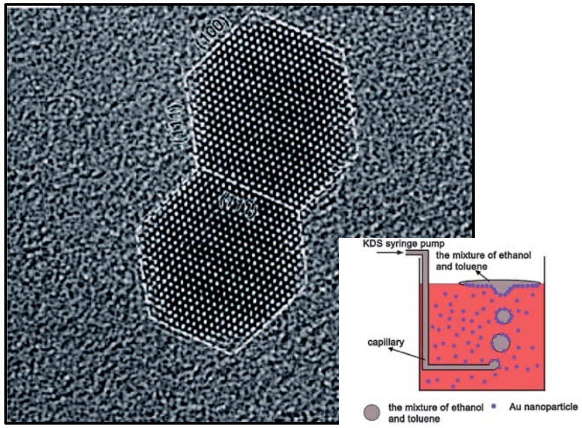
<u>Refs:</u> F. Moszner et al, J Mater Sci Eng B 6 (2016) 226

J. Janczak-Rusch et al, J Mater Eng Perf 23 (2014) 1608

Joining of nanostructures and materials

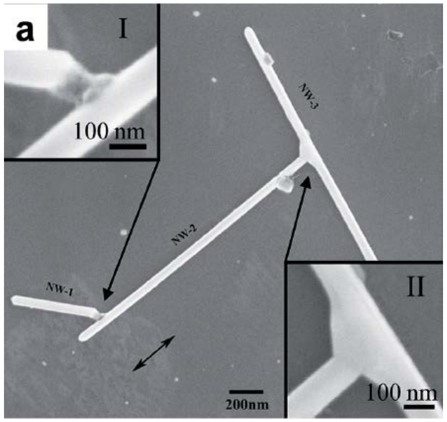
Joining of 1D nanostructures and nanoblocks to assemblies: **a bottom up assembly technique**

- **Challenges:** nano-manipulation and joining with low, local energy
- **Status:** joining of nanowires and nanoparticles was demonstrated
- **Processes**: cold welding, laser-induced, ultrasonic and diffusion welding, nanosoldering



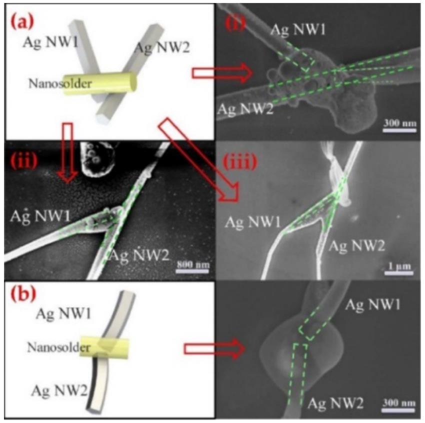
Cold welded Au nanoparticles (chemically controlled coallescence) by Liu et al.

Source: C. Liu et al., Chem. Commun., 2011



Femtosecond laser welded Ag nanowires for plasmonic circuits by Lin et al.

C. Lin et al., Nanotechnology, 2017



Nanosoldering of Ag nanowires by Li et al.

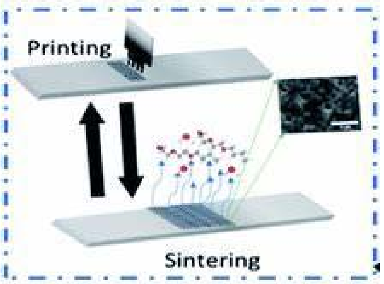
Q. Li et al., Optics Letter, 2018

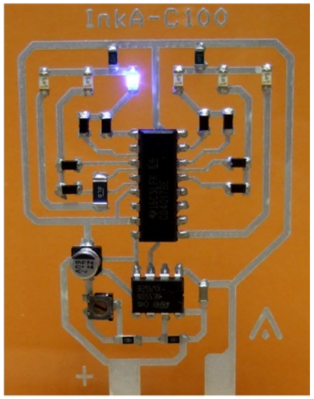
Joining of/with nanoparticle (NP) inks

Enabling technology across industries

NP inks: aqueous or organic solvent dispersions of NPs stabilized by surfactants and polymers. 3D functional patterns are achieved through low-temperature sintering of printed NP inks.

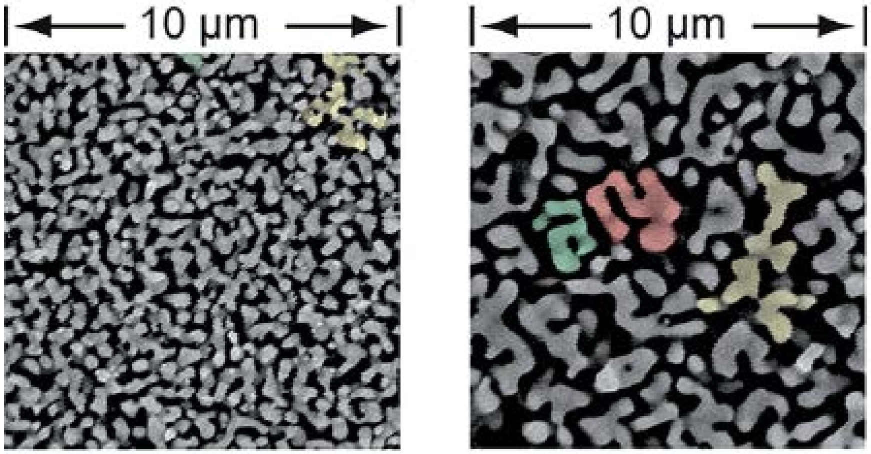
- **Status:** commercial nanotechnology (Ag NP-based inks)
- **Process:** sintering (“welding”)





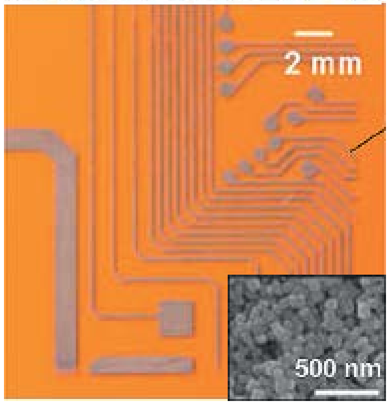
Printed Ag patterns after sintering (200°C) of Ag NP inks and component bonding

K. Rajan et al., Nanotechnology , Science and Applications, 2016



Welded Au nanoparticles 3D network through sintering (500-520°C) by Schade et al.

Source: L.Schade et al., Langmuir, 2014



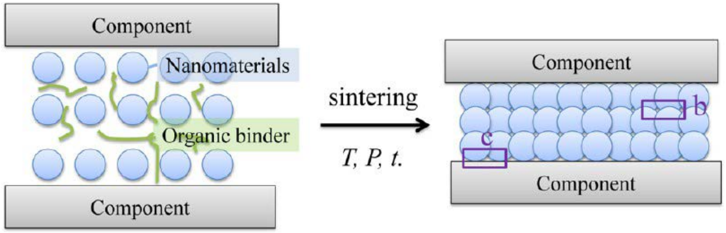
Printed Cu patterns for electronics made by welding of Cu NP inks

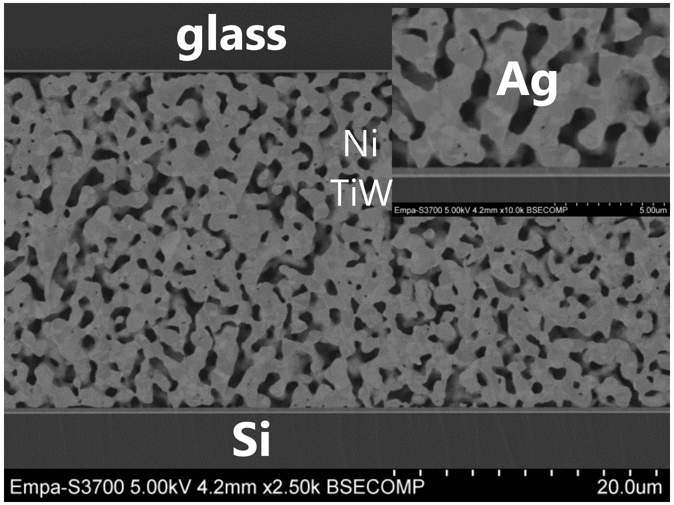
S.Jeong, Adv. Funct. Mat. , 2008

Joining with nanoparticles

NP pastes for low-temperature joining

- **Status :** commercial nanotechnology (**Ag nanoparticle pastes**)





Joint of borosilicate glass-to-Si with **Ag NP** (nanoTach-X)paste

Pressure-less process at 250°C/ 10 min on flip chip bonder, av. shear strength: 30-45 MPa

Empa-ETHZ Master Research Project: M. Nydegger

  - Process temperature < 275 °C (T_{mAg}=961°C) depending on the paste and pressure used
  - Service temperature > 250 °C
  - Excellent performance
  - Thermal conductivity: ≥ 2 W/mK^{-1}
- **Drawbacks and challenges (Ag NPs):** need of pressure use for T < 250 °C for pore-free joints, electromigration, costs
- **New developments:**
  - Cu, CuO nano-pastes

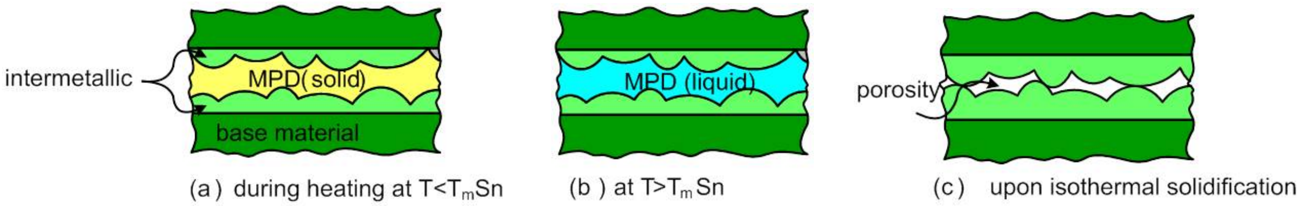
Low-temperature bonding process for high-temperature joints

Joining <u>with</u> nanoparticles (NPs)

Encapsulated NPs for fast TLP bonding processes

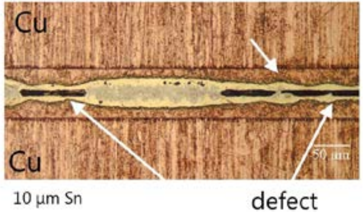
Transient Liquid Phase (TLP) Bonding: diffusion-based process with a partial melting of the interlayer

Limitation for microelectronics: long processing time (critical interlayer thickness for defect free bonding)



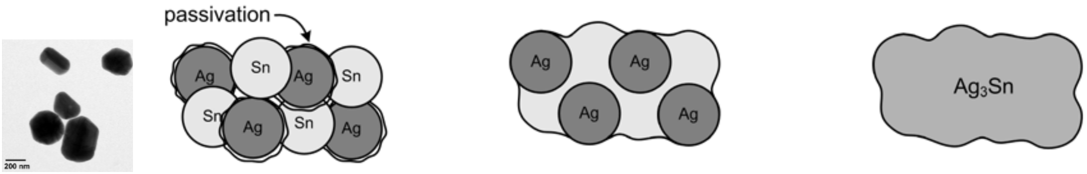
(a) during heating at T<T_mSn (b) at T>T_mSn (c) upon isothermal solidification

insufficient interlayer thickness



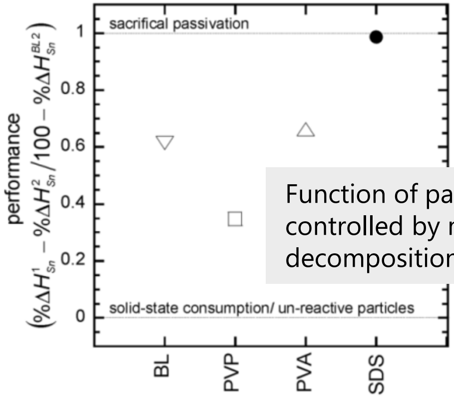
N.S. Bosco et al. Acta Materialia, 2004

Concept: use of NPs with a "**sacrificial passivation**" to control the diffusion and eliminate the critical thickness



→ Nano-TLP Bonding with **reduced bonding time**

K. K. Sobol, PhD Thesis, ETHZ, 2014



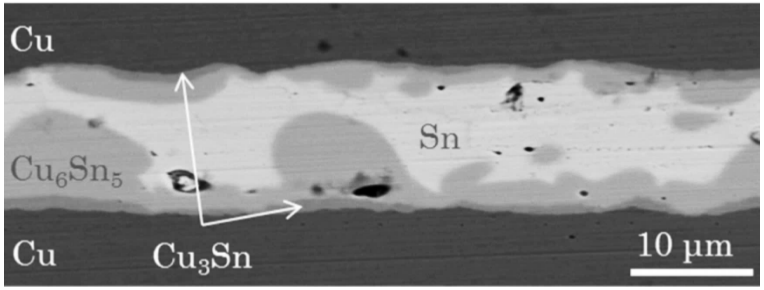
Function of passivation controlled by mass and decomposition temp.

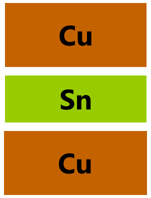
Ref.: N.S. Bosco, B. Manhat, J. Janczak-Rusch, Scripta Materialia, 58(10)2008.

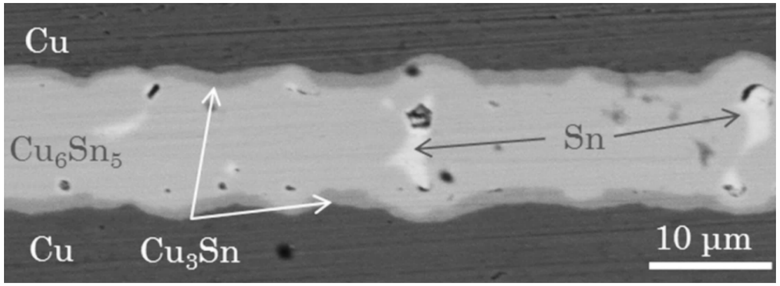
Diffusion control by surface engineering allow fast TLP processes

Towards fast TLP bonding processes

Controlling the bond formation mechanisms and bond quality by the heating rate







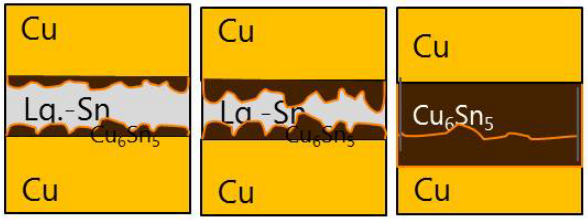
Slow heating rate (20 K/min)

K. K. Sobol, PhD Thesis, ETHZ, 2014

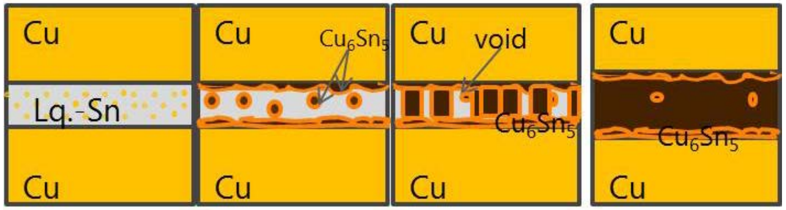
→

Fast Heating rate: 350K/min

Less formation of interfacial IMCs



Interfacial IMC growth and total transformation of the interlayer into IMC

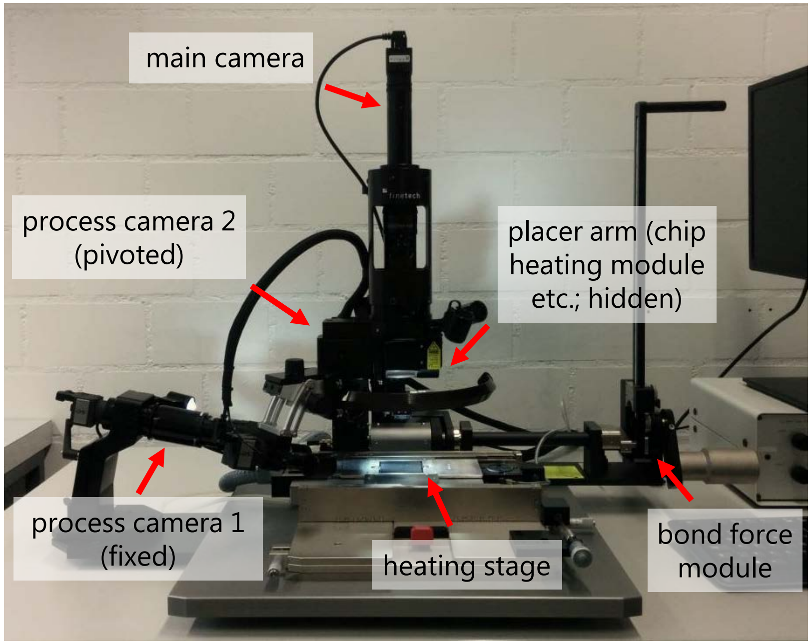


Dissolution and saturation of the Cu in liquid Sn; IMC growth at the interface and in liquid Sn (Sn supersaturated by Cu); total transformation of the interlayer into IMC

Fast heating rates enable formation of good quality joints within short process time

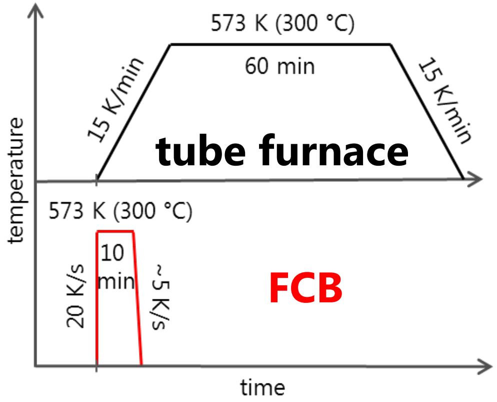
Towards fast TLP bonding processes

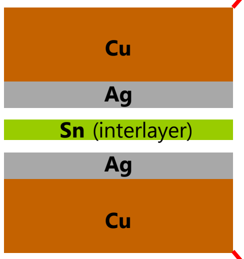
Transfer of the TLP process from furnace to Flip-Chip Bonder



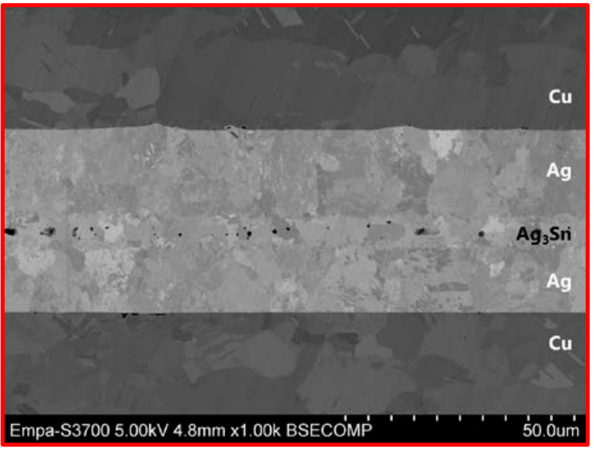
Flip chip bonder assisted TLP process

Empa-ETHZ Master Research Projects: R. Kalt, M. Nydegger





bonding set-up



SEM image of Cu-to-Cu joint with Ag/Sn/Ag interlayers (350°C, 0.375 MPa)
Typical shear strength: 60 MPa

Flip-Chip TLP Bonding: high strength joints in a fast process

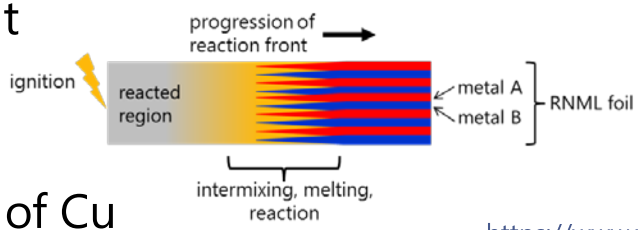
Joining with nanomaterials

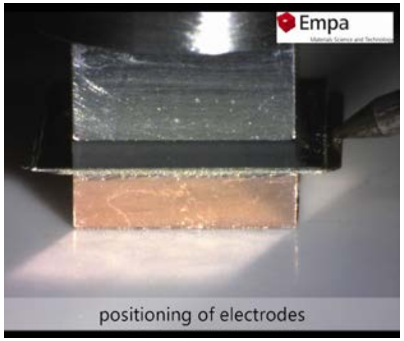
Flip-chip bonder assisted joining with reactive nanomultilayers

Reactive joining with Ni/Al nanomultilayers: low-temperature bonding process, without external furnace

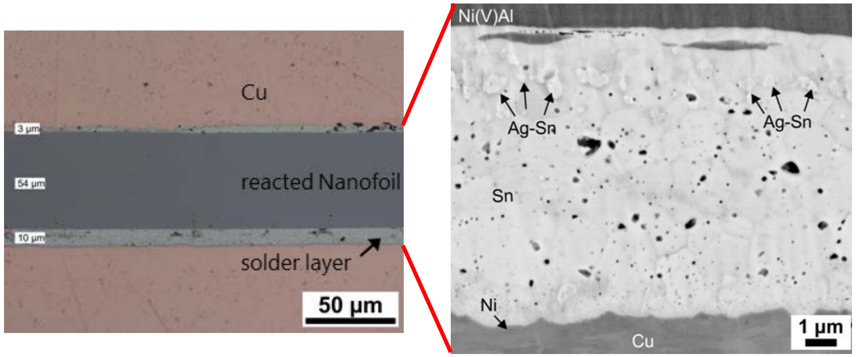
- **Status**: commercial nanotechnology
- **Challenges:** heat management

Example: Cu-to-Cu joints
Problem: high heat conductivity of Cu

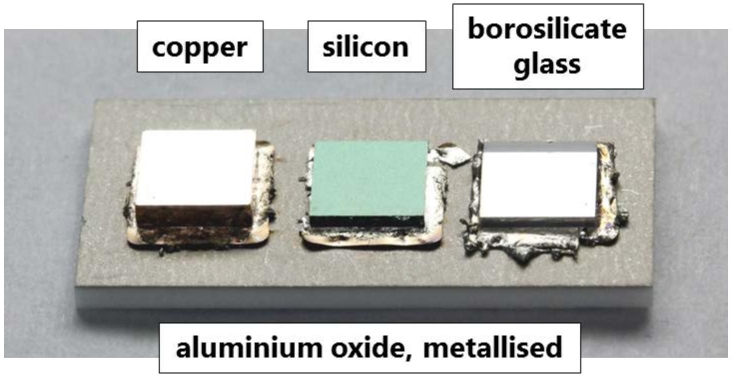




https://www.youtube.com/watch?v=1ti4JJR3piQ



Cu-to-Cu joint with Ni/Al reactive nanofoils.
Galvanic pre-soldered Cu. av. shear strength: 40 MPa



Dissimilar material joints with Ni/Al nanofoils

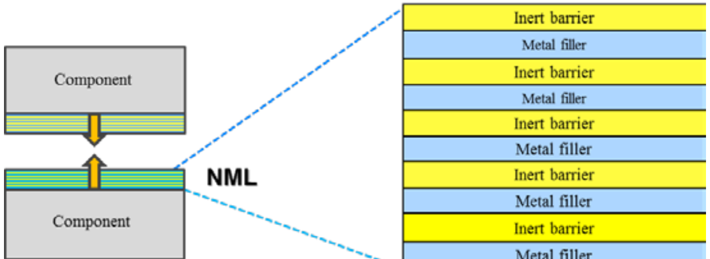
B. Rheingans et al., Applied Sciences, 9 (2019) 262
B. Rheingans et al., J. of Electronic Packaging 140 (2018)

“Portable” and benign process for sensitive components and materials

Joining with nanomultilayers (NMLs)

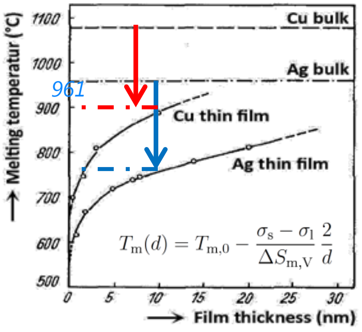
Nano-Brazing Fillers

Brazing Filler/Inert Barrier NMLs:
Ag/AlN, Cu/AlN, Cu/W, Al/AlN, AlSi/AlN, AgCu/AlN … deposited on components



- Nano-confinement of the metal filler by inert (ceramic) barrier layers
- No solid-state reaction between the metallic and the barrier material upon heating
- Mass transport through NML

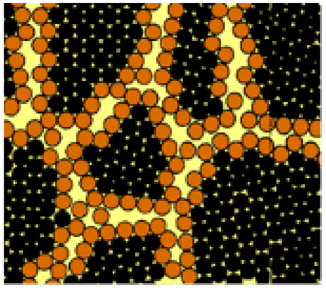
Melting point depression (MPD)



MPD up to a few hundred degrees is predicted for very thin nanolayers → lower process temperatures

J.Wilden, DVS Abschlussbericht,2006

Short circuit diffusion



University of Virginia, MSE2090

The mass transport by grain boundary diffusion is a few orders of magnitude faster than through volume diffusion → faster processes

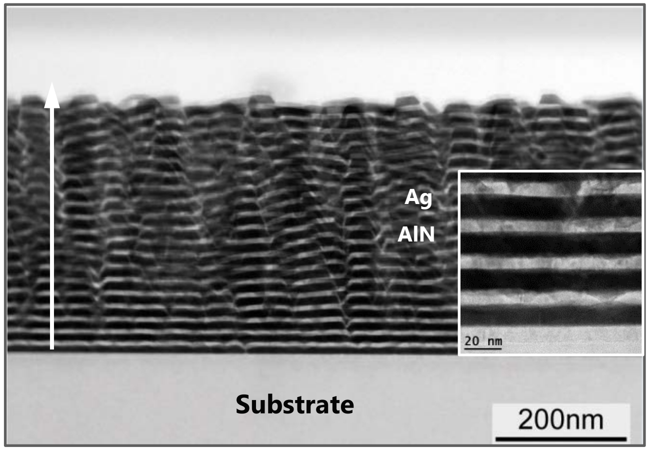
Lower temperatures, shorter processing time

Ag-based nano-multilayers (Ag/AlN)

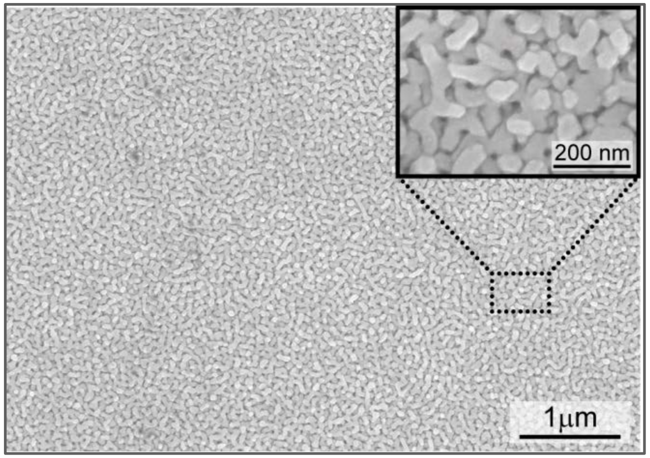
Fast mass transport at low temperatures

As-deposited NML

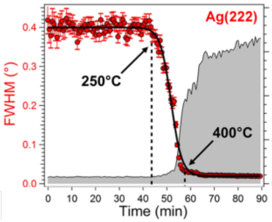
Cross-section



Planar-view

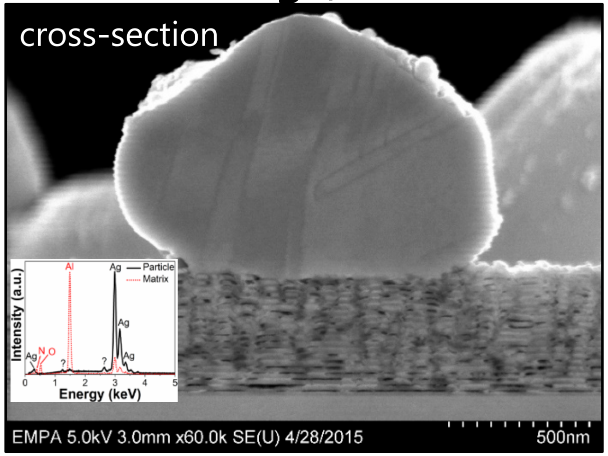


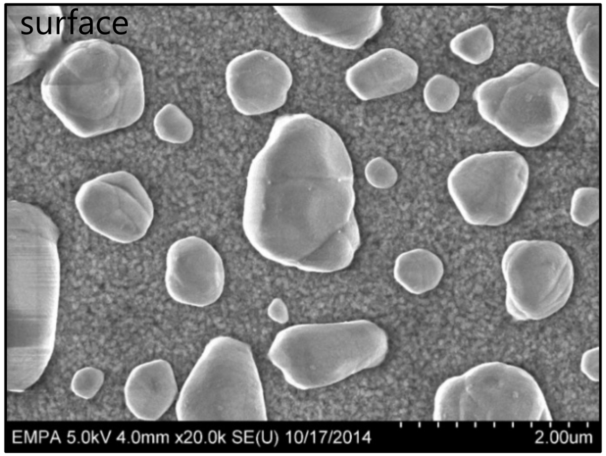
T ↑ 420°C
in air



Ref: J Mater Chem C4 (2016)

After heating (420°C/30min)





Extensive Ag migration to surface well below bulk melting point (962 °C)

Joining with nanomultilayers

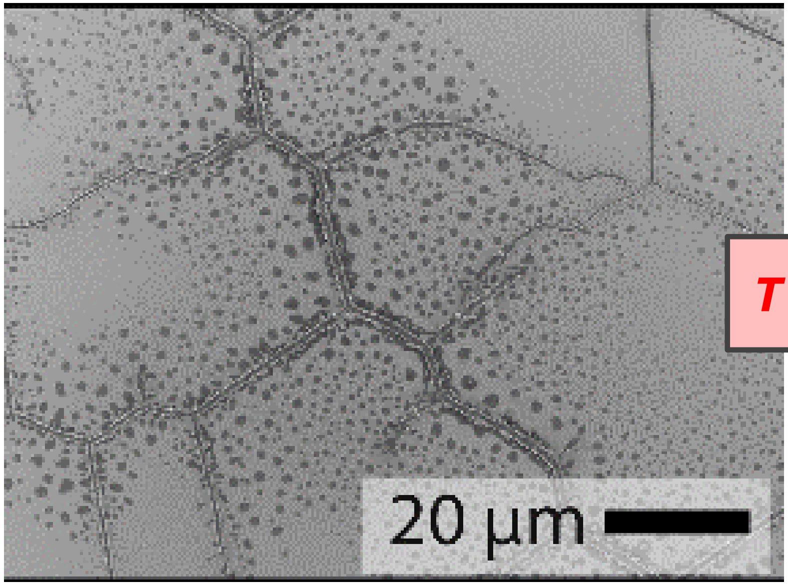
Controlling the outflow by NML design

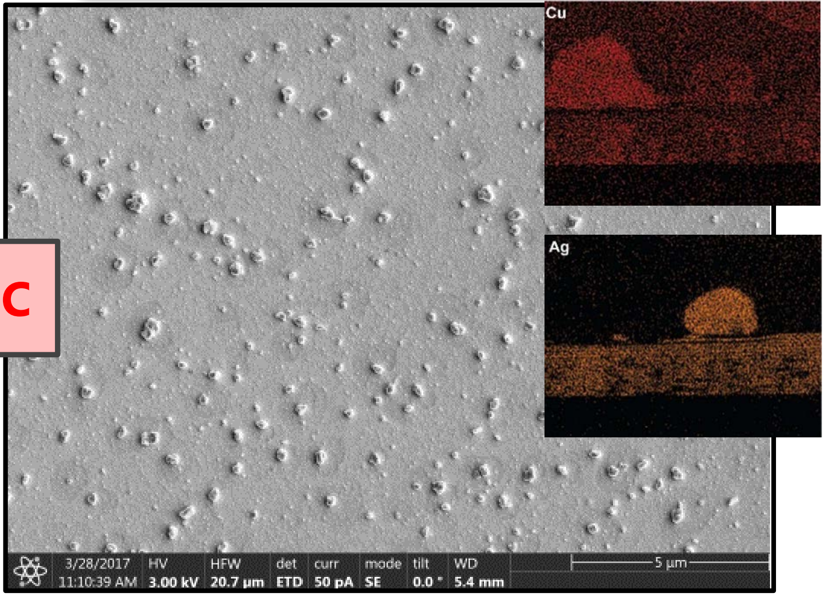
Ag-Cu$_{40\text{at.}\%}$/AlN NML, isothermally annealed

Thick AlN barrier (10 nm)

Thin AlN barrier (4 nm)

***T* > 300 °C**





V. Araullo-Peters et al., ACS Applied Materials & Interfaces 11 (2019) 6605

- Patterned outflow of Cu
- Void formation
- Fracturing of AlN barrier layers

- Homogenous outflow of Cu <u>and Ag</u>
- No void formation
- Sintering of AlN barrier layers

It is feasible to control the outflow material and pattern by the NML design

Conclusions

Nanojoining offers new approaches for microelectronics and photonics applications and should be consider in the early development stage as enabling technology (novel architecture, thermal interfaces …)

1. Low-temperature sintering with/of nanoparticles is a settled nanojoining process (Ag NP inks, «soldering» with Ag Np pastes) and undergoes further development
2. Joining with reactive nanofoils, TLP bonding, allow fast processes at relatively low-temperatures
3. Nanomultilayers creates new opportunities for selective bonding and complex patterning
4. Joining of nanoobjects (under development) will enable bottom-up assembly process

Materials (nanojoints) are becoming a functionalised part of a device !

ACKNOWLEDGEMENTS

Empa
Materials Science and Technology

Current Joining Team

- ✓ Dr. Lars Jeurgens
- ✓ Dr. Bastian Rheingans
- ✓ Dr. Claudia Cancellieri
- ✓ Dr. Luchan Lin
- ✓ Dr. Hans-Rudolf Elsener
- ✓ Tobias Burgdorf
- ✓ Dr. Sebastian Siol

Former Team Members

- ✓ Dr. Vicente Araullo-Peters
- ✓ Dr. Vinzenz Bissig
- ✓ Dr. Mirco Chiodi
- ✓ Benjamin Lehmert
- ✓ Dr. Joanna Lipecka
- ✓ Dr. Frank Moszner
- ✓ Dr. Giancarlo Pigozzi

Funding Agencies

FNSNF
Fonds National Suisse
Schweizerischer Nationalfonds
Fondo Nazionale Svizzero
Swiss National Science Foundation

Seventh Framework Programme

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Swiss Confederation

Commission for Technology and Innovation CTI

interreg
Alpenrhein | Bodensee | Hochrhein

SWISS PHOTONICS

International Collaborators

- ✓ Prof. Norman Zhou, University of Waterloo, Canada
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- ✓ Prof. Malgorzata Lewandowska, Warsaw Univ. of Technology, Poland
- ✓ Prof. Rafal Abdank-Kozubski, Jagiellonian University, Poland
- ✓ Prof. Daniel Ariosa, Universidad de la República, Uruguay
- ✓ Prof. George Kaptay, Bay Zoltan Nonprofit Ltd., Hungary
- ✓ Dr. Gunther Richter, MPI for Intelligent Systems, Germany
- ✓ Dr. Andrej Antušek, Slovak University of Technology
- ✓ Dr. S. Yoon, University Stuttgart, Germany

Selected papers

- *ACS Applied Materials & Interfaces 11 (2019) 6605*
- *Applied Sciences, 9 (2019) 262*
- *J. of Electronic Packaging 140 (2018)*
- *J Mater Chem C 4 (2016), 4927*
- *Phys Chem Chem Phys 17 (2015) 28228*
- *Acta Materialia 107 (2016) 345*
- *Scr Mater 130 (2017) 210*
- *J. Mater. Sci. Eng. B 6 (2016) 226*
- *J Mater Eng Perform 25 (2016) 3275*