Welcome

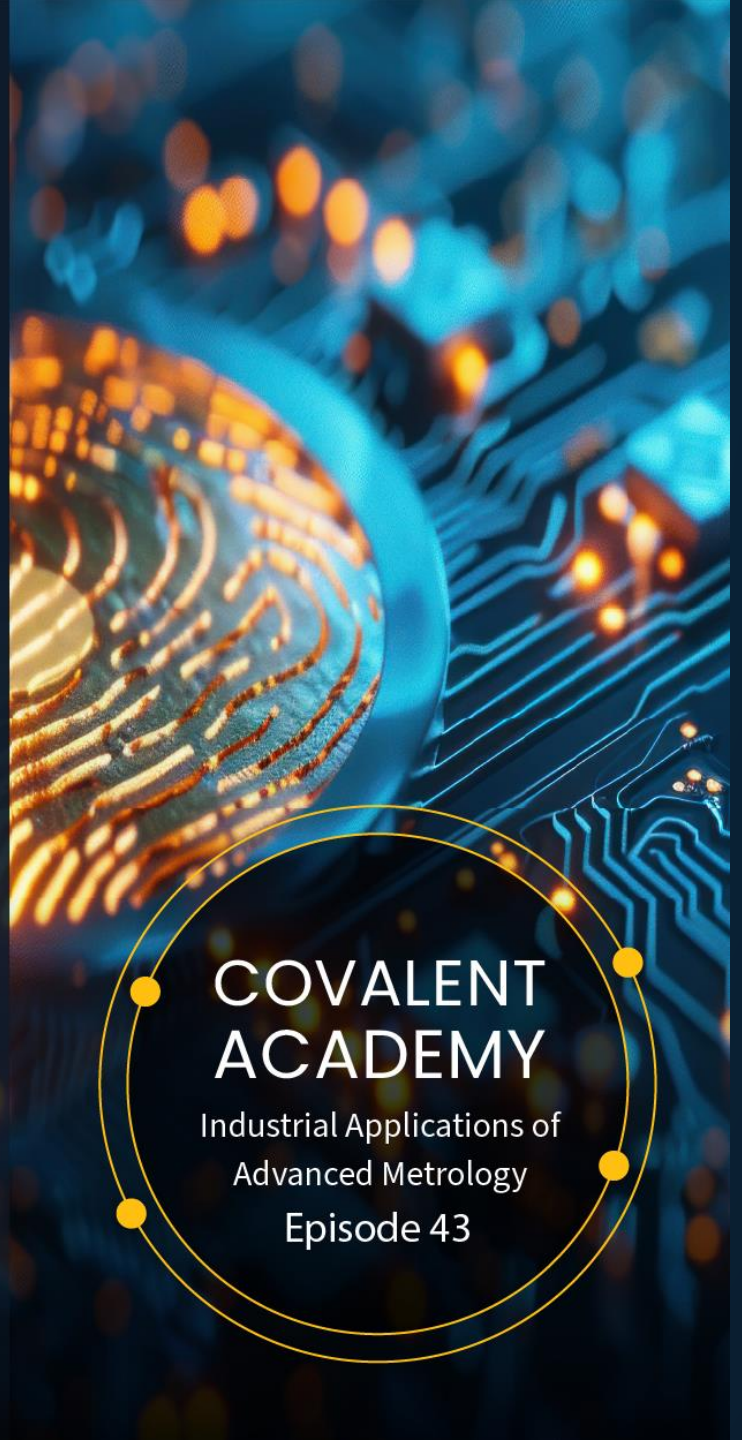
to today's episode:

Tackling Miniaturization Challenges

High-Resolution Interface Analysis in Advanced Semiconductor Packaging

Naohiko Kawasaki, PhD
Manager of Electron Microscopic Analysis Team
Toray Research Center, Inc.

JUN 19, 2025
11 AM Pacific Time



'TORAY'
Toray Research Center, Inc.

COVALENT METROLOGY

COVALENT METROLOGY

Modern, digitally-empowered analytical services platform delivering quality data and expert analysis to accelerate advanced materials and device innovation.

Comprehensive Solutions Stack

50+ Cutting-edge instruments in-house, 150+ Techniques

Analytical Services

Advanced Modeling

Method Development

Custom Consulting Solutions

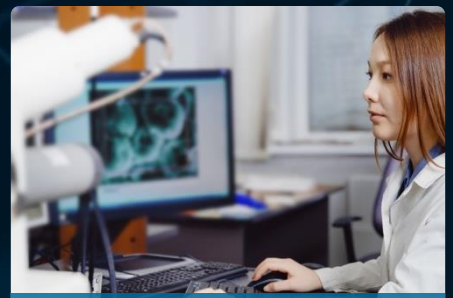
High-touch, High-Quality Services

Nexus Membership Program

Enterprise Metrology Solutions

Instant, Secure Access to Data and Reports

Expanding Toolkit in Custom Digital Platform



Flexible Business Models

LiveView™ (real-time collaboration)

Co-op and Tool-share Opportunities

Training and Certification on Instrumentation

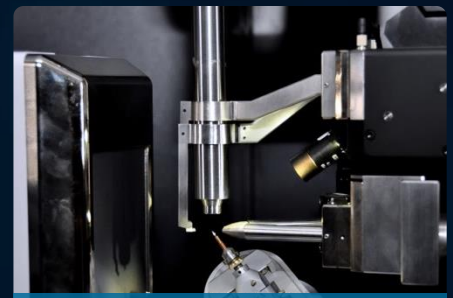
Laboratory Audits

Rich Network of Partnerships

Partner to World's Leading Instrument Manufacturers and Labs

Expanding access to Advanced Instruments and Analysis Tools

Lab Connections and Applications Learning



Who We Are, Who We Serve

80+ People, 21 PhDs

Comprehensive, Modern Analytical Capabilities

Headquarter Lab in Sunnyvale, CA

800+ Clients, 15-30 new clients / week

Covalent's Analytical Services & Technical Groups

COVALENT METROLOGY

Enterprise Metrology Solutions: Failure Analysis & EM

Electron Microscopy

- S/TEM
  with EDS; EELS; Electron Diffraction; SAED
- FIB-SEM & HR-SEM
  with EDS; EBSD; 3D Tomography
- Lamella Preparation
  incl. specialized lift-outs

Failure Analysis

- DPA / Mechanical X-section
- Dye & Pry Test
- EBIC / OBIC failure analysis
- Hot Spot Detection
- NIR / IR Imaging
- Emission Microscopy
- Root-Cause Failure Analysis

Materials, Chemicals, and Surfaces

Microscopy & Profilometry

- Chromatic Aberration
- Digital Optical Microscopy
- Laser Scanning Confocal Microscopy
- White Light Interferometry
- Scanning Acoustic Microscopy (SAM)

Analytical Chemistry

- Mass Spectroscopy: ICP-MS and LA-ICP-MS; GCMS
- ICP-OES / GDOES
- Raman
- NMR (solid / liquid + 1,2,3 nuclei)
- XPS, UPS, ISS
- SIMS, TOF-SIMS

X-ray Characterization

- X-Ray Diffraction (XRD)
- X-Ray Reflectometry (XRR)
- Micro-computed X-ray Tomography (Micro-CT)
- 2D / 2.5D / 3D X-ray Inspection & X-ray Radiography
- ED-XRF / WD-XRF

Mechanical Testing

- AFM & Advanced AFM Modes (EFM, KPFM, MFM, PFM, PiFM)
- Nano-indent / Nano-scratch
- Rheometry / Viscosity
- DMA / TMA (bend/stretch/compression)
- Tensile testing

Misc. Material Properties

- Thermal Analysis: DSC, TGA
- Surface Zeta Potential
- Porometry / Pycnometry
- Gas Adsorption / Chemisorption
- Foam Density / Skeletal Density / Tap Density
- Particle Analysis: DLS / ELS / size distribution / zeta potential

Optical Characterization

- Fourier Transformed Infrared Spectroscopy (FTIR and ATR-FTIR)
- **Spectral Ellipsometry & Advanced Optical Modeling**
- UV-Vis-NIR Spectroscopy

Toray Research Center, Inc.

Founded in 1978, being started from R&D, Analysis division of TORAY

'TORAY'
Toray Research Center, Inc.

Problem to be solved in R&D, manufacturing

Commissioned analysis

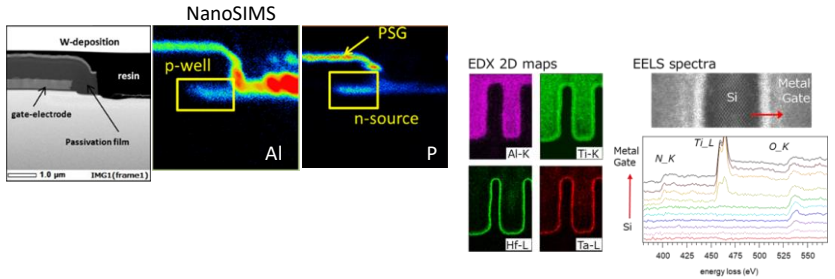
Clients

- Company
- University
- Public Institute

Cause analysis
Problem solving
Reverse engineering

Advanced physical analysis for semiconductor devices

- Nano-SIMS
- Aberration-corrected STEM-EDX/EELS
- μ-RBS, ESR, PL, CL, DLTS, AFM-IR, SNOM-Raman
- D-SIMS, TEM, XPS, XRD, FT-IR, XRR, Raman



Covalent Exclusive Partnership with Toray Research Center

COVALENT METROLOGY

TORAY
Toray Research Center, Inc.

- **Strategic Alliance**: Exclusive North American partnership with Toray Research Center (TRC), a global leader in advanced materials characterization.

- Opens to North American customers access to world class analytical capabilities and scientific and engineering consulting:
  - **Enhanced Capabilities**: Access to TRC's cutting-edge techniques such as: NanoSIMS, RBS, TERS, AFM-IR, SNOM, and more
  - **Comprehensive Solutions**: Joint expertise in failure analysis, process optimization, materials design, and quality assurance.

- **Streamlined Access**: Single point-of-contact through Covalent for world-class TRC services.

Other Covalent Partners

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Introducing today's speaker

COVALENT METROLOGY

Dr. Naohiko Kawasaki

Manager of Electron Microscopic Analysis Team, Toray Research Center, Inc.

- Over 20 years of experience in various nano-scale characterization technique
  - Specializes in:
    - STEM-EELS (Scanning Transmission Electron Microscopy – Electron Energy Loss Spectroscopy)
    - Cathodoluminescence
    - *In-situ* TEM (Transmission Electron Microscopy)
- Held research positions at
  - University of Tokyo
  - Université Paris-Sud
- Holds a Doctor of Science degree from Kyoto University

Agenda

1. Electronic packaging – recent trend and physical analyses

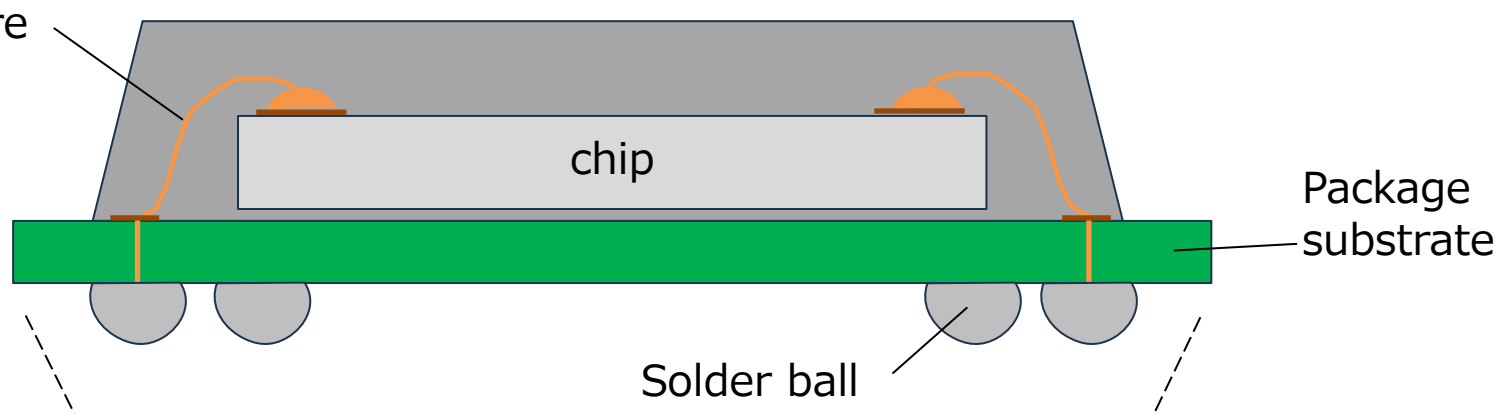
2. Direct observation of the annealing effect for under bump metal using in-situ TEM observation

3. Direct observation of the annealing effect at Cu/Cu hybrid bonding interface

4. Investigation of poor adhesion/electric reliability root cause at the Cu/PI interface

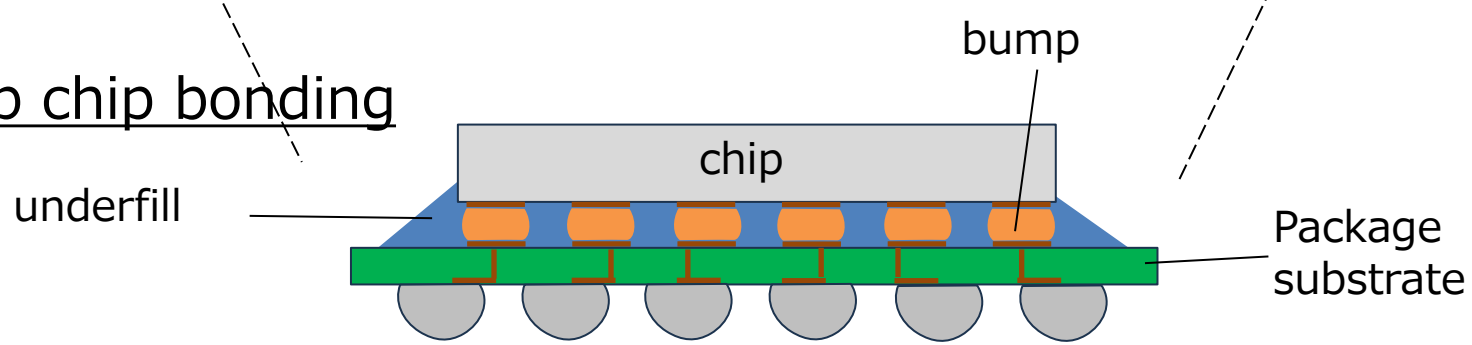
Electrical connection to IC-chip

Wire bonding



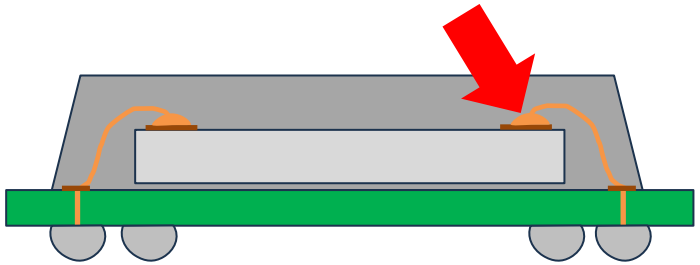
Many number of bonding with a scale of μm order

Flip chip bonding



Bump size : 30 ~ 100 μm

Plastic deformation at wire bonding joint – SEM-EBSD



X-ray microscope

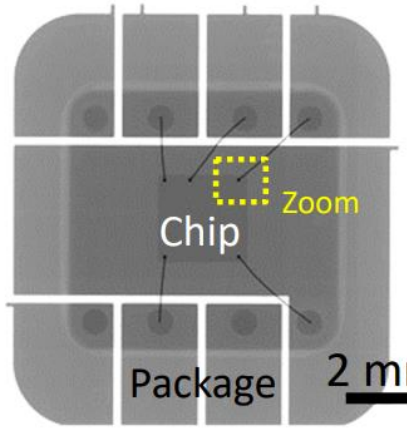
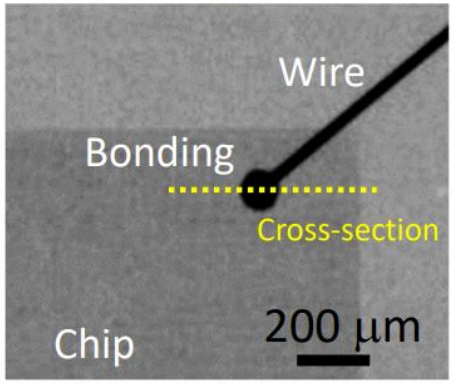


Fig.1. Top-view XRM images of the semiconductor package



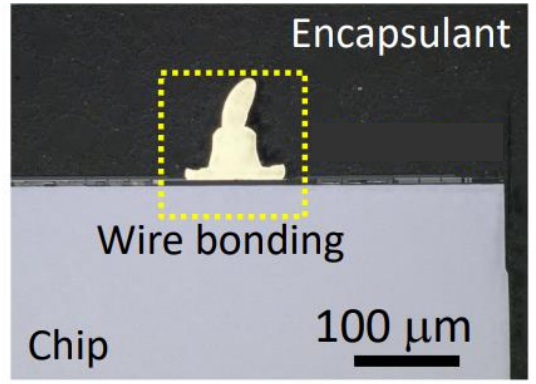
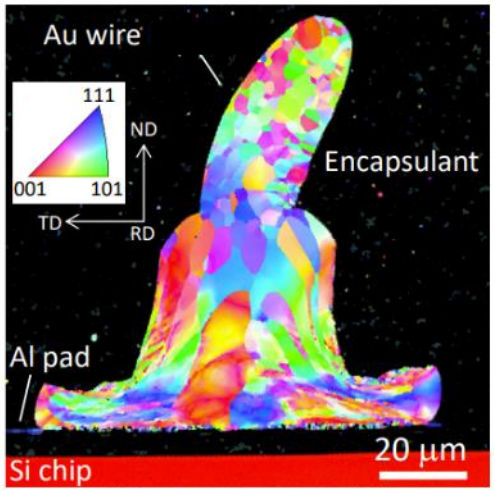
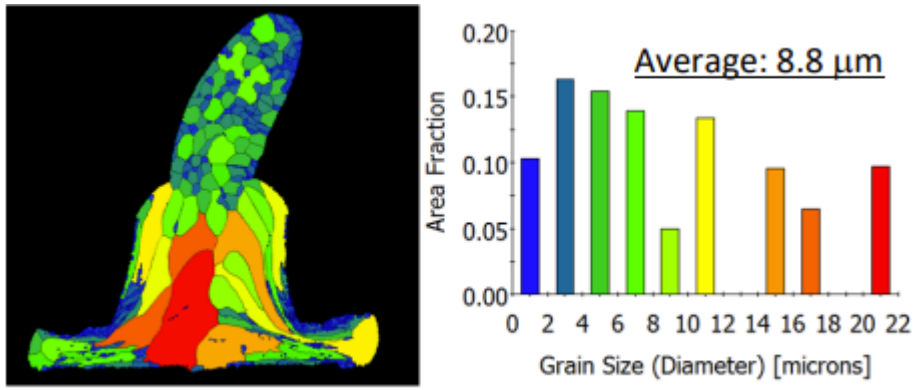


Fig.2. The cross-sectional optical microscope image

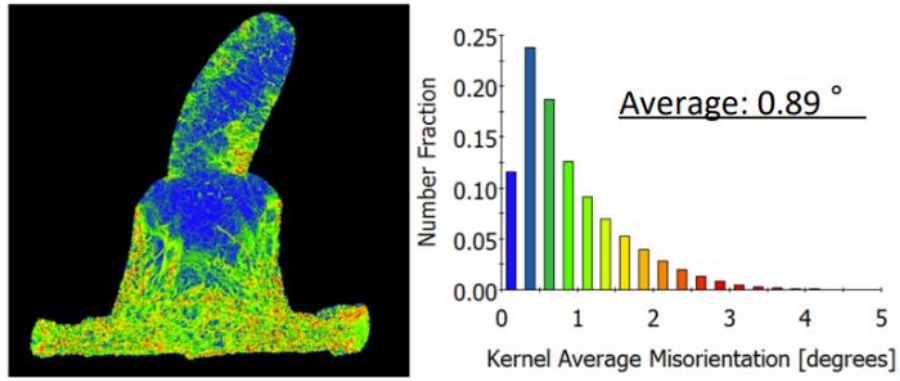
SEM-EBSD



(a) crystal orientation map (ND)

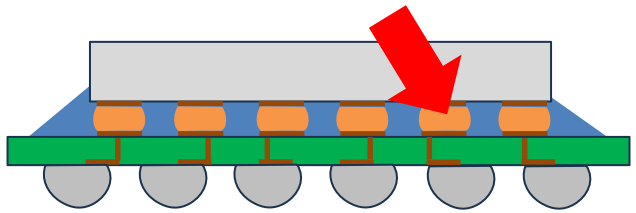


(b) The grain-size map and chart



(c) The KAM map and chart

Alloy phase assignment at solder joint – SEM-EBSD/EDX



Cross-section at solder joint

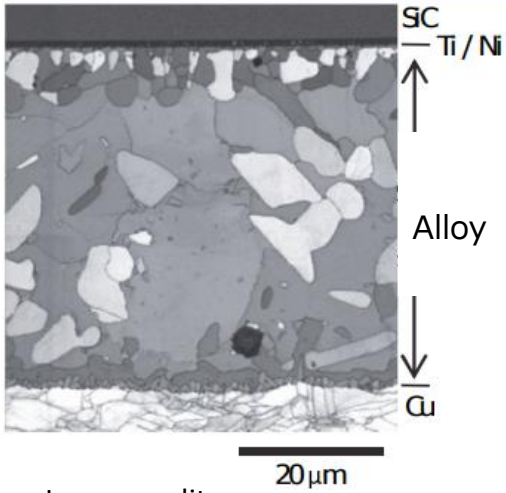
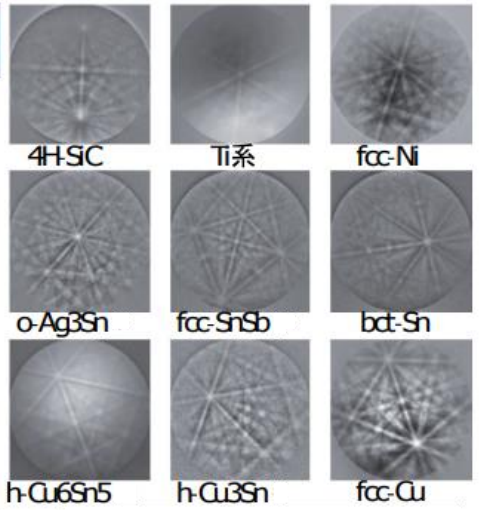
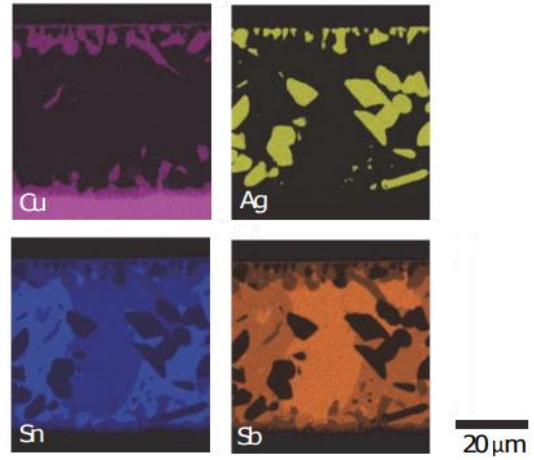


Image quality map

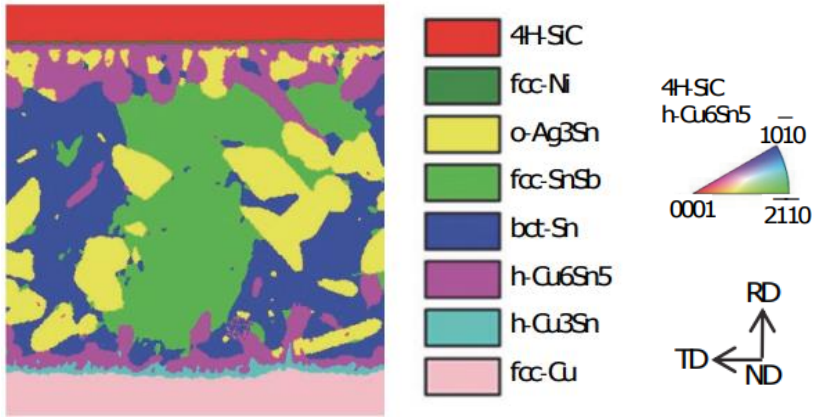


EBSD pattern

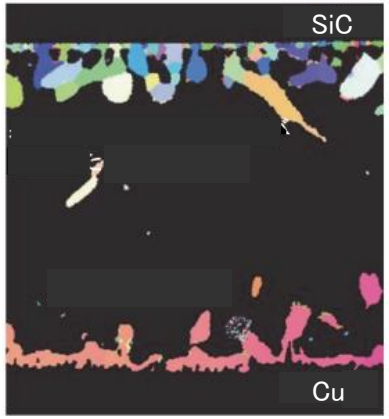
EDX map



Accurate phase assignment using simultaneous EBSD-EDX

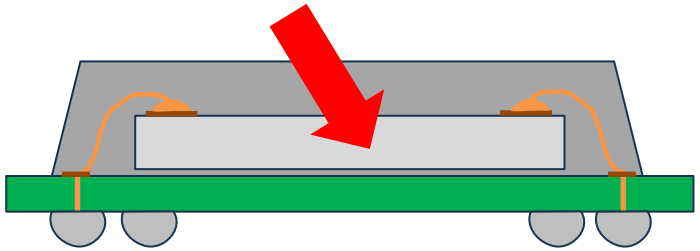


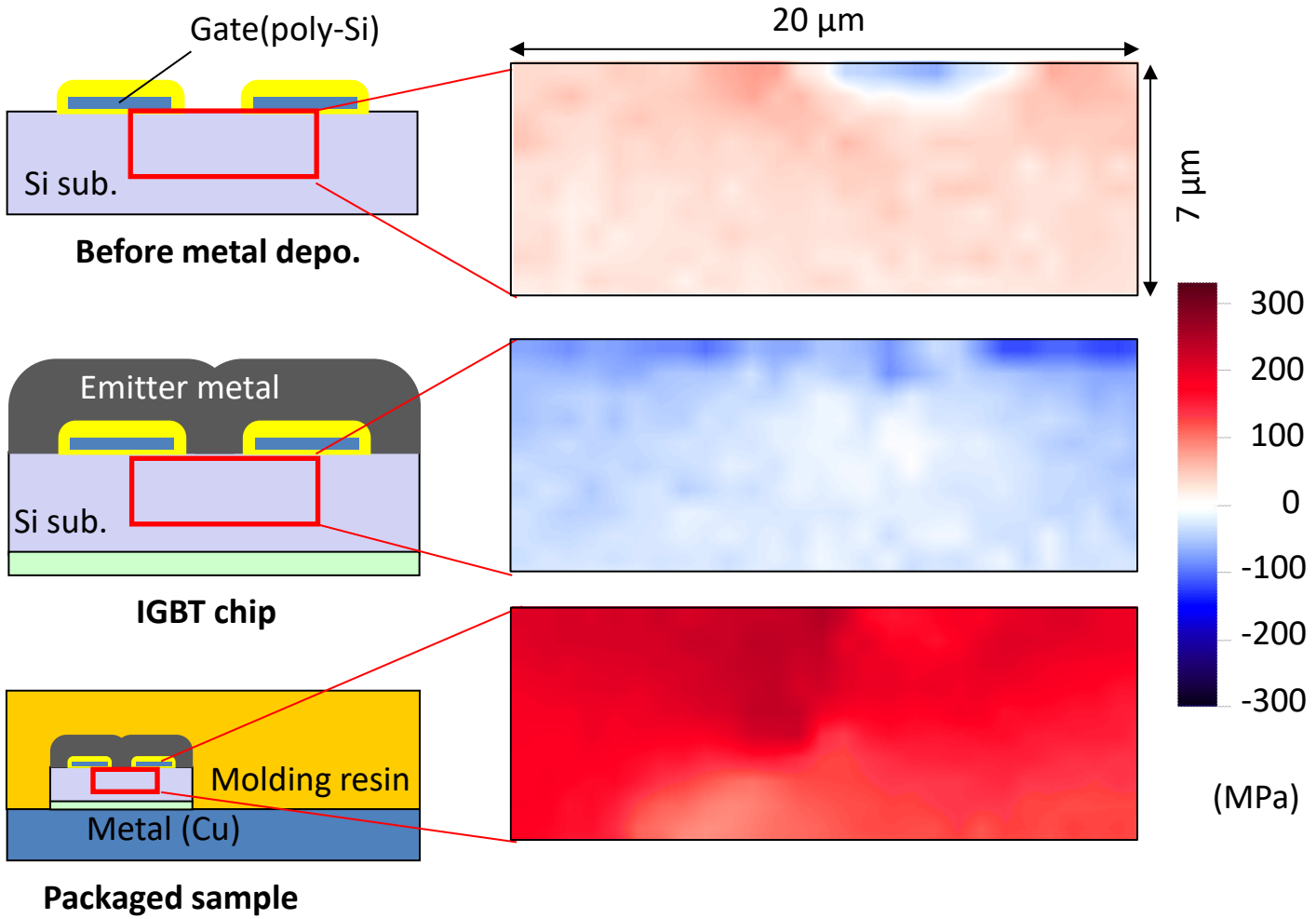
Crystal phase of h-Cu6Sn5 (RD)



Different crystal orientation/grain size between SiC and Cu side

Stress evaluation on to Si chip – Raman spectroscopy





Packaging process - large compressive stress in the chip.

Detection limit : 1 MPa

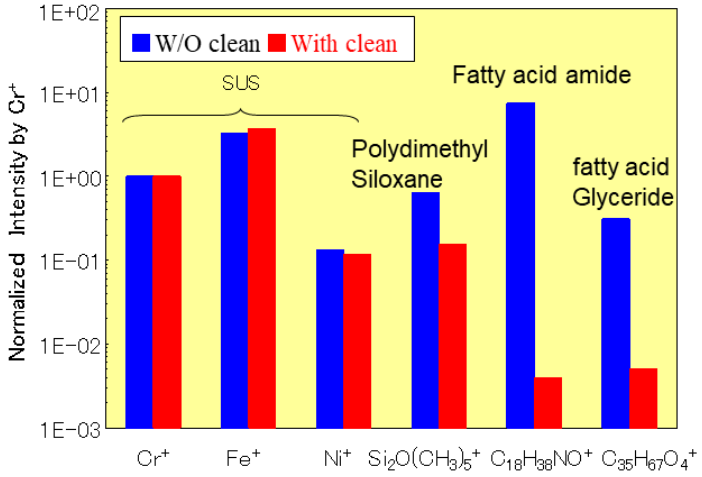
Cause analysis of poor adhesion problem – SIMS/FT-IR

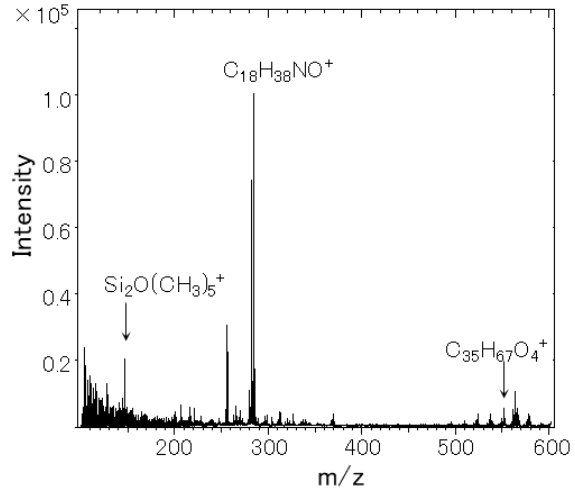
Contamination / Foreign object

TOF-SIMS

Bonding strength at SUS/epoxy resin with or w/o cleaning of SUS surface

	W/O cleaning	With cleaning
Peeling strength (N/mm^2)	9.5	20.0



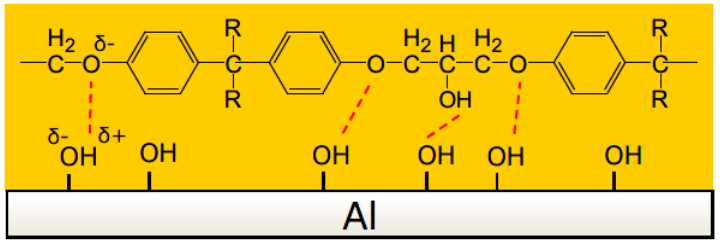


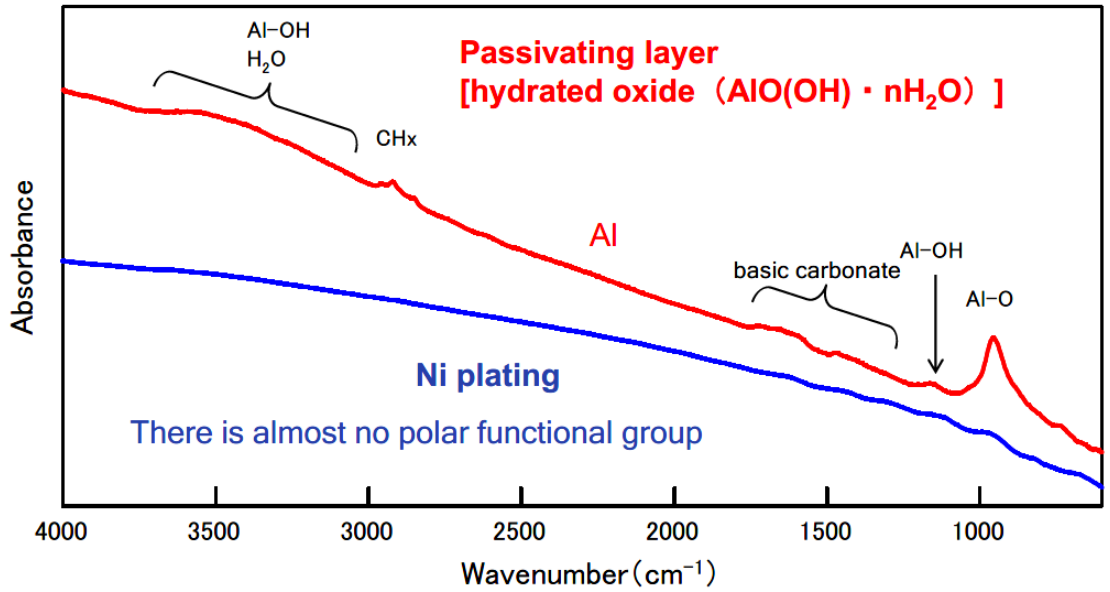
Metal surface functional groups

FT-IR

Adhesion of metal plate and epoxy resin

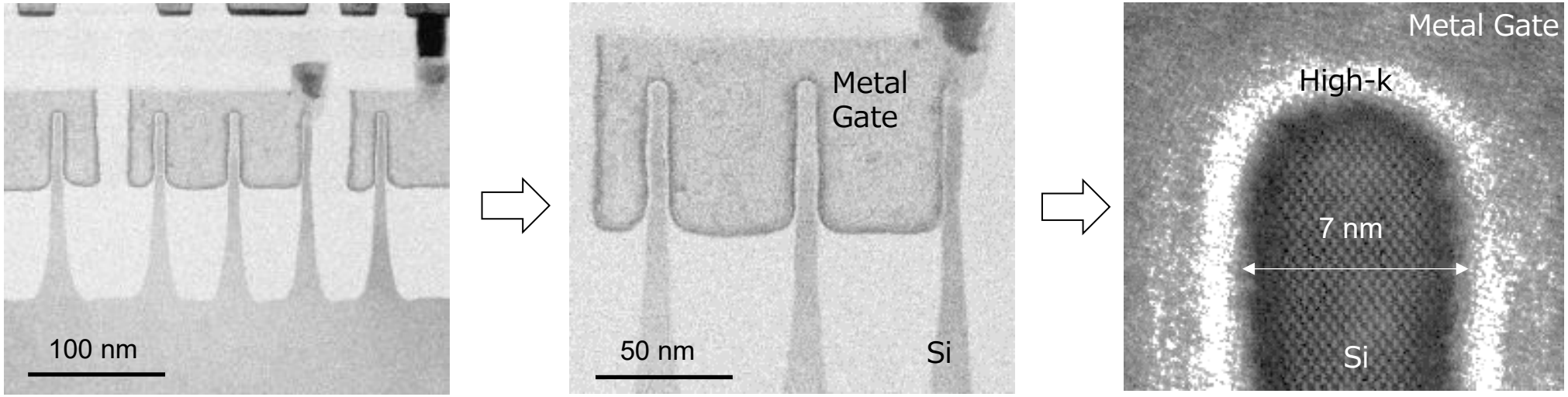
Al > Ni



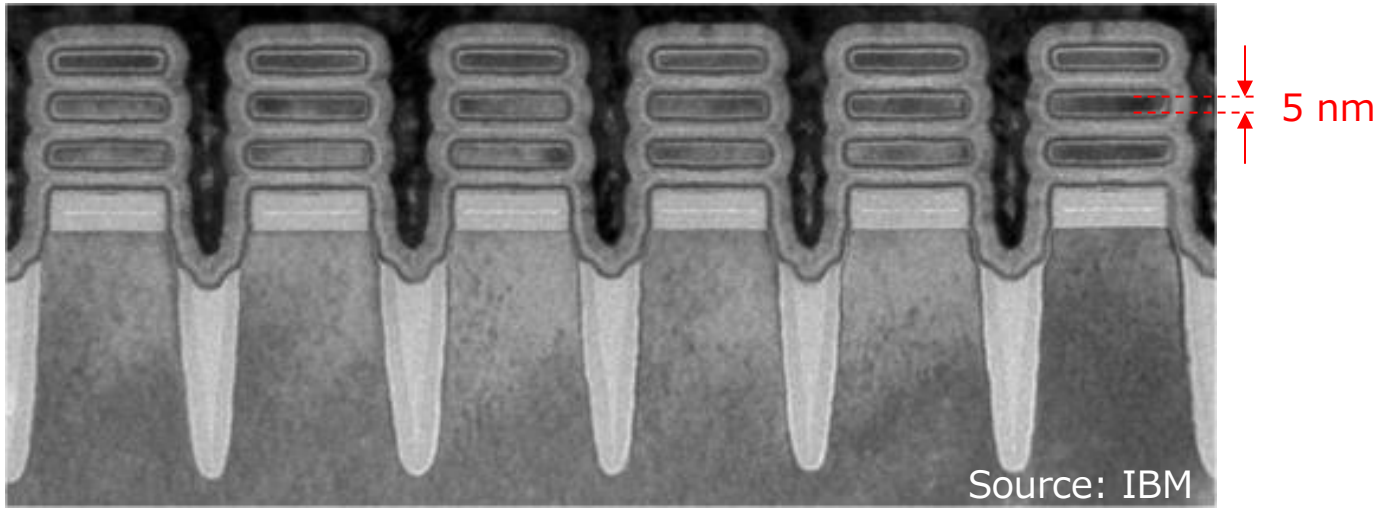


Recent trend in front-end process

7 nm FinFet



Nano-sheet (GAA-FET)



It is difficult to achieve drastic miniaturization in MOSFET scaling.

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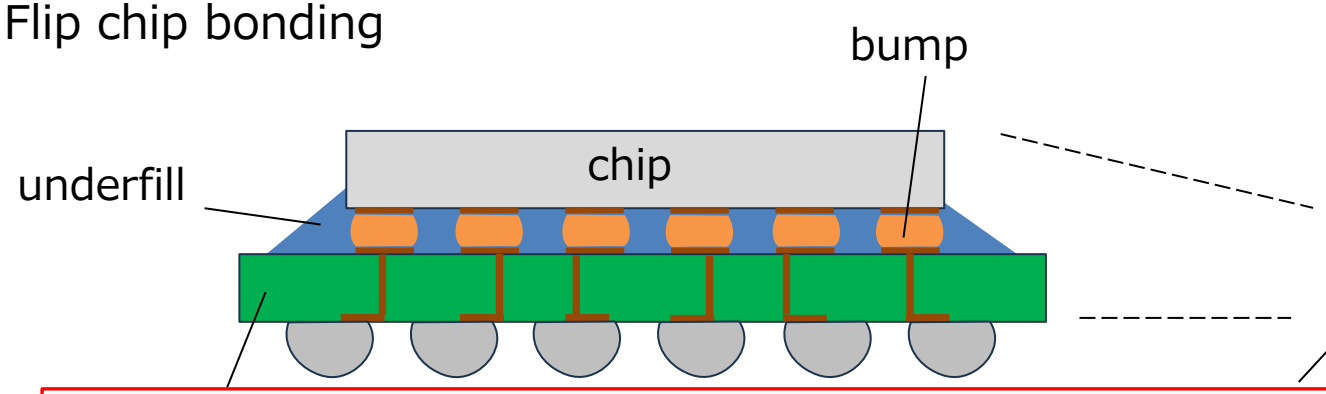
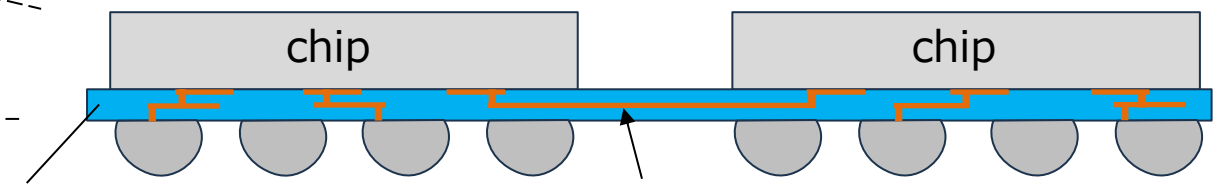
Miniaturization in back-end process.

Recent trend in electronic packaging

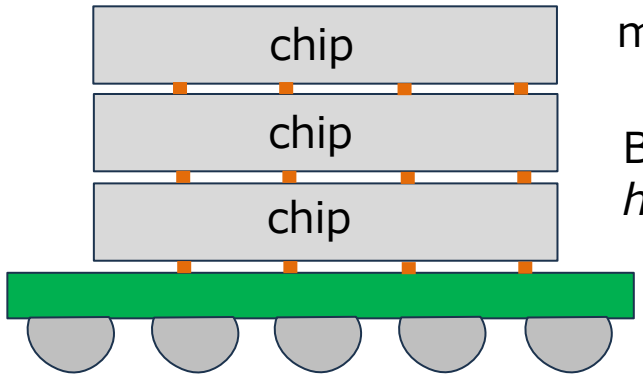
Flip chip bonding



2D-packaging

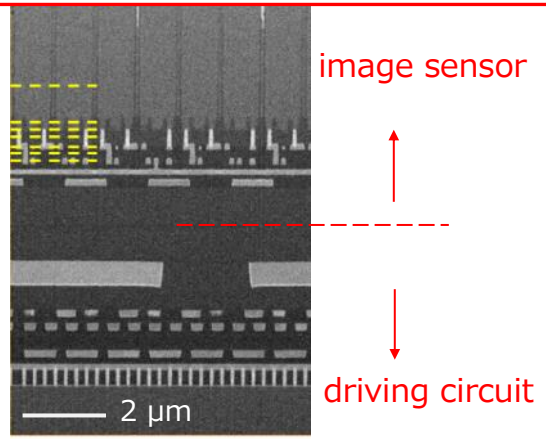


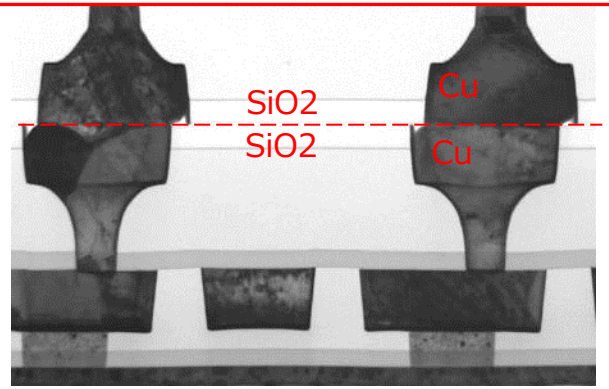
The importance of
heterogeneous/homogeneous interface evaluation
with high spatial resolution



micro bump < 10 μm

Bump-less ⇒
hybrid bonding





Agenda

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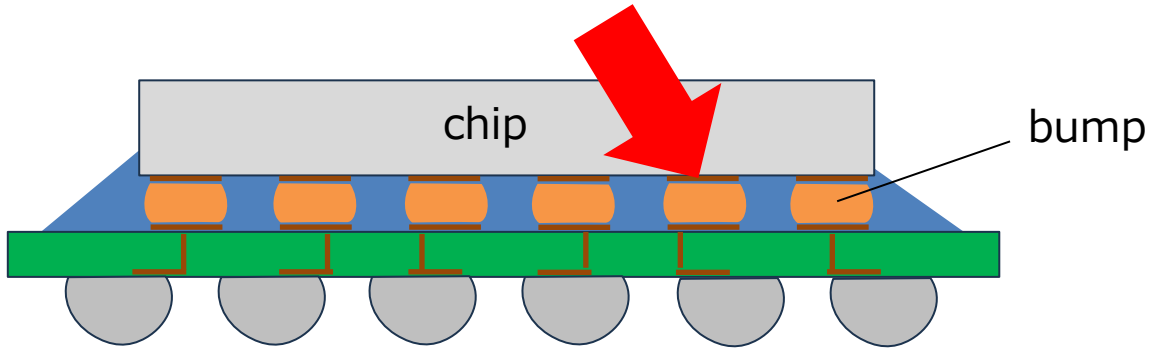
2. Direct observation of the annealing effect for under bump metal using in-situ TEM observation

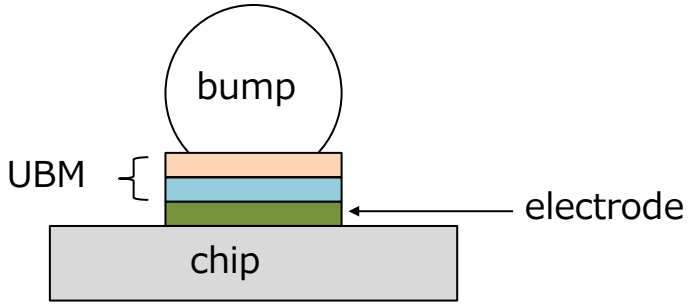
3. Direct observation of the annealing effect at Cu/Cu hybrid bonding interface

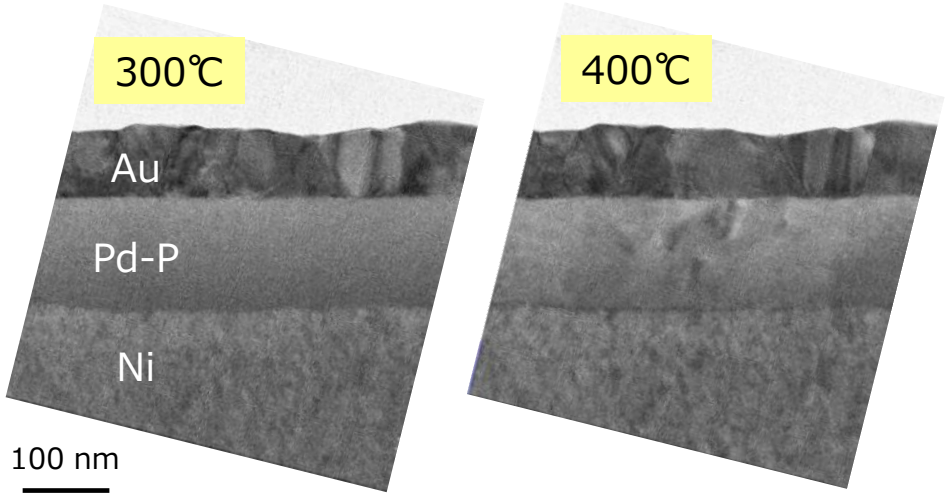
4. Investigation of poor adhesion/electric reliability root cause at the Cu/PI interface

The annealing effect for under bump metal



Sample : Au／Pd-P／Ni
UBM（under bump metal）





annealing

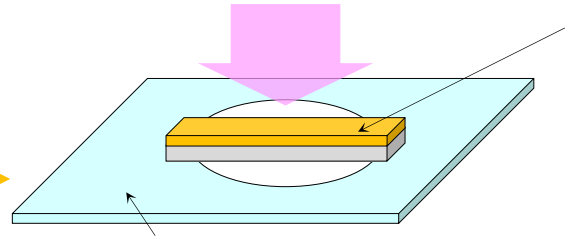
↓

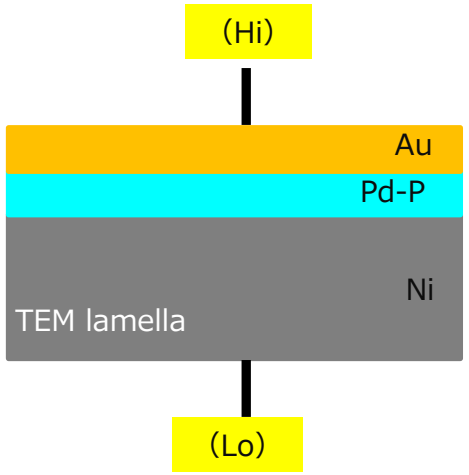
Improvement of
adhesion strength
electric property

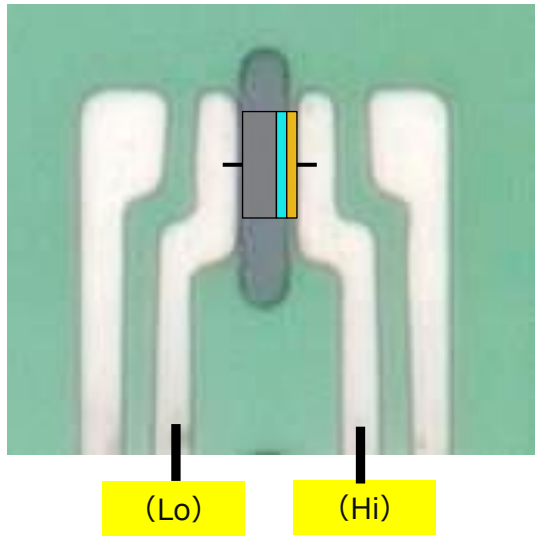
Understanding of the mechanism the improvement using in-situ TEM measurement

In-situ heating/biasing TEM observation

TEM specimen holder



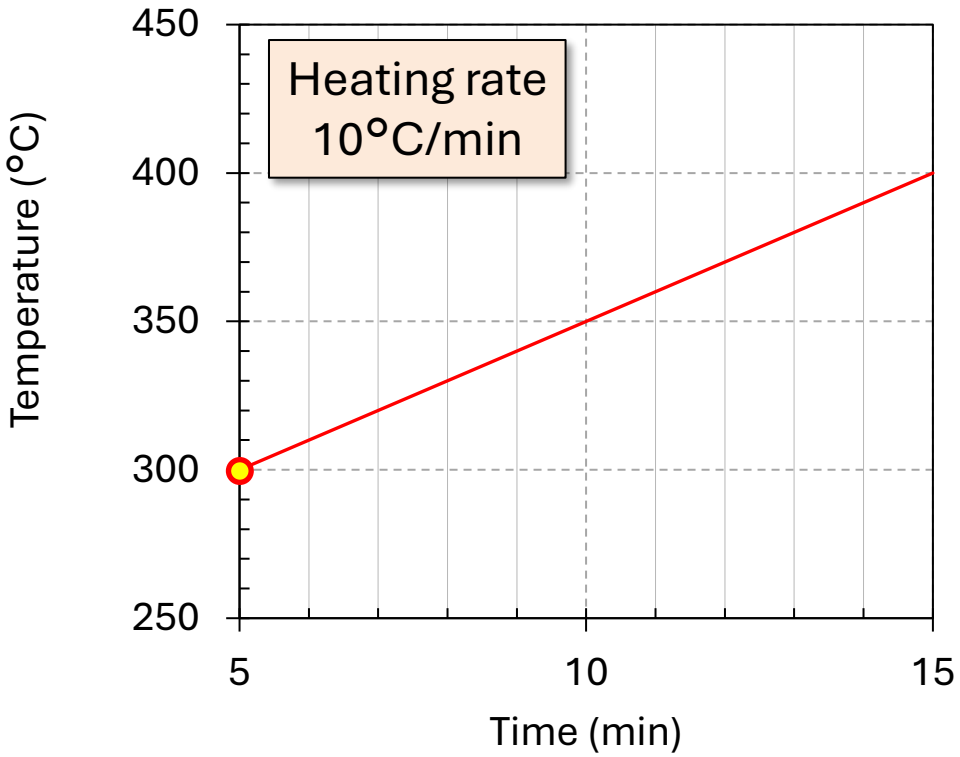




lamella specimen setting for in-situ Biasing TEM

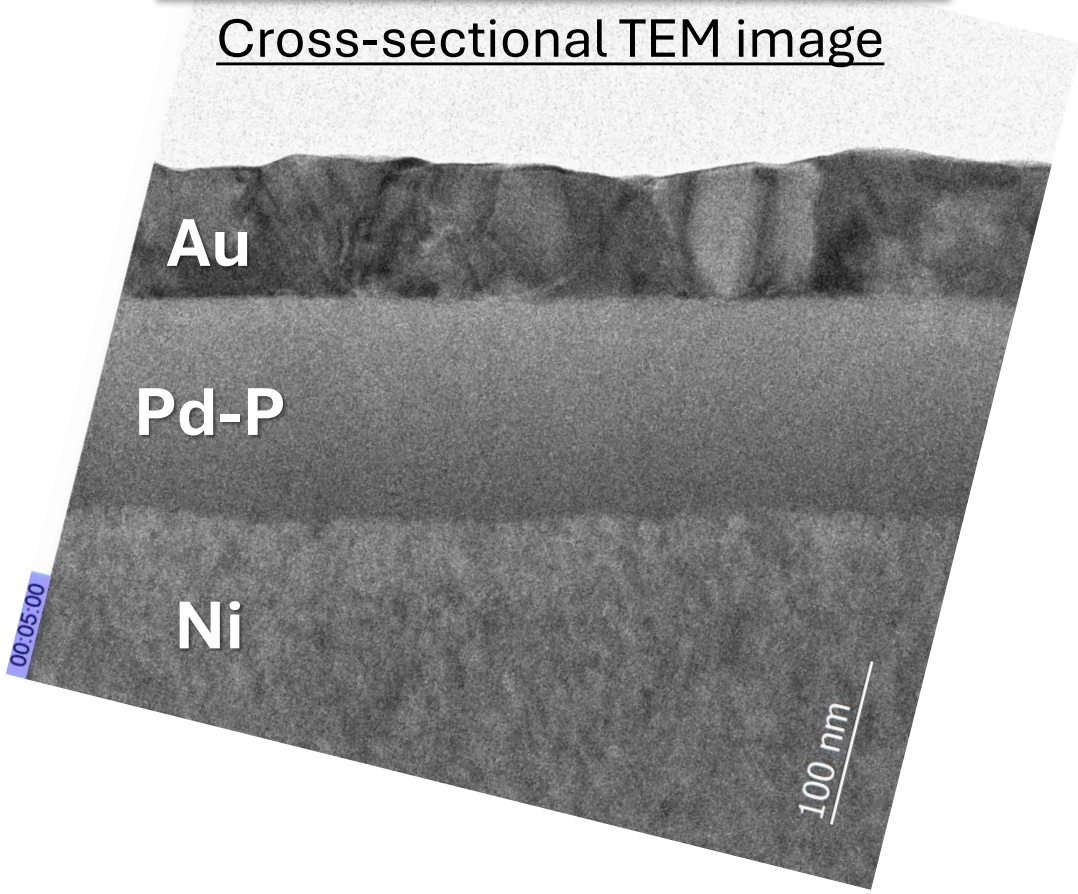
Direct observation of thermal behavior (Movie)

Time-Temperature profile

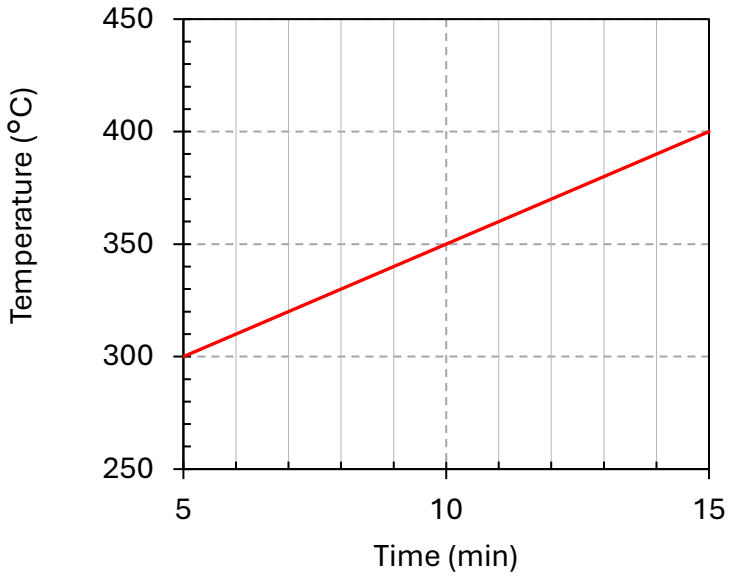


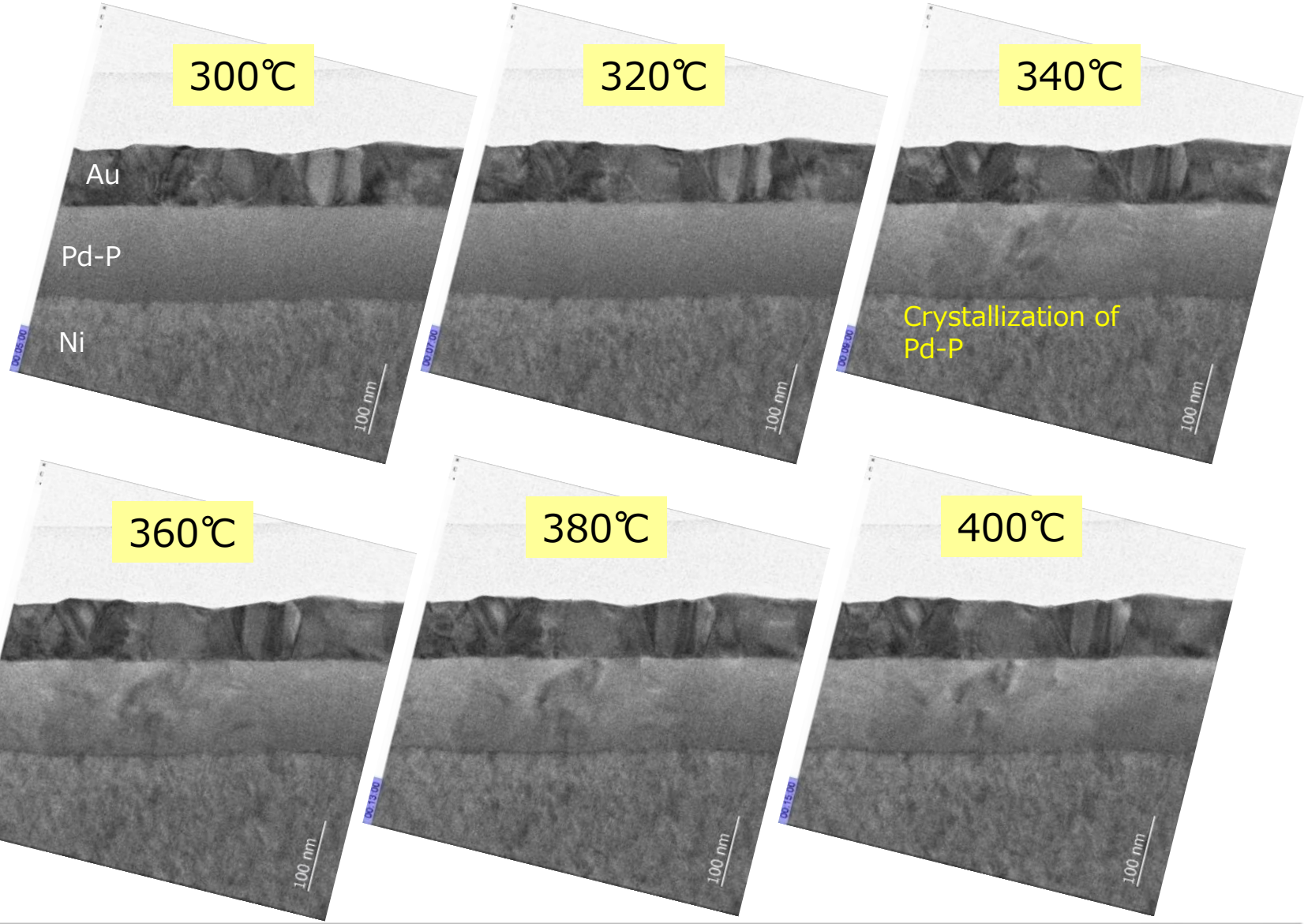
TEM Movie (@300 to 400°C)
Playback speed: 60x

Cross-sectional TEM image

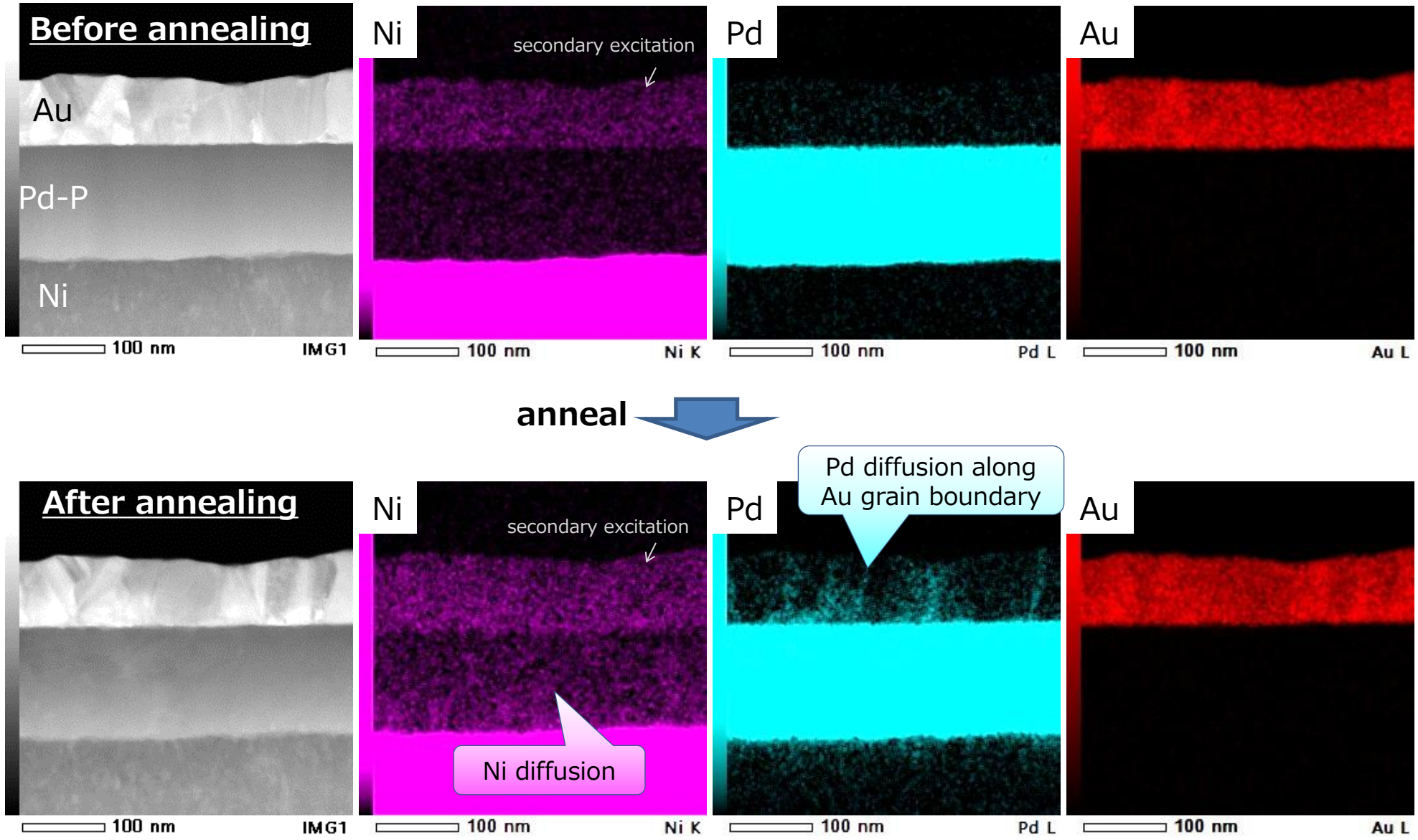


Thermal behavior of Under Bump Metal





Metal diffusion before/after annealing – STEM-EDX maps



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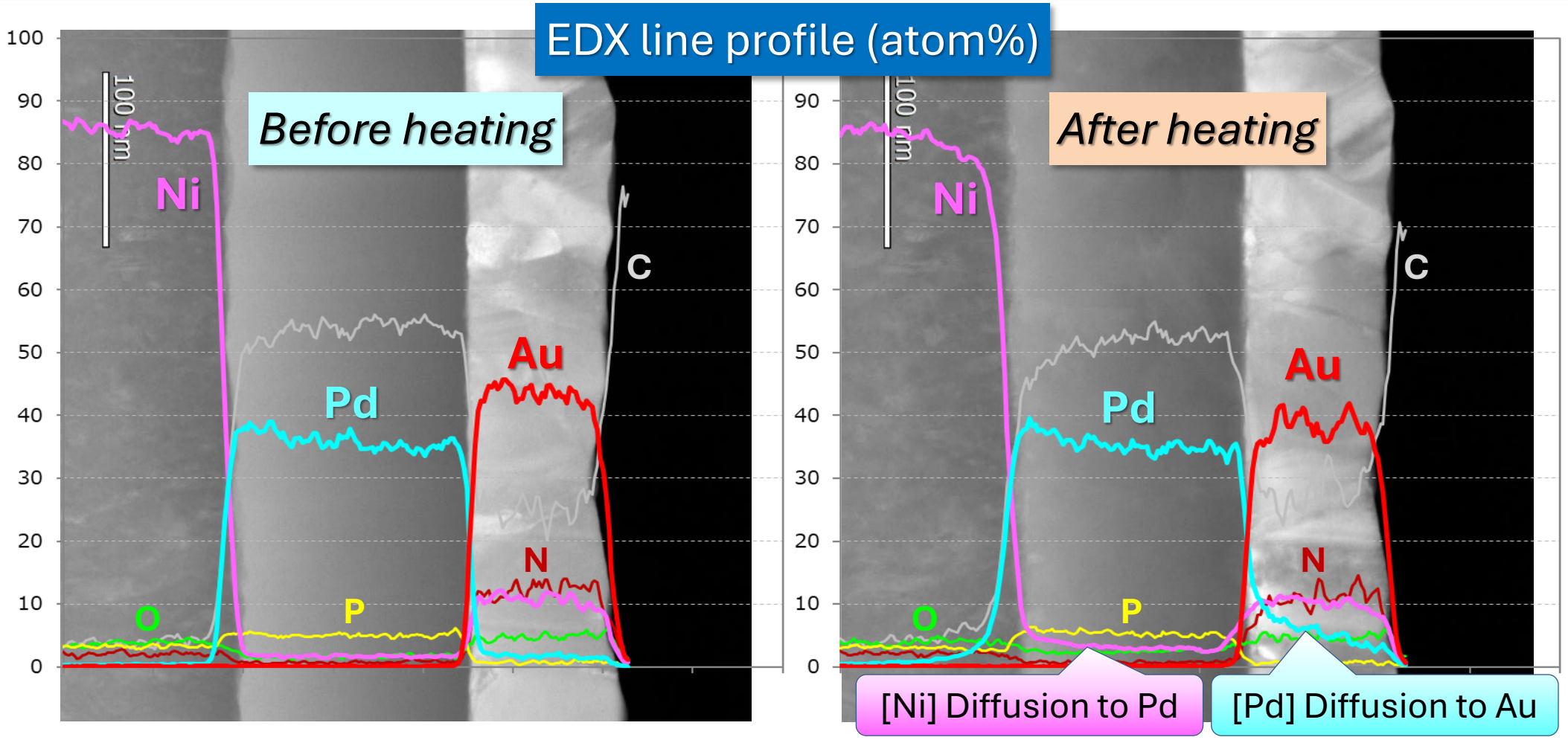
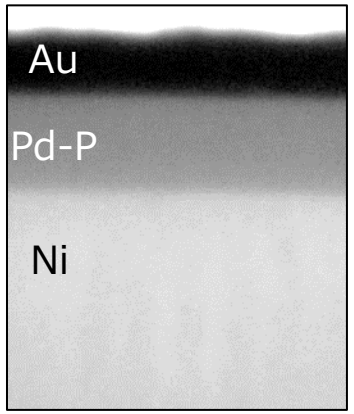


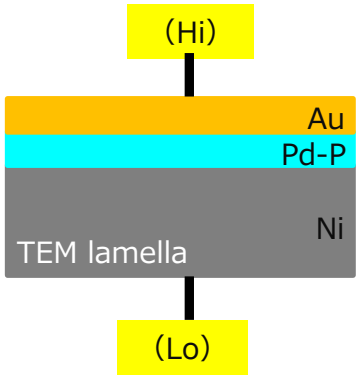
Metal diffusion evaluation with a spatial resolution of nm level

Electric resistivity change – in-situ biasing/heating measurement

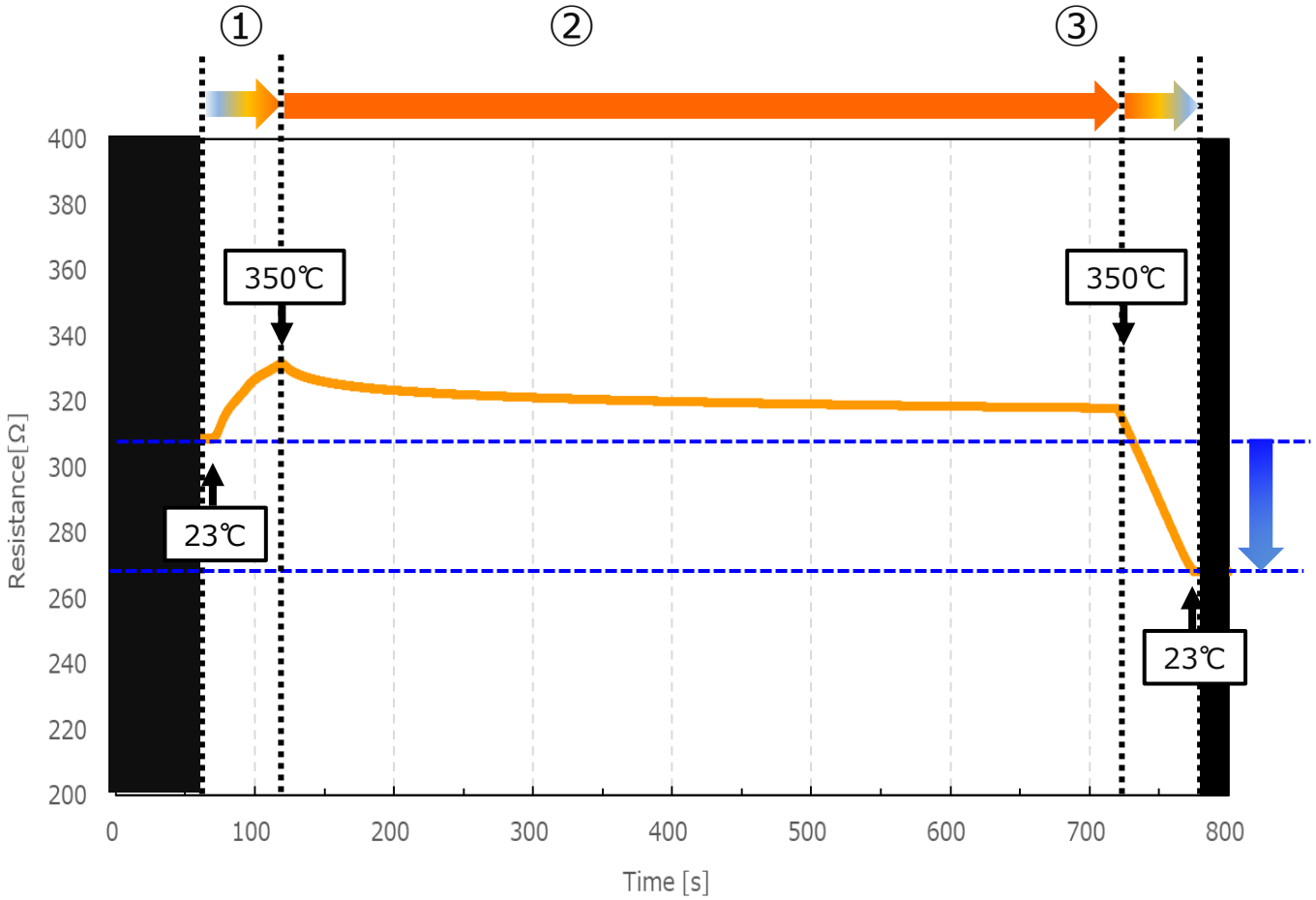
Before annealing



200 nm

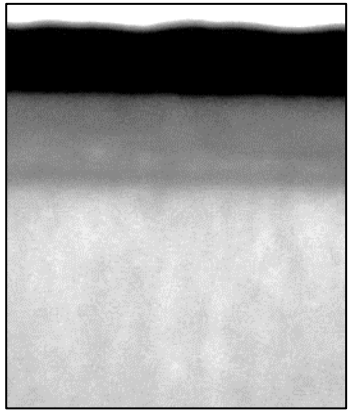


Electric resistivity variation during heating



resistivity

After annealing



crystallization

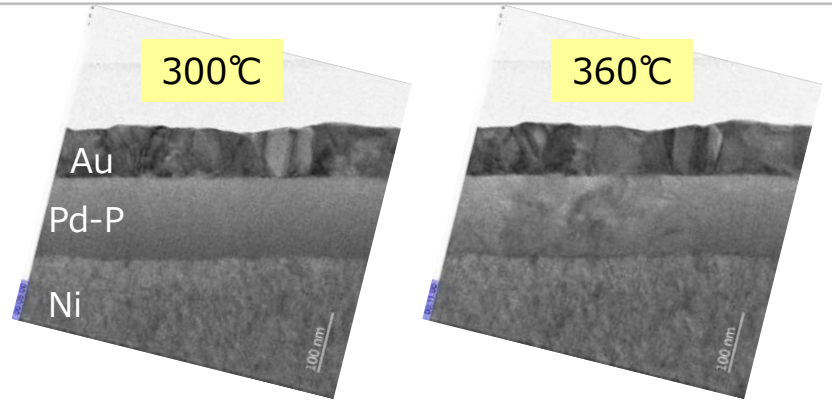
Electric resistivity change could be successfully detected during heating in TEM.

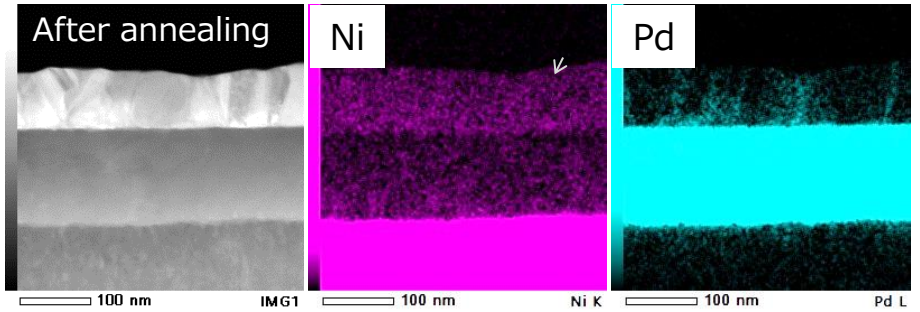
Summary – the annealing effect for under bump metal

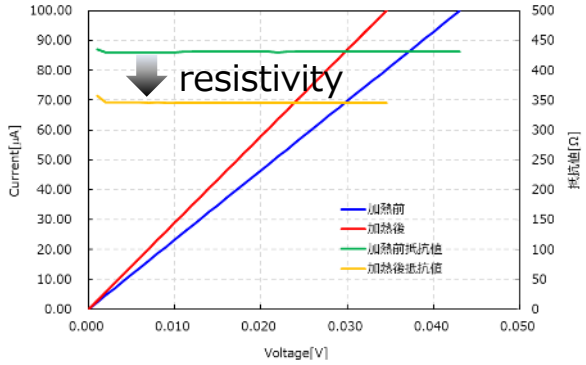
The mechanism of
adhesion strength
electric resistivity improvement

- Crystallization of Pd layer
- Metal diffusion

Optimized annealing temperature ~ 350 °C







Agenda

1. Electronic packaging – recent trend and physical analyses

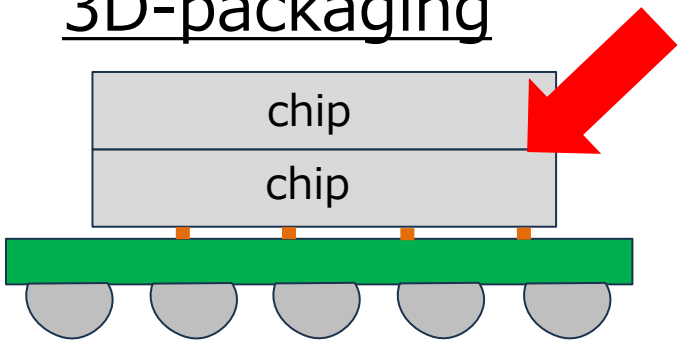
2. Direct observation of the annealing effect for under bump metal using in-situ TEM observation

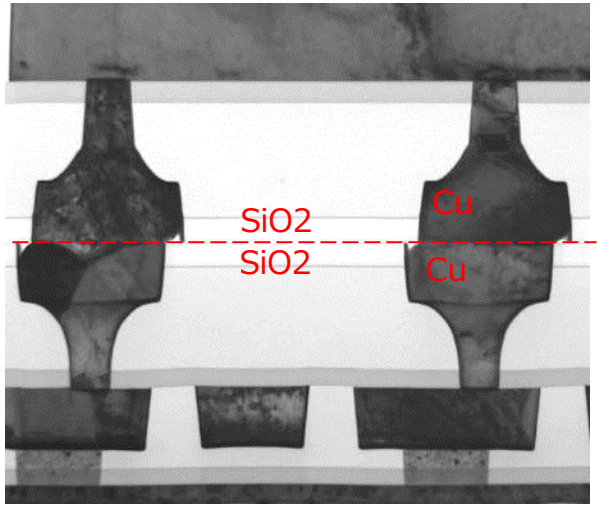
3. Direct observation of the annealing effect at Cu/Cu hybrid bonding interface

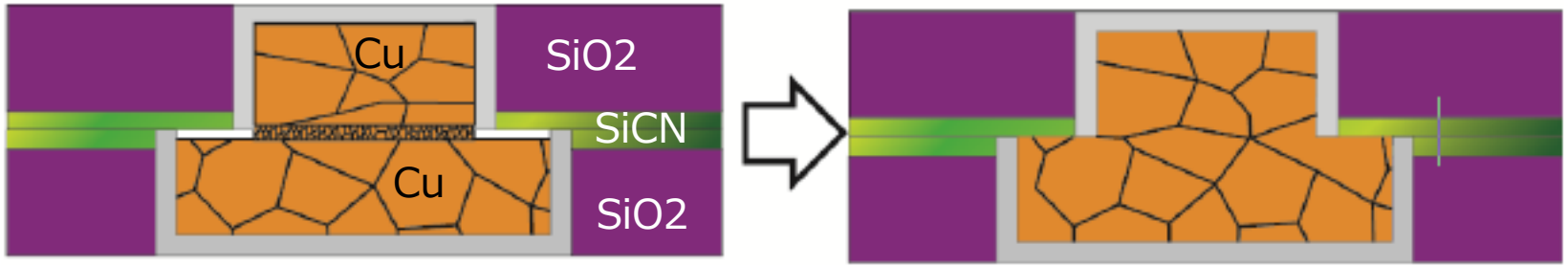
4. Investigation of poor adhesion/electric reliability root cause at the Cu/PI interface

Mechanism of hybrid bonding for 3D-packaging

3D-packaging





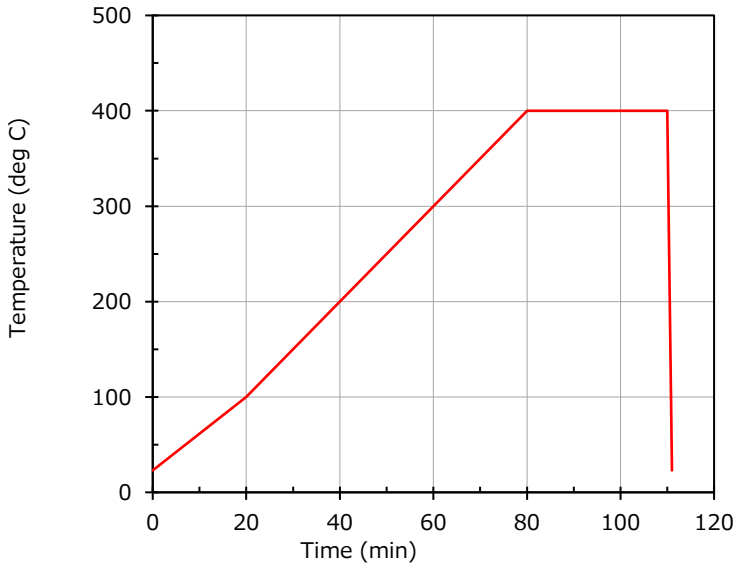


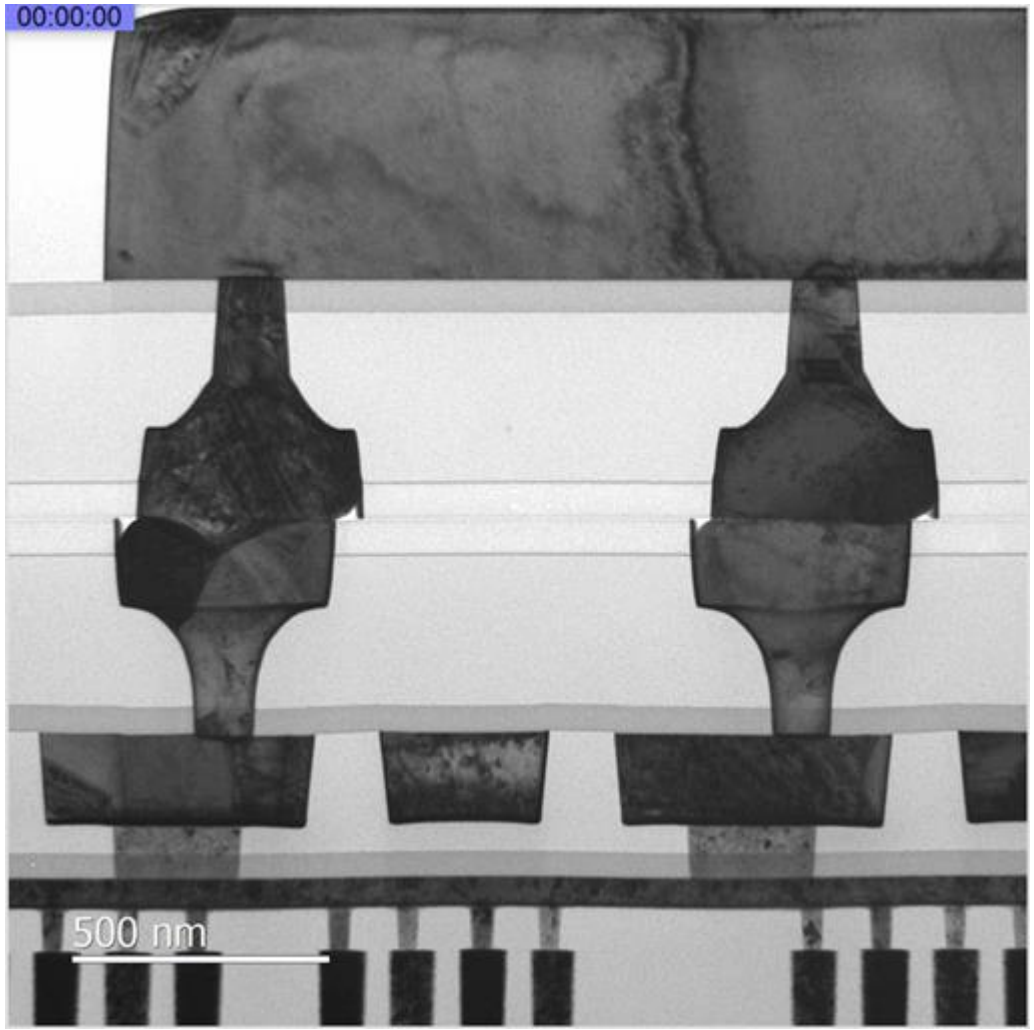
IEEE ELECTRON DEVICE LETTERS, VOL. 42, NO. 12, DECEMBER 2021
INOUE *et al.*: AREA-SELECTIVE ELECTROLESS DEPOSITION OF Cu FOR HYBRID BONDING

Different mechanism from heterojunction
Cu/Cu, dielectrics/dielectrics

In-situ heating test observation of Cu/Cu hybrid bonding

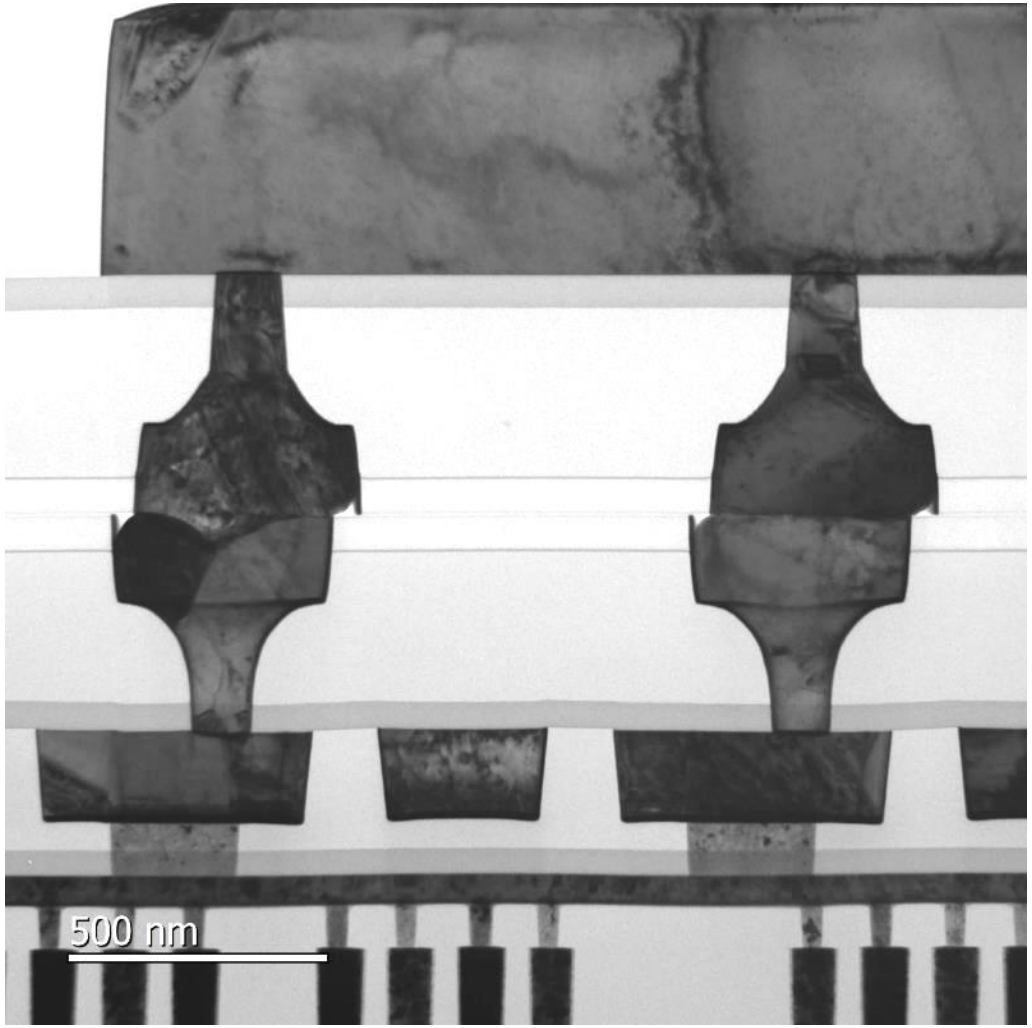
Movie（r. t.→400°C（0→110 min.））



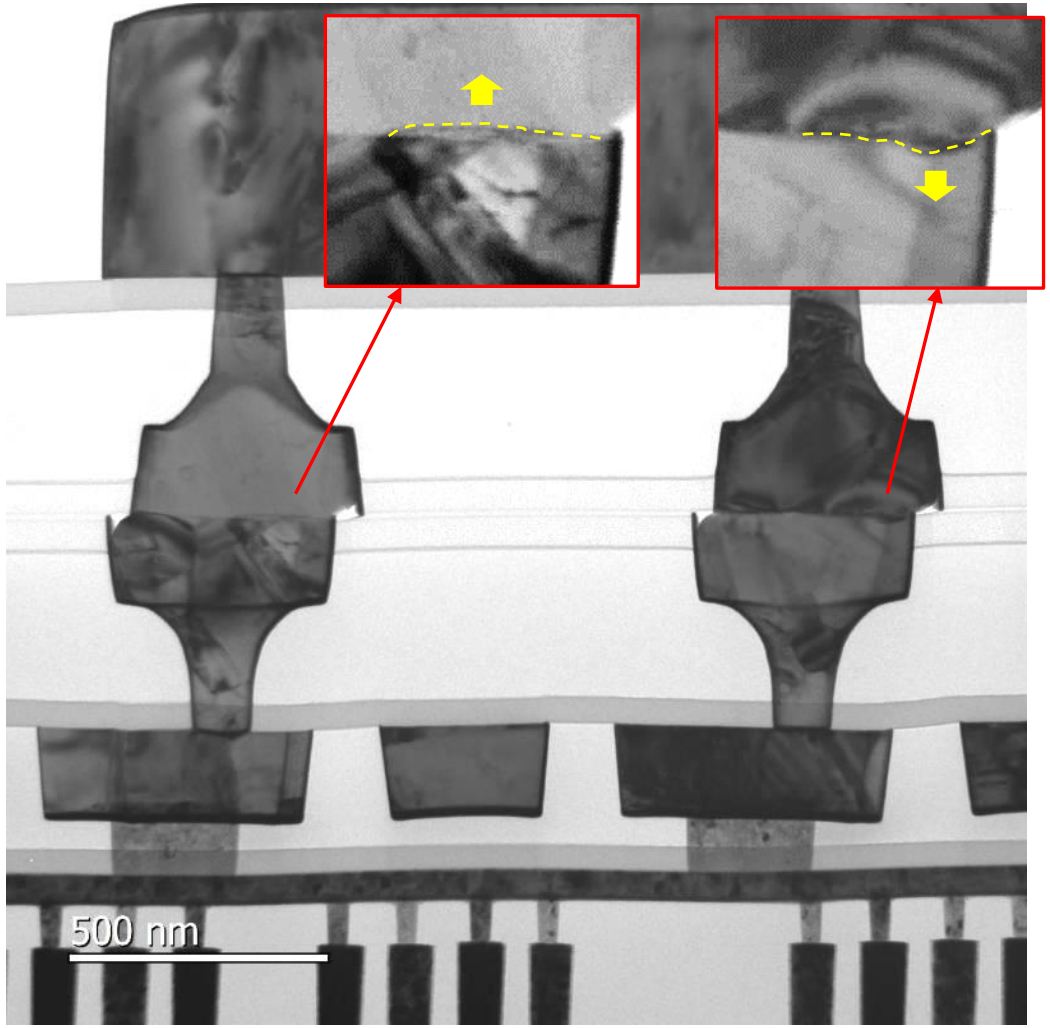


In-situ heating test observation of Cu/Cu hybrid bonding

Before anneal

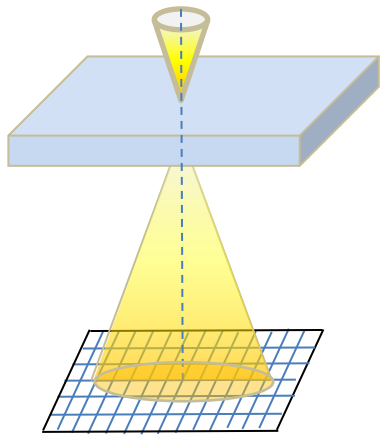


After anneal (400 °C)

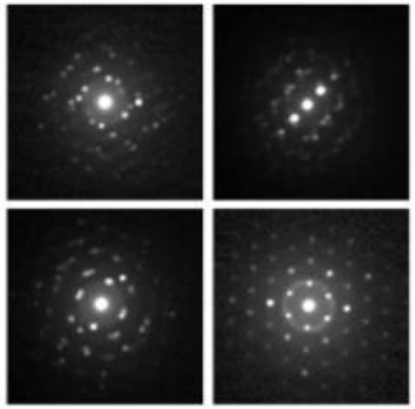


ACOM-TEM investigation - grain size/orientation

(Automated crystal orientation mapping)



diffraction pattern at each pixel



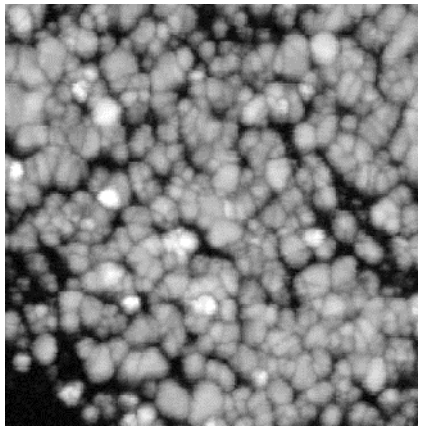
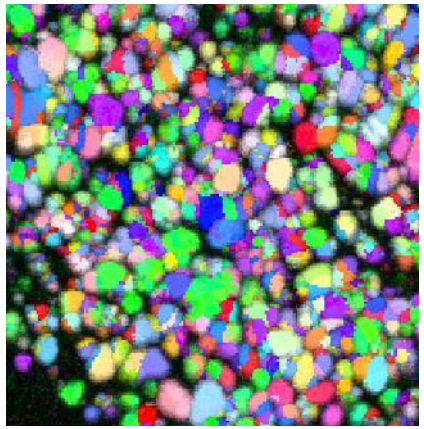
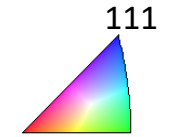


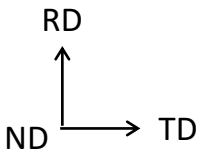
Image Quality map

40 nm

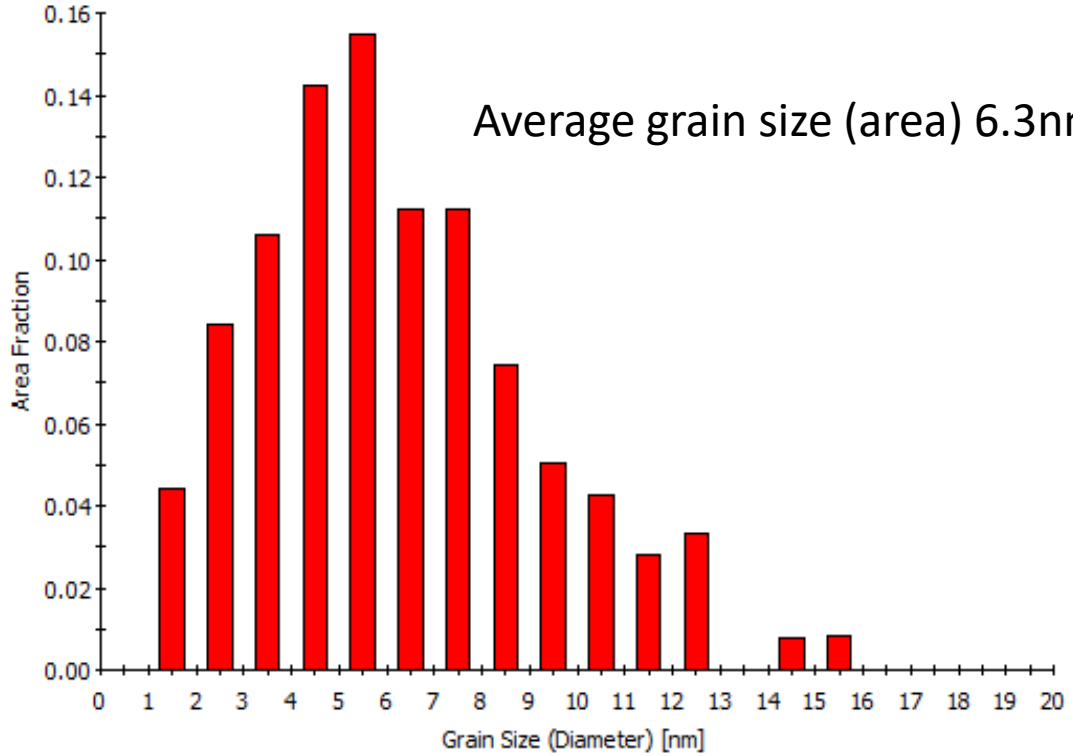


Crystal orientation Map (ND)





Grain Size Distribution Chart



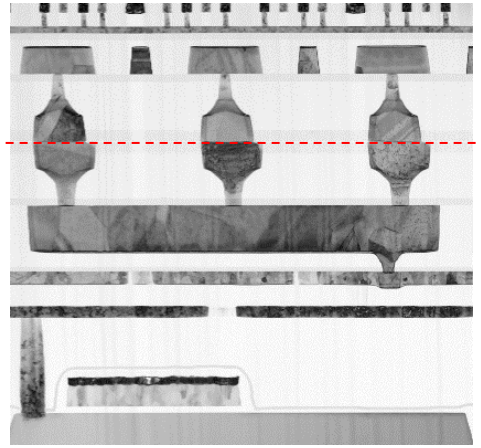
Average grain size (area) 6.3nm

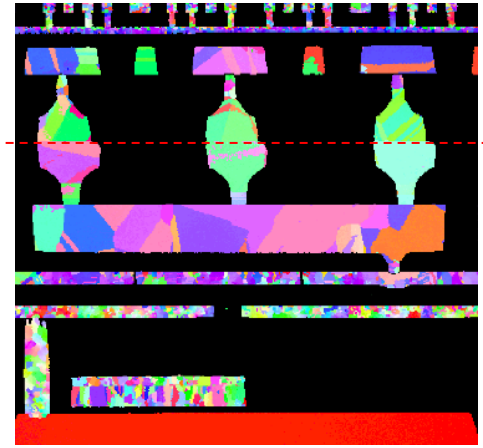
ACOM-TEM before/after heating treatment

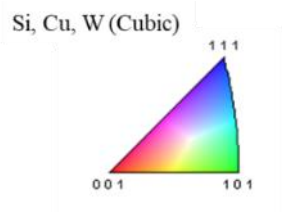
BF-STEM Image

Crystal Orientation Map (RD)

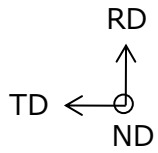
bonding interface







800 nm



Before heating

After heating

600 nm

Grain Map (excluded twin boundaries)

Some grain-boundaries disappeared by annealing.

Average grain size

Before heating	After heating
340 nm	440 nm

In-situ heating ACOM-TEM for the understanding of hybrid bonding mechanism.

R. Fujimoto. EPTC 2023

Agenda

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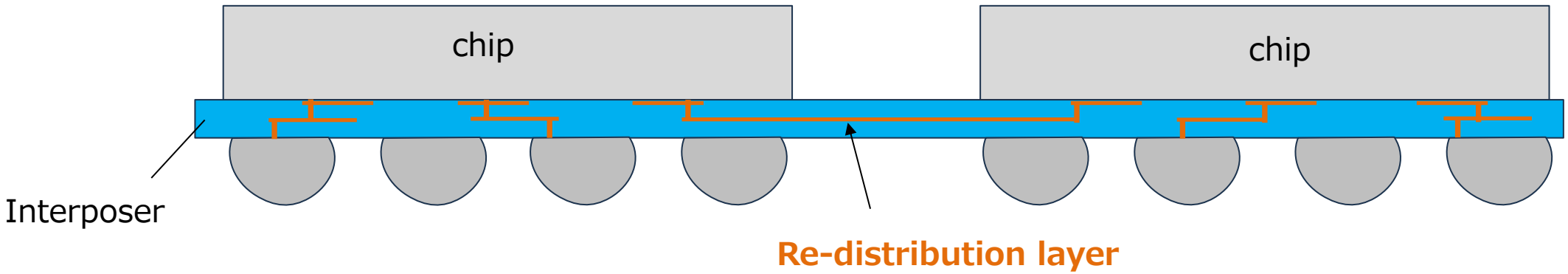
Cu redistribution layer in organic interposer

2D-packaging



Pros. of organic interposer over Si interposer

Lower cost, lower transmission loss (lower dk), higher flexibility

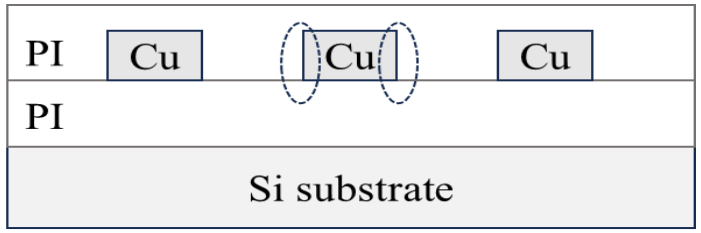
Cons. of organic interposer over Si interposer

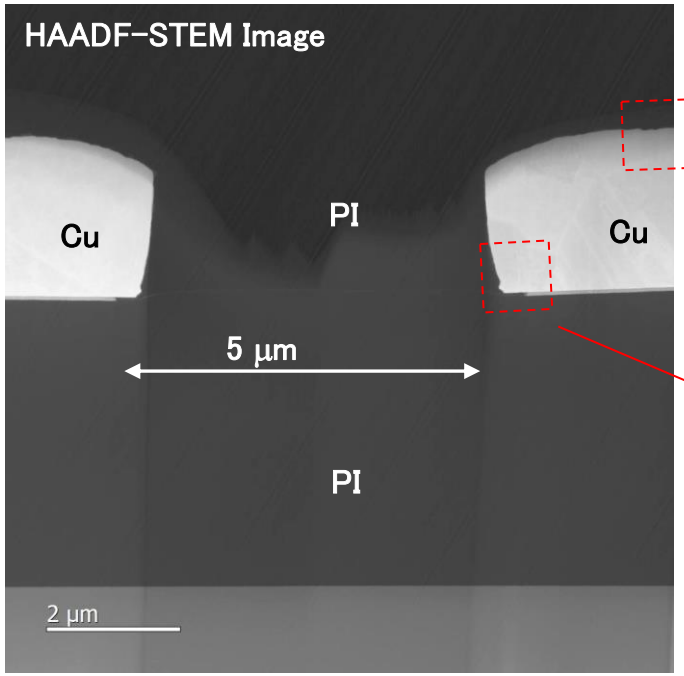
Fine-pitch interconnect limitation

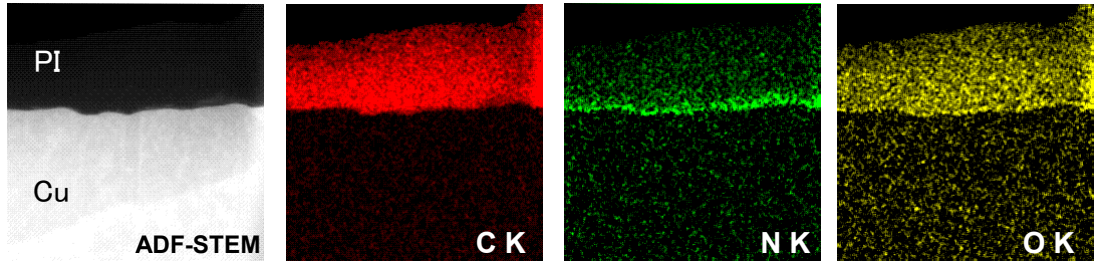
Lower insulation reliability, lower adhesion with Cu

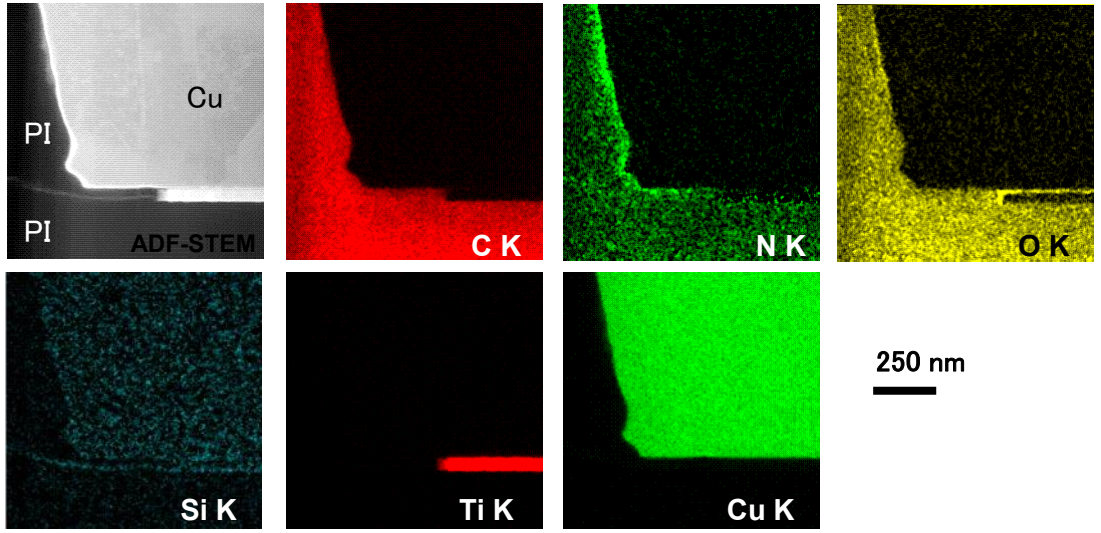
→ Root cause analysis of these issues by detailed physical analyses

Elemental distribution at Cu/polyimide– XSTEM-EDX –



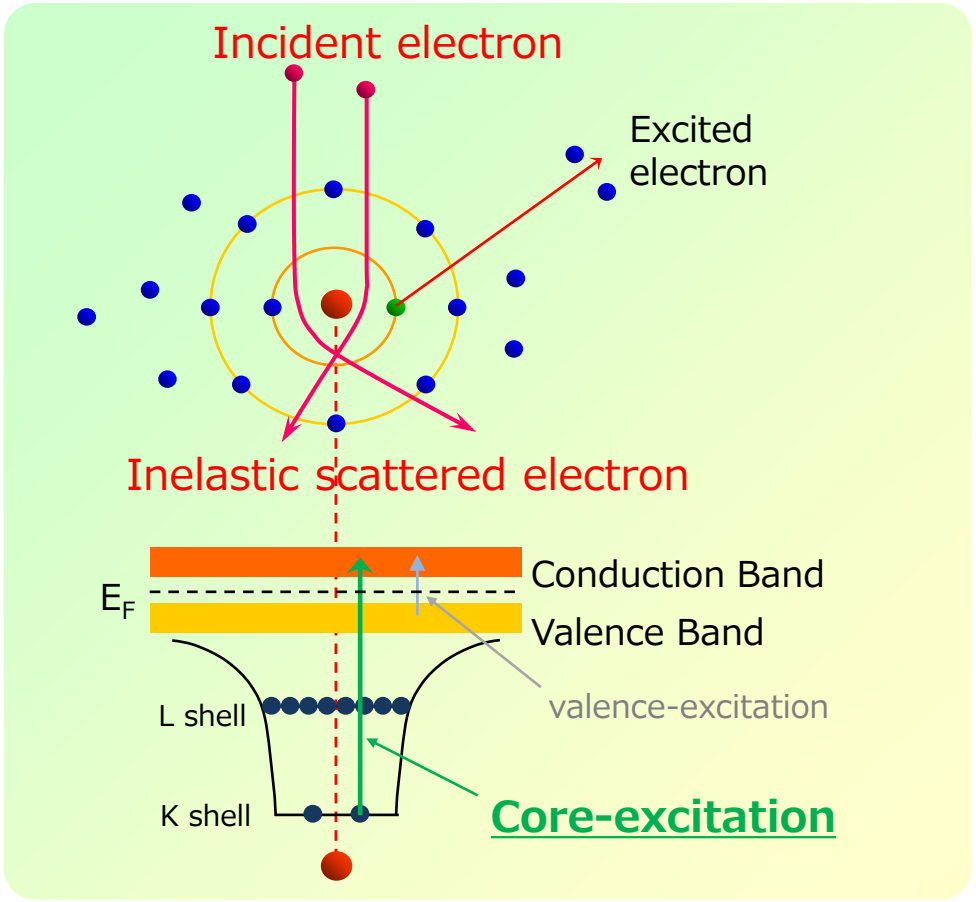


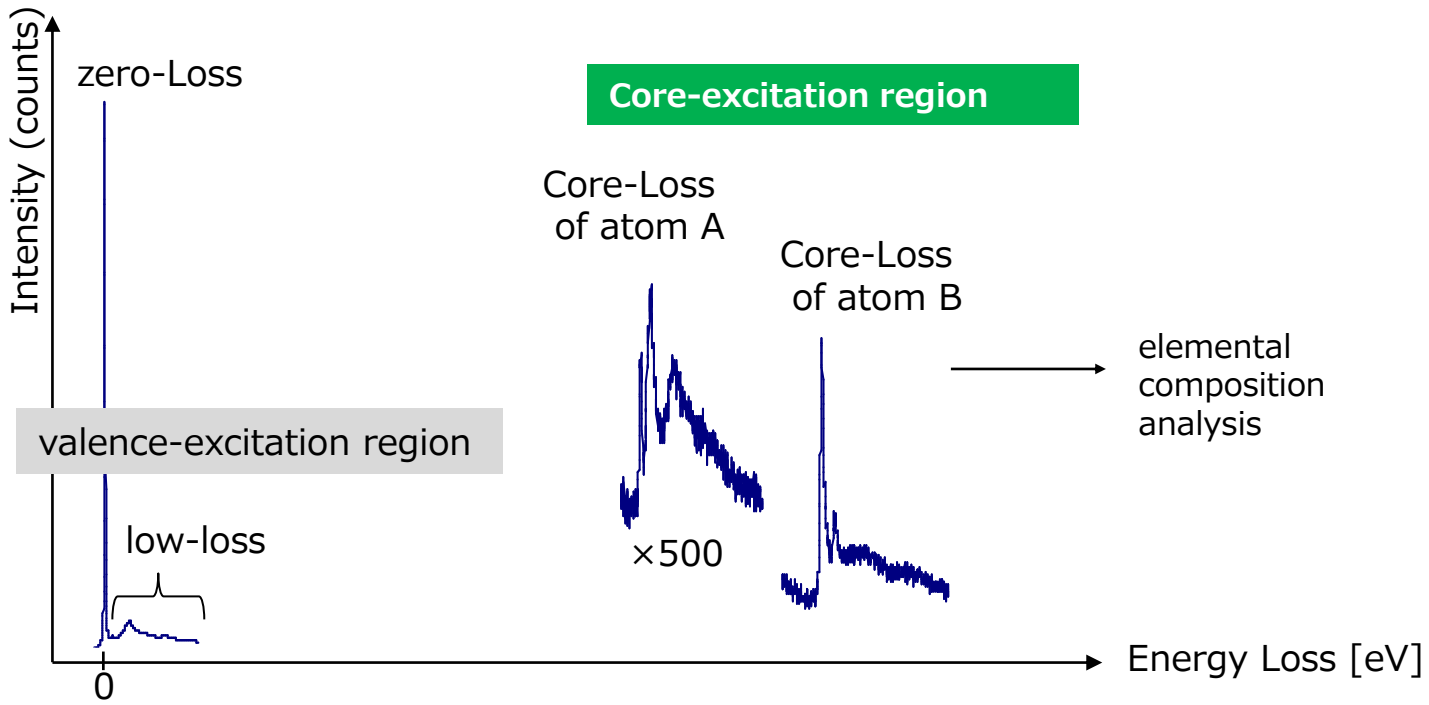




High amount of nitrogen at Cu/PI interface

STEM-EELS: Electron Energy-loss Spectroscopy





core-loss EELS

Elemental composition

Bonding structure

\+

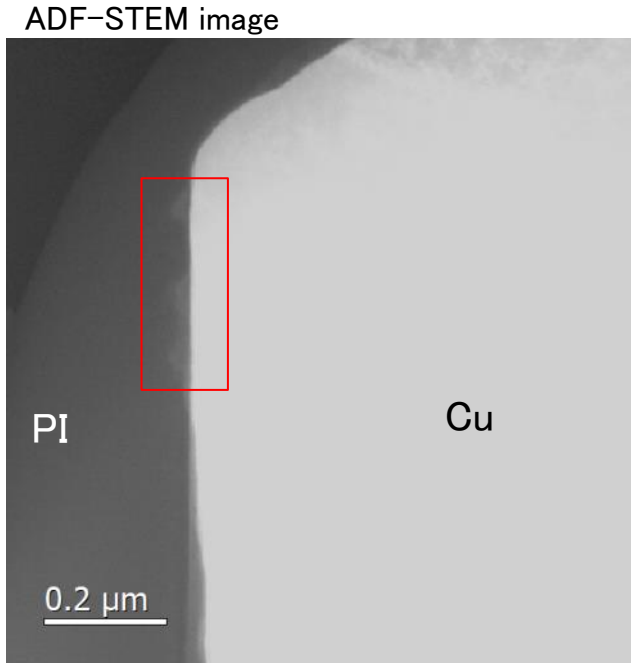
low-loss EELS

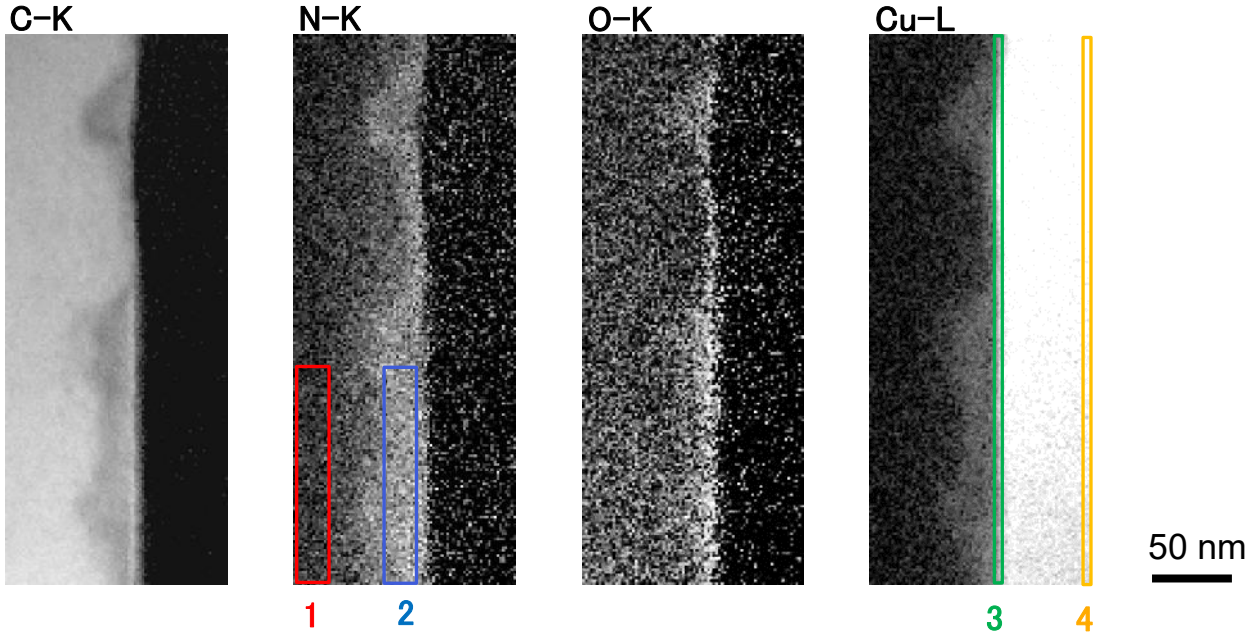
Optical property

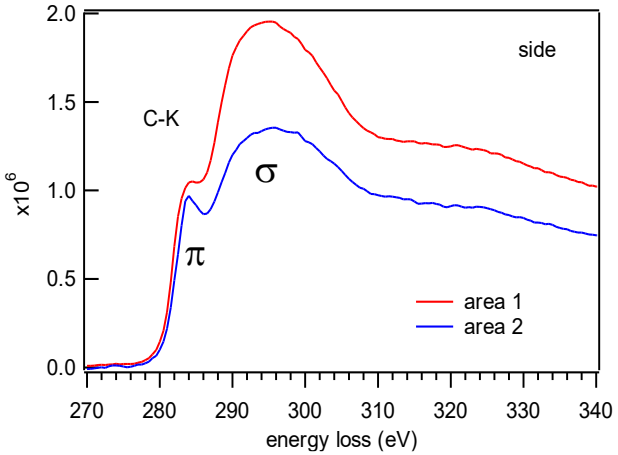
Dielectric property

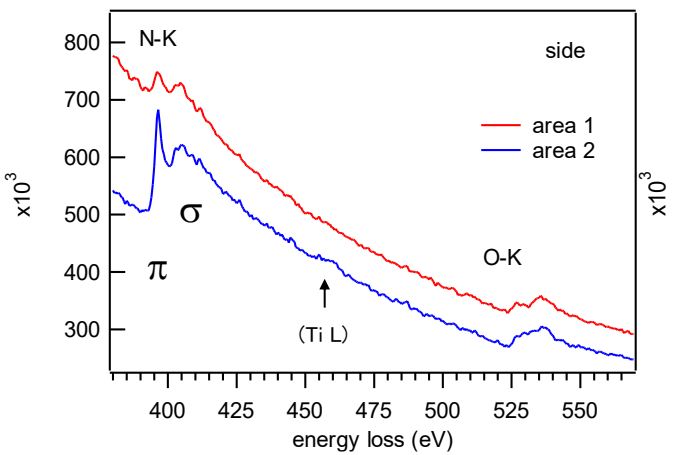
with nm spatial resolution

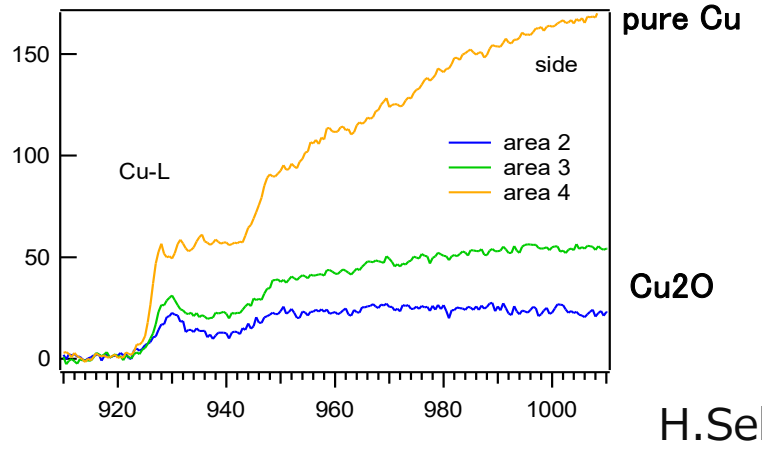
Bonding structure at polyimide/Cu interface – STEM-EELS











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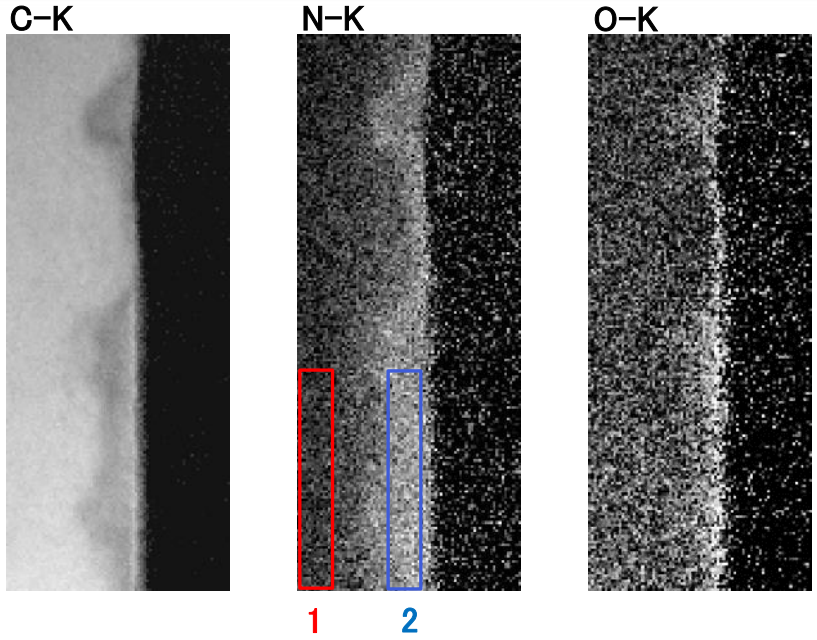
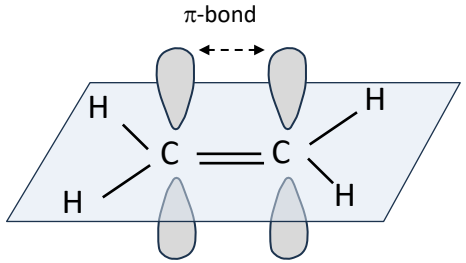
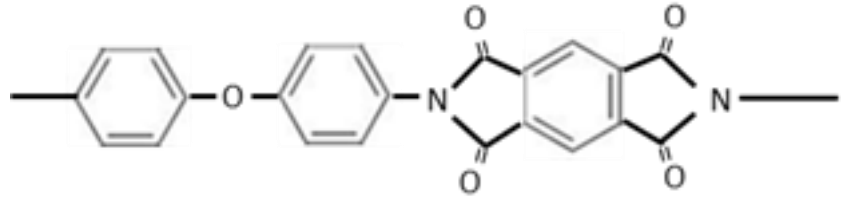
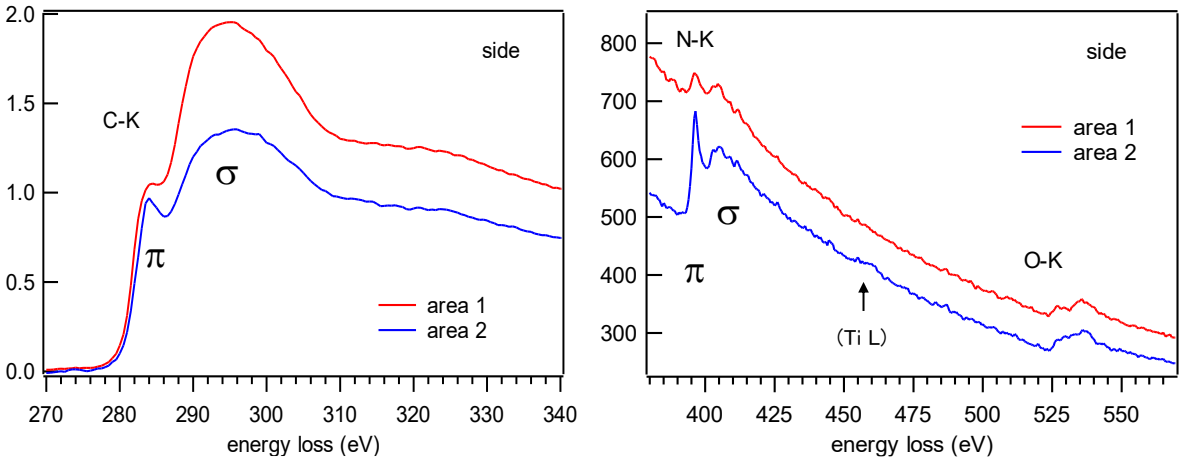
Bonding structure at polyimide/Cu interface – STEM-EELS





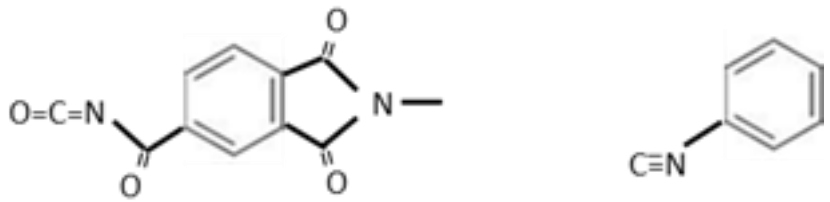
polyimide





Bonding structure change at Cu/PI interface（C=N , C≡N）

Estimated structure

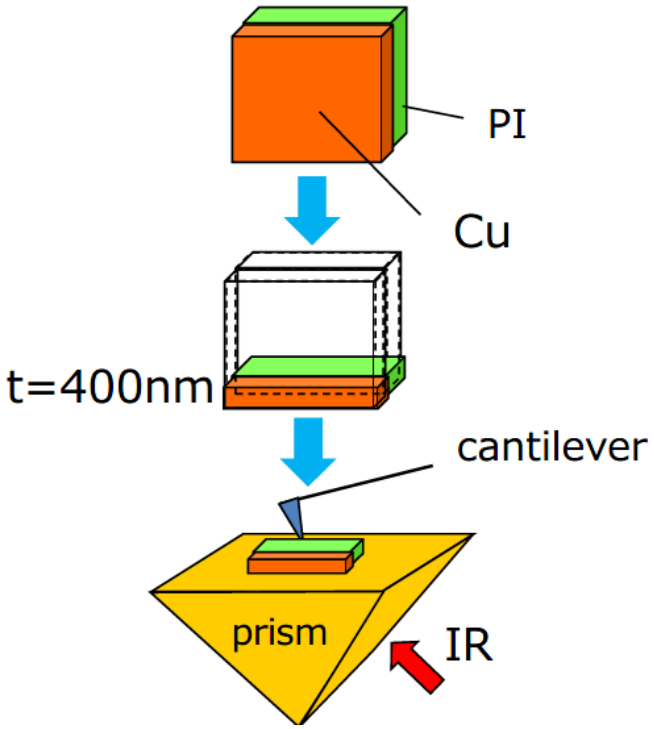


<u>Cu diffusion from Cu2O</u>→ decomposition of polyimide
Double or triple bond between C and N

→ **Cause of the poor adhesion failure at Cu/PI**

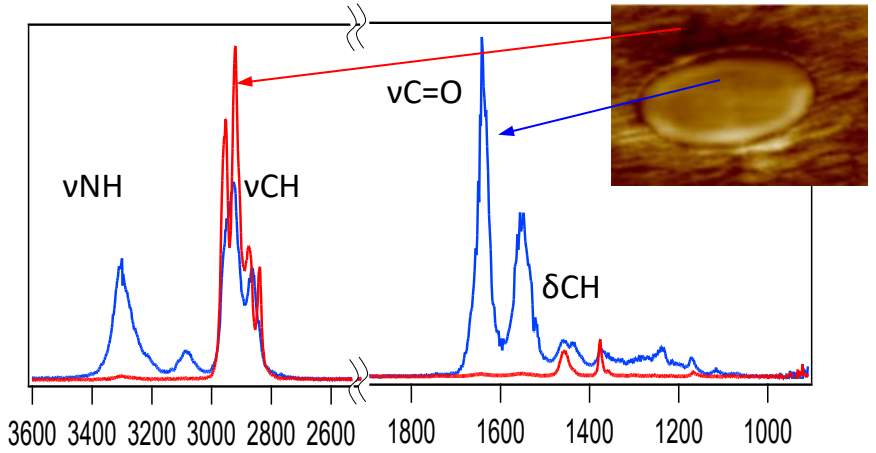
AFM-IR

The absorption of the IR laser and thermal expansion of the sample → the cantilever oscillation



Fourier-transforming of the cantilever oscillation amplitude

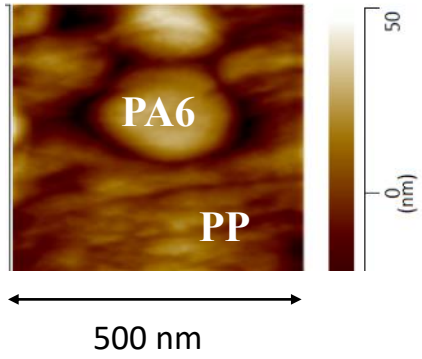
→ IR absorption spectra of the sample



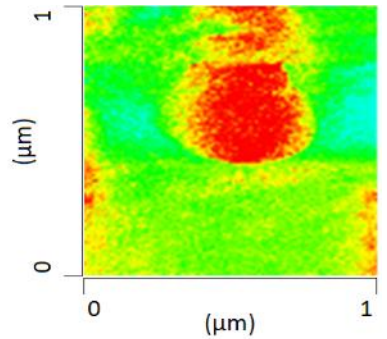
Spatial resolution ~ 100 nm

Peak-intensity map of AFM-IR

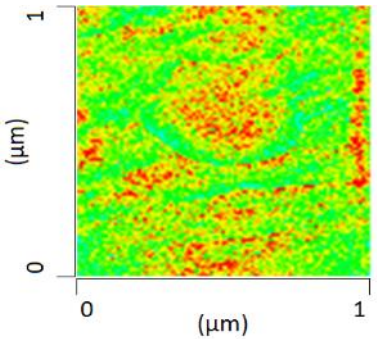
AFM image of poly-propylene (PP) / Polyamide 6 (PA6) alloy



(a) PA6
1640 cm^{-1} (Amide : νC=O)

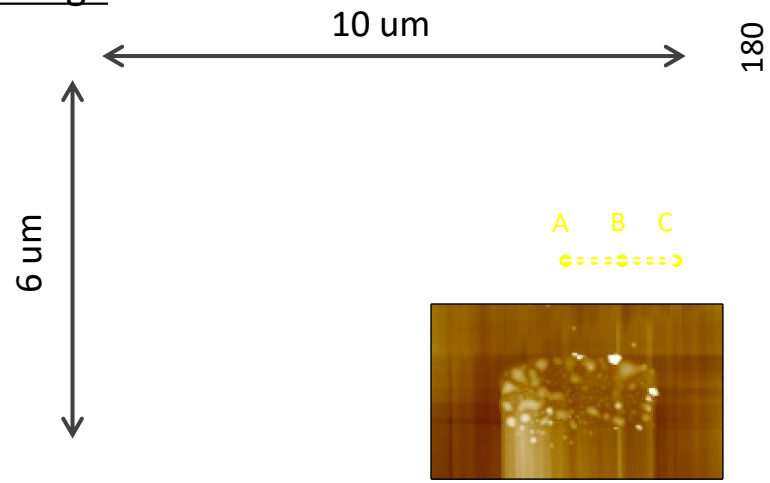


(b) PP
1376 cm^{-1} (CH_3 : δCH)

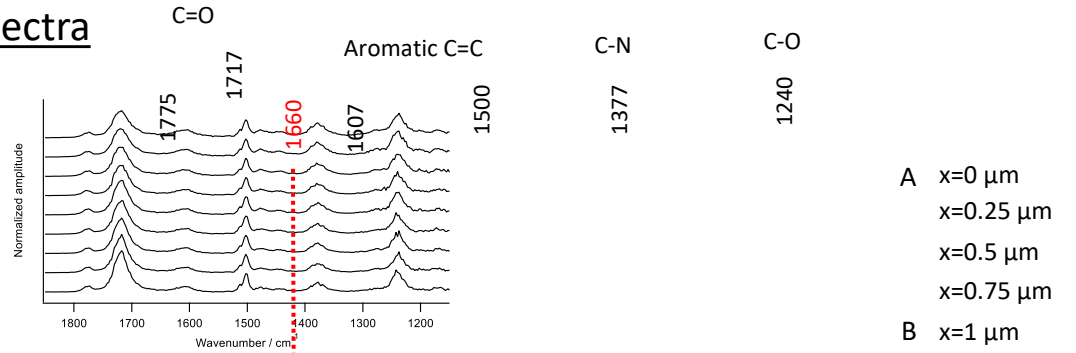


Chemical structure of polyimide around the interface with Cu

AFM image

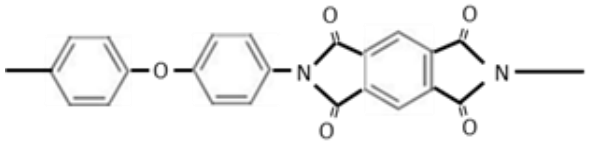


AFM-IR spectra

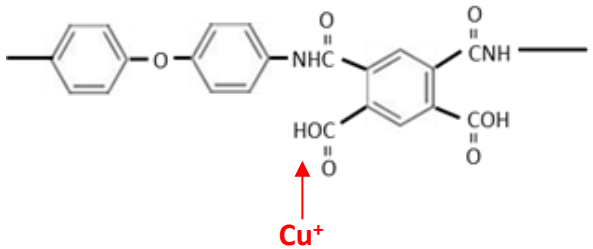


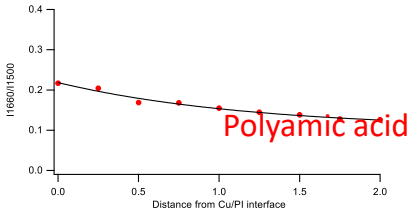
polyamic acid C=O

polyimide



polyamic acid





Polyamic acid diffusion length : 1.7 µm

Cu diffusion from Cu2O → imide ring open → The generation of polyamic acid

→ **Cause of electric failure**

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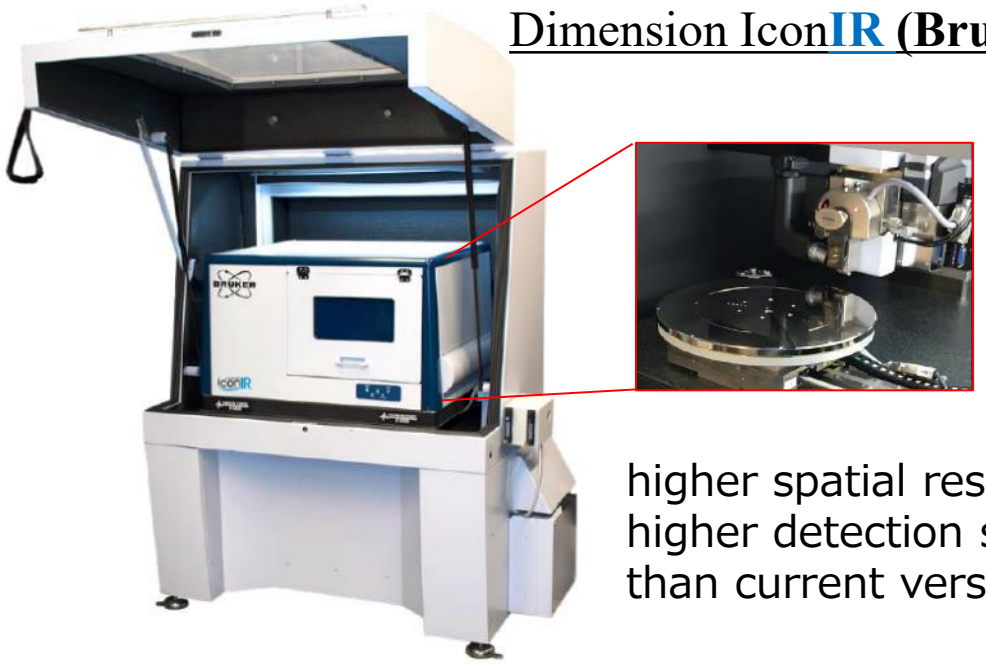
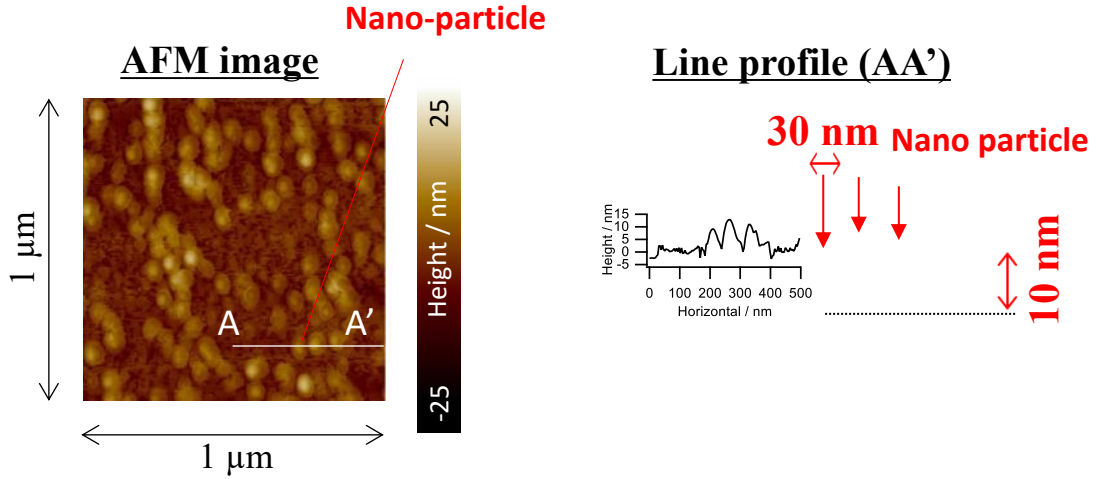
New AFM-IR instrument – coming soon -

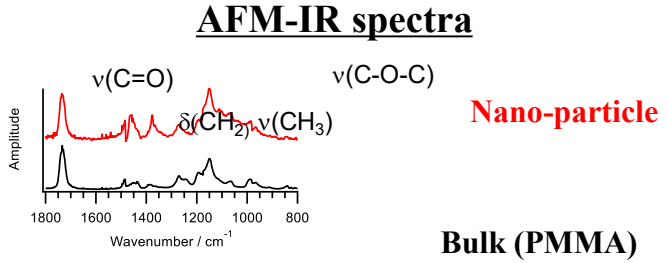


Dimension IconIR (Bruker)

higher spatial resolution
higher detection sensitivity
than current version

	Icon-IR
AFM-IR mode	Contact/Tapping mode Resonance-enhanced mode Surface sensitive mode Resonance-enhanced force volume mode
Spatial resolution	**< 30 nm**
Detection depth	**30 nm**
XY scan area	90 µm x 90 µm
Specimen size	150 mm diameter

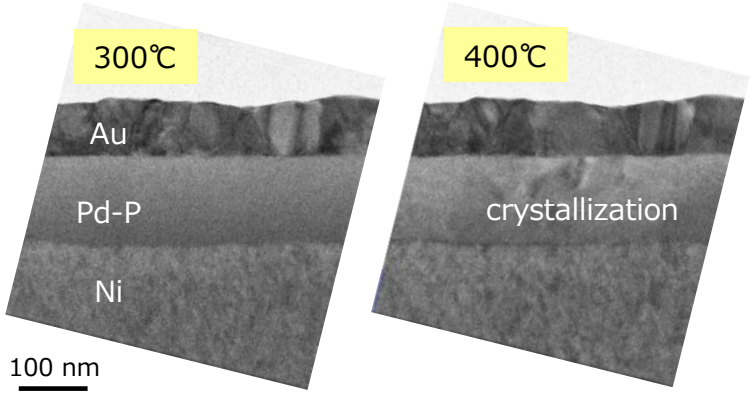




Summary

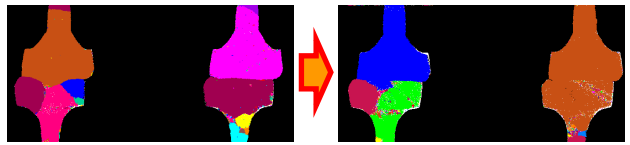
Evaluation of heterogeneous/homogeneous interface with high spatial resolution for recent electronic packaging

in-situ TEM



The mechanism of adhesion strength /electric resistivity improvement by annealing

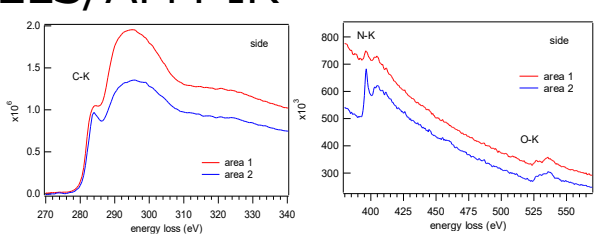
Under bump metal

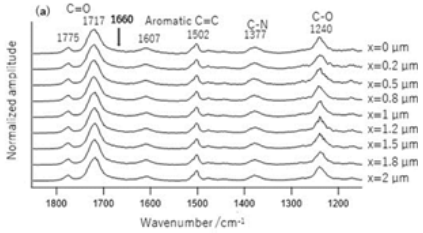


The mechanism of Cu/Cu hybrid bonding

Hybrid bonding

STEM-EELS/AFM-IR





The cause of poor adhesion / low electric reliability

Redistribution layer in organic interposer


Thank
You
Suksama
Maake
Asante
Shukria
Dhanyavadagalu
Vinaka
köszönöm
Kiitos
Manana
Dankon
Suksama
Dank Je
Dankscheen
спасибо
Mauruuru
Biyan
நன்றி
Dziekuje
Chokrane
Arigato
Juspaxar
Gracias
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ধন্যবাদ
cảm ơn bạn
Grazas
Ua Tsaug Rau Koj
Bedankt
Dakujem
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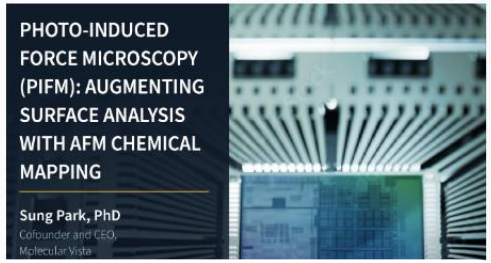

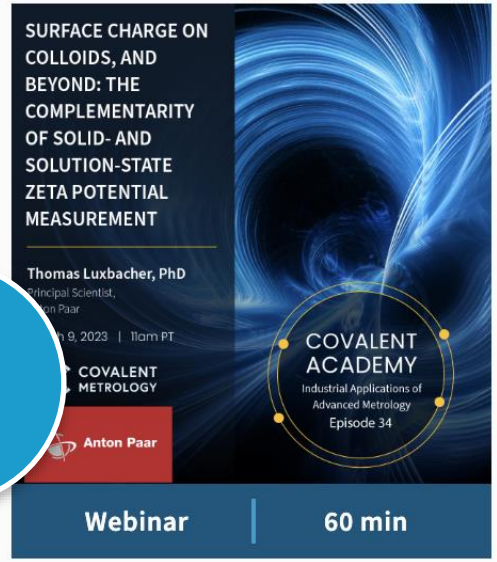

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Q & A Session

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Thank you.