Cu-Cu TCB – A key enabler for ultra fine-pitch heterogeneous applications

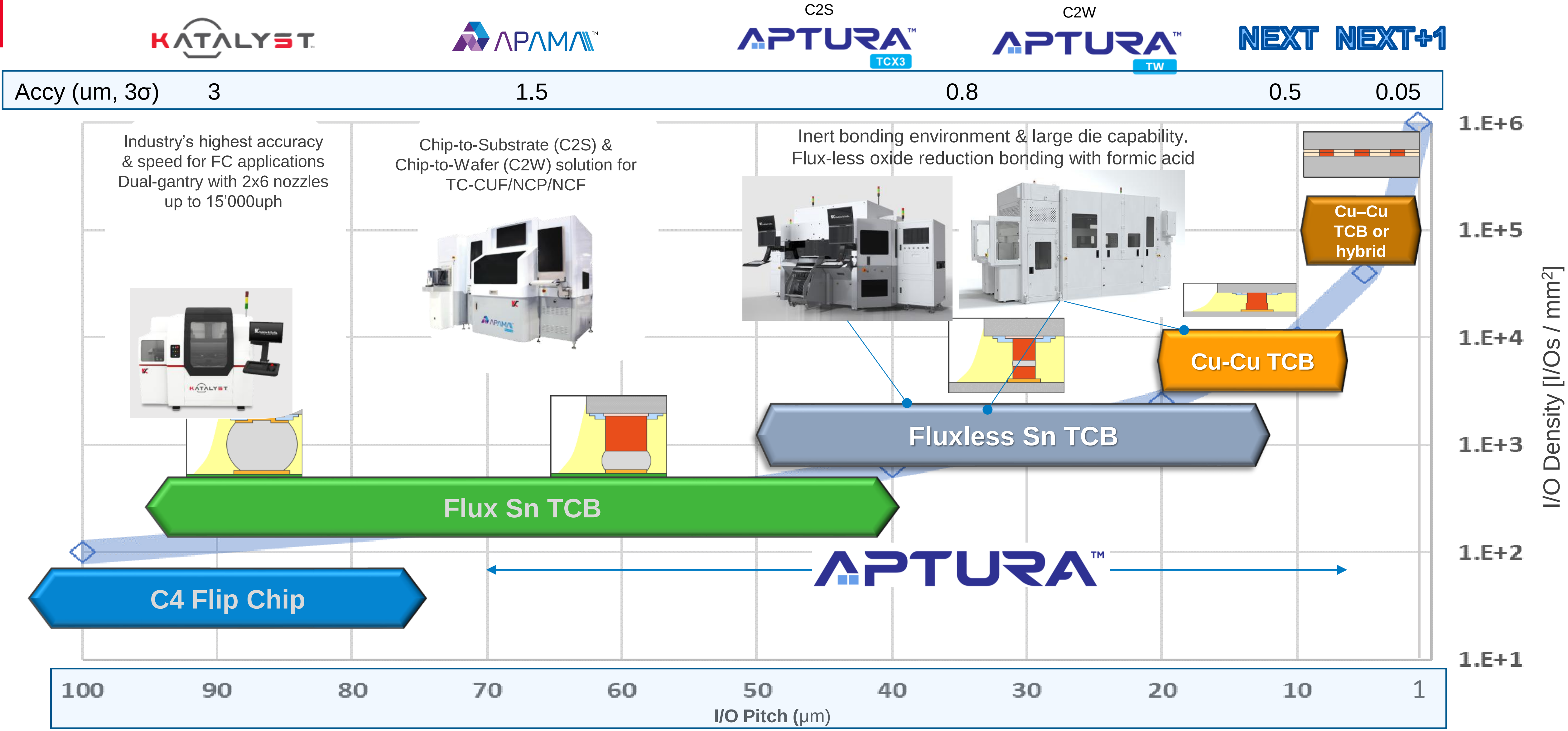
March 05, 2025

Kulicke & Soffa®

Outline

- Formic acid based fluxless TCB
- Mechanism of Cu-Cu TCB
- Post TCB underfill – variants
- Cu-Cu TCB with pre-applied underfill
- Material prep., Bonding Bonding results
- Summary

K&S Flip Chip and TCB Solutions

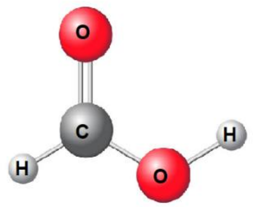


APTURA™ – 3rd Generation TCB Tool

- Specifically designed for the most demanding TCB processes
  - Large die, ultra-fine pitch ~10um, multi-die (chiplets)
- High throughput dual head bonding
- 1mm to 70mm die size range
- Accuracy 0.8µm 3σ XY (extending to 0.5 µm
- Active co-planarity control with non-contact measurement
- Advanced TCB process options
  - Inert environment bond chamber < 100 ppm O2
  - K&S patented flux-less bonding

Sn and Cu Oxide Reduction via Formic Acid Vapor

- Molecular formula: HCOOH
- Example of Sn and Cu oxide-state reduction



Formic acid monomer

Step 1: Cu (II) formate creation (100 °C < T <180 °C)

$$CuO_{(s)} + 2HCOOH_{(g)} \longrightarrow Cu(COOH)_{2(s)} + H_2O_{(g)}$$

Step 2: Sn and Cu (II) formate decomposition (T > 200 °C)

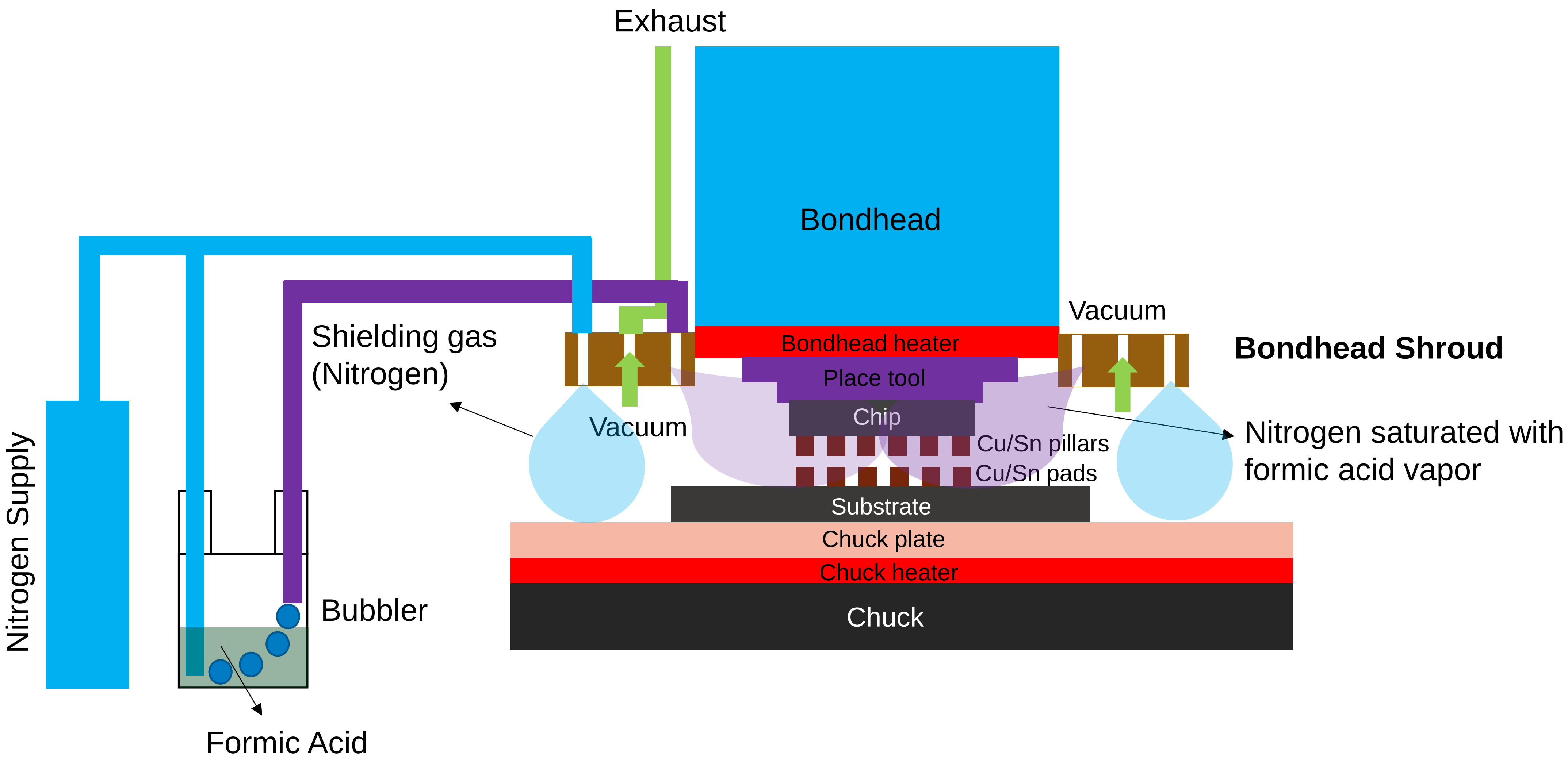
$$Sn(COOH)_{2(s)} \longrightarrow Sn_{(s)} + 2CO_{2(g)} + H_{2(g)}$$

tin layer remains on solder surface

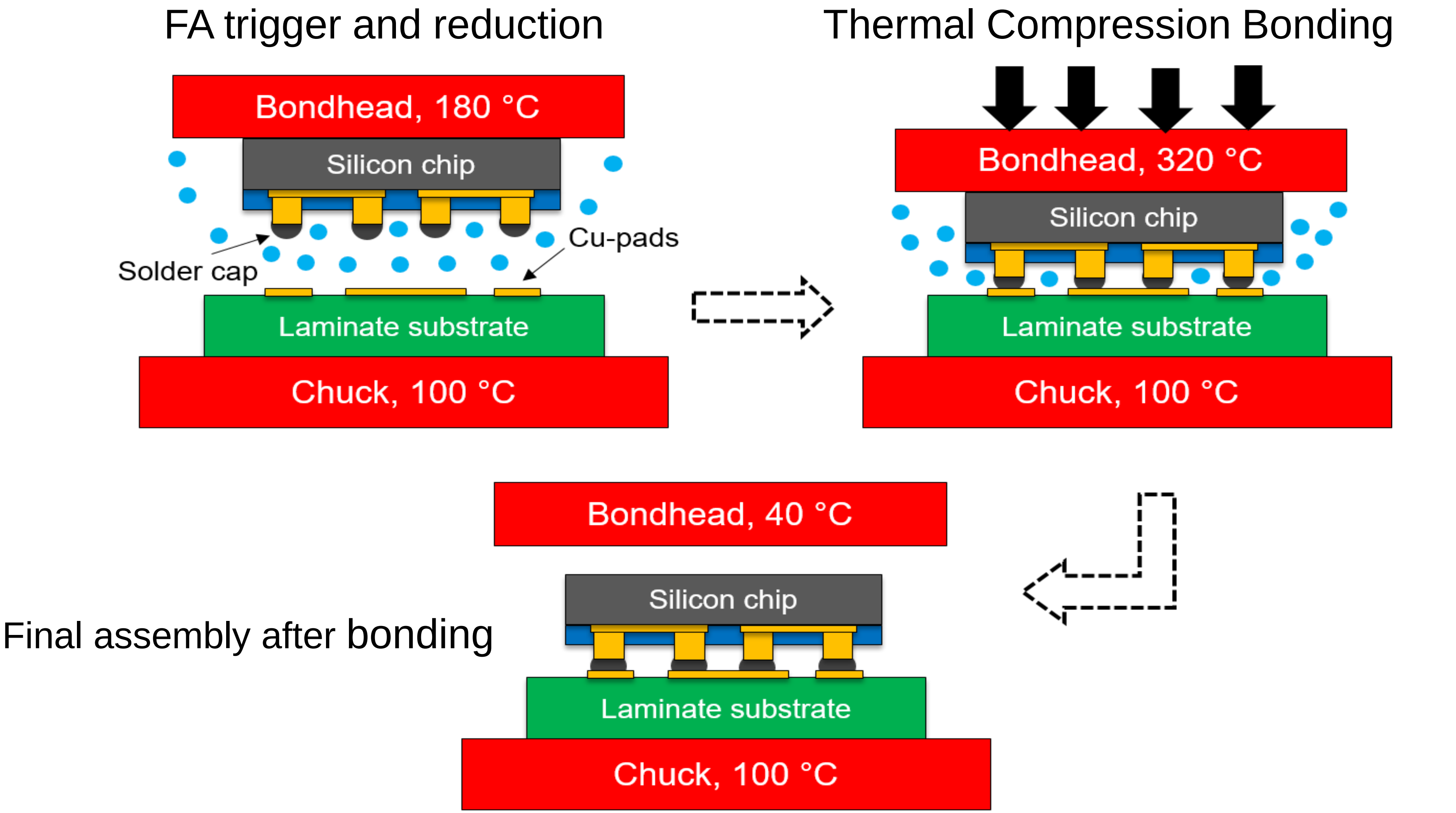
carbon dioxide and hydrogen byproducts

$$Cu(COOH)_{2(s)} \longrightarrow Cu_{(s)} + 2CO_{2(g)} + H_{2(g)}$$

Schematic of a Formic Acid Delivery System



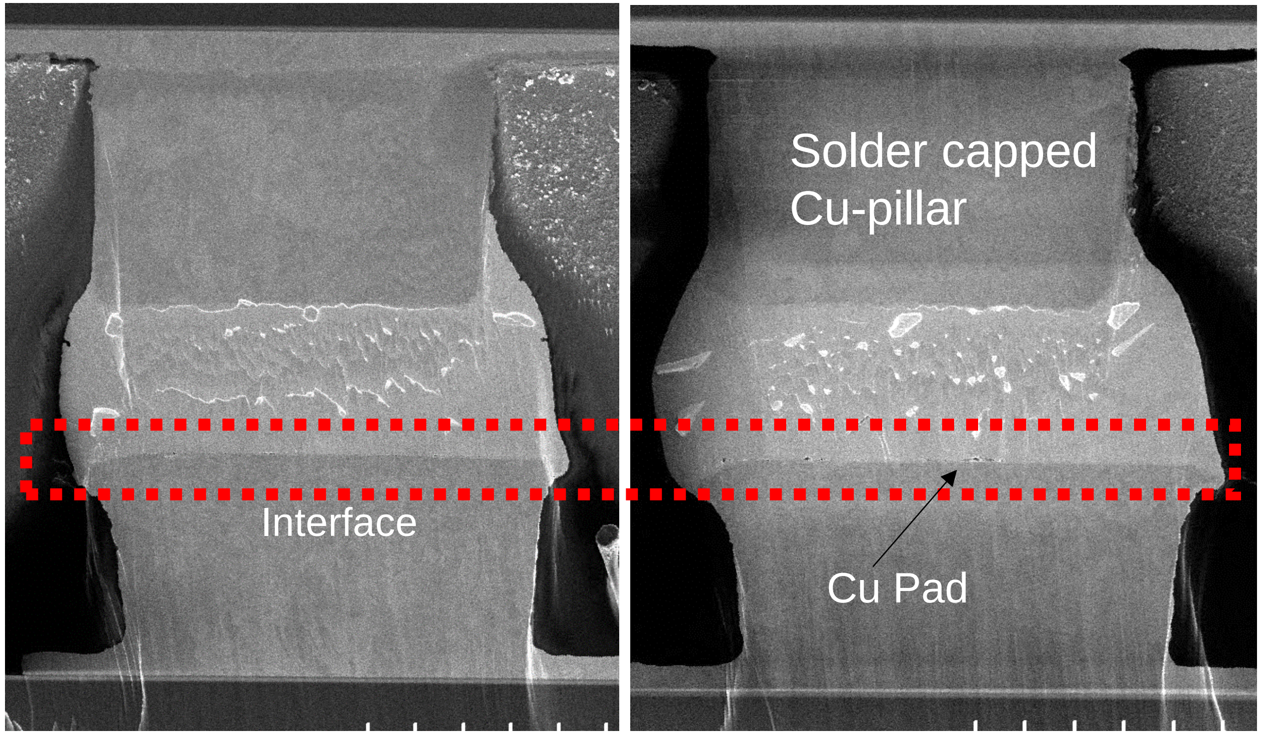
In-Situ Formic Acid TCB Process Flow



Fluxless Cu-Solder Bonding in Inert Environment after 45 min Heat Exposure

- Pre-bond FA vapor cleaning time 1 sec

- Cu surface was held at 150 C in nitrogen for 45 min before bonding process as a robustness test
- Oxygen concentration in nitrogen chamber was less than 100 ppm
- Localized FA supply gets rid of any existing copper oxides prior to bonding step allowing for fluxless bonding
- Only fluxless ultra fine pitch process in high volume production



Extension of Fluxless Process to Fine Pitch Cu-Cu Bonding

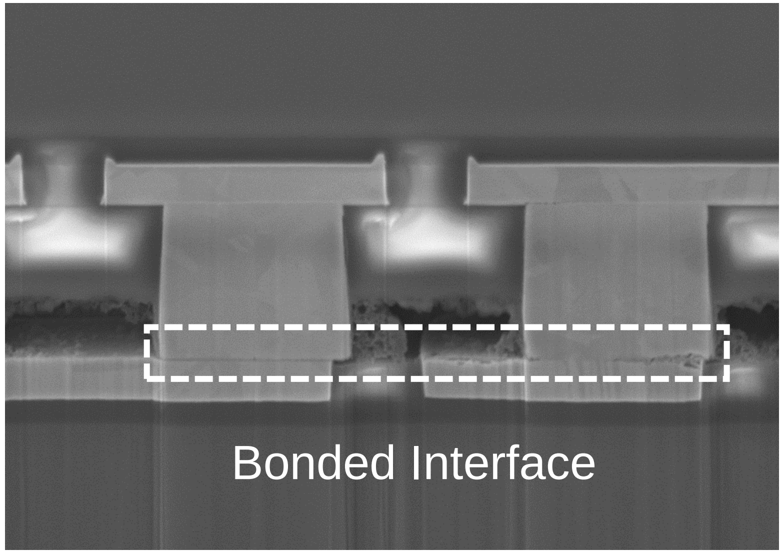
- Direct Cu-Cu bonding
  - Allows sub-10 µm interconnect pitch
  - Cu exhibits superior electrical and thermal properties
- Sub-10 µm pitch scaling is challenging
  - Solder extrusion & bridging
  - Brittle inter-metallics formation
- Formic acid vapor-based copper oxide reduction
  - Reduces copper oxides and allows pure metal contact

High Density Cu-Cu Interconnects : K&S-UCLA Partnership

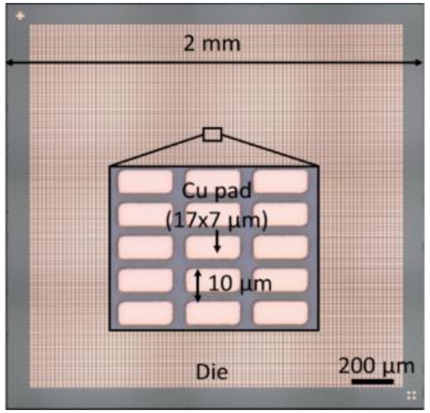
- Cu Pillar pitch: 10 µm
- Total contacts per chip: 36,000
- Roughness on both pillar & pad : < 2 nm
- Test vehicles fabricated by UCLA
- 3 um gap between die

UCLA

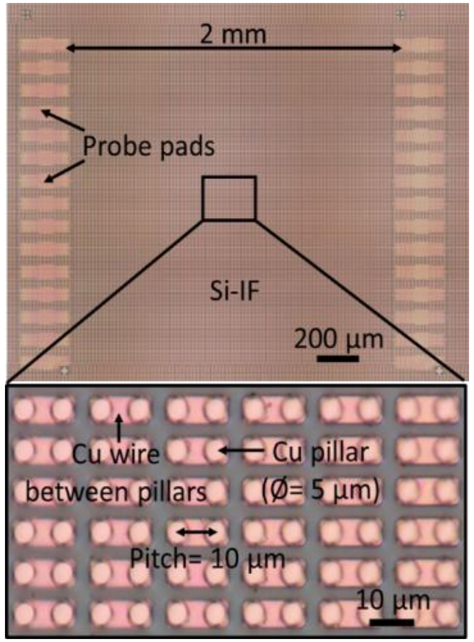
CHIPS
CENTER FOR HETEROGENEOUS INTEGRATION AND PERFORMANCE SCALING



Chip with bond pads

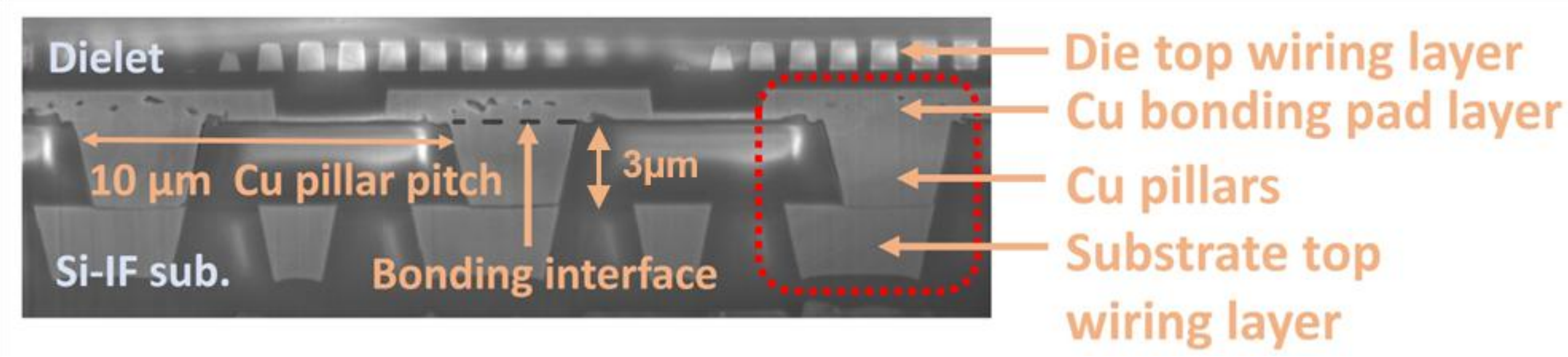


Substrate with Cu-pillars



Cu-Cu TCB Work with UCLA Chips

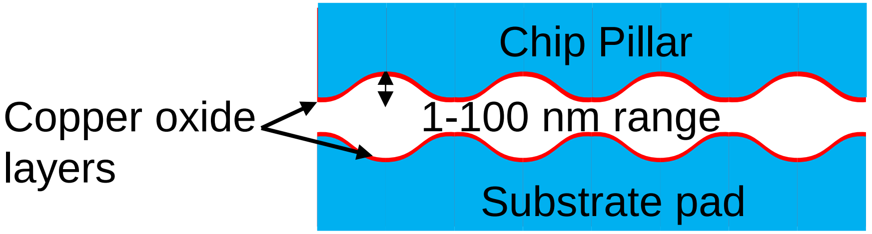
- UCLA / K&S10µm pitch Cu-Cu bonding (3µm gap between bonded devices)
- Performed Cu-Cu TCB to attach the chip, followed by a gang anneal process
- ALD process was used to coat (passivate) the exposed pillars in the 3 um gap
- Accelerated stress tests (HAST) at 130 °C and 85 % relative humidity for 96 hours (JEDEC JESD22-A118 test condition A) and saw no electrical resistance change



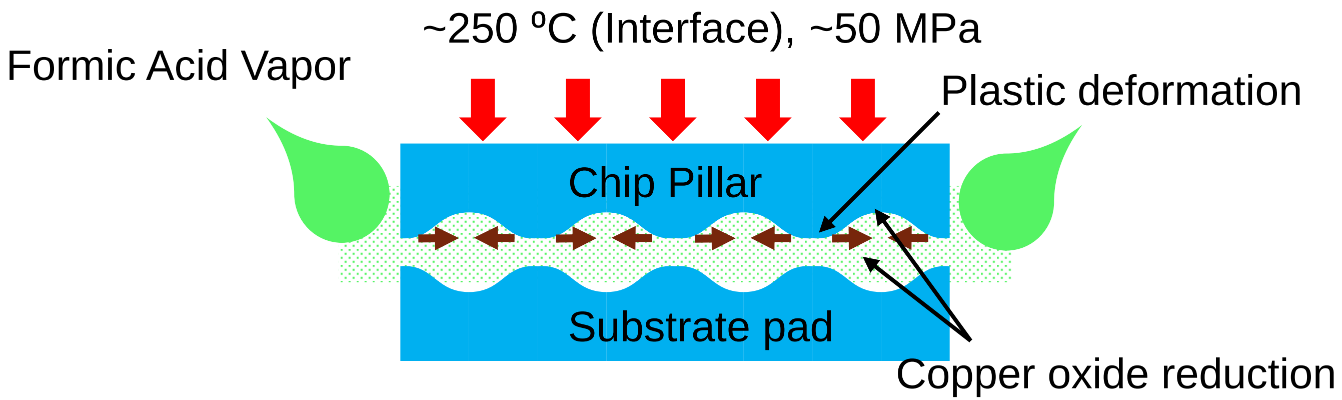
A CMP treated copper pillar attached to CMP treated copper pad (Courtesy: UCLA CHIPS)

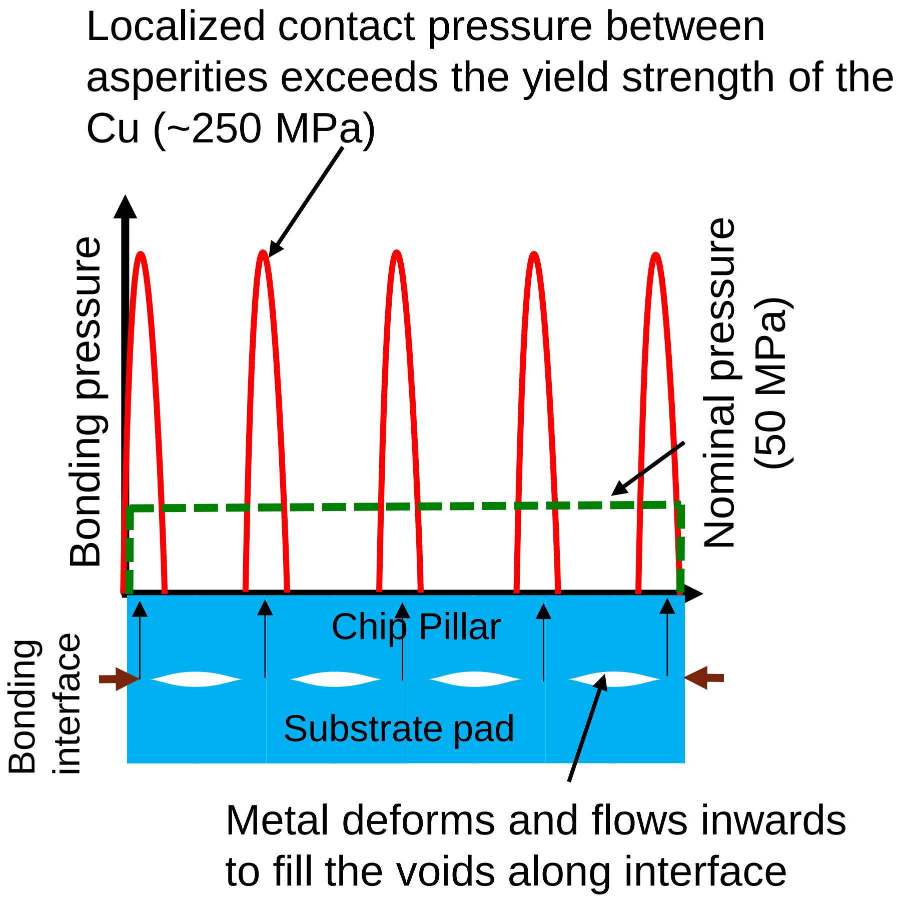
K. Sahoo, H. Ren and S. S. Iyer, "A High Throughput Two-Stage Die-to-Wafer Thermal Compression Bonding Scheme for Heterogeneous Integration," 2023 IEEE 73rd Electronic Components and Technology Conference (ECTC), Orlando, FL, USA, 2023, pp. 362-366, doi: 10.1109/ECTC51909.2023.00067

Mechanism of Cu-Cu TCB with In-situ Oxide reduction



TCB Process with In-situ Oxide Reduction





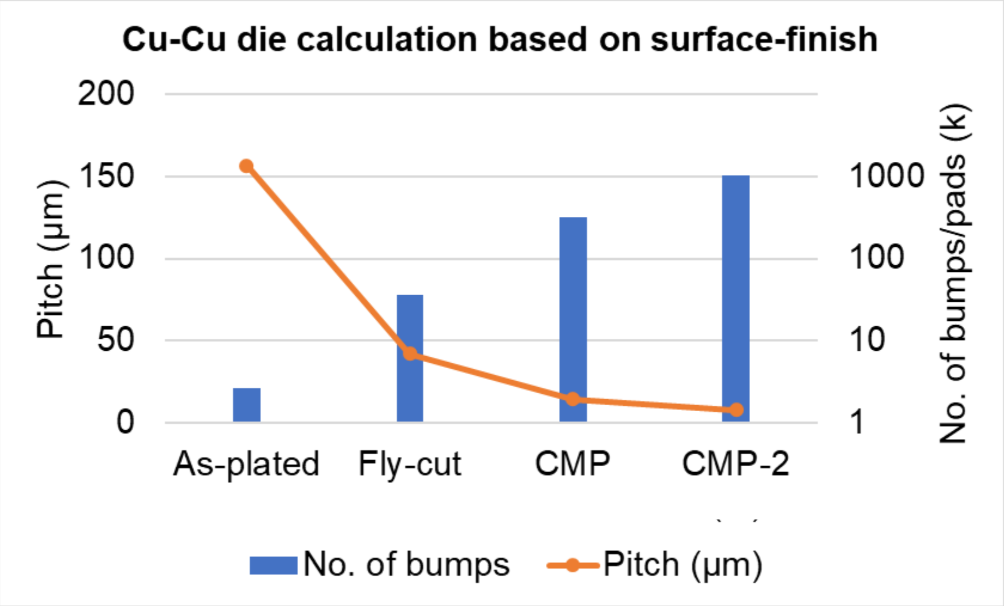
Smoother surface finishes i.e. CMP planarization, will require less pressure to achieve a good bond!

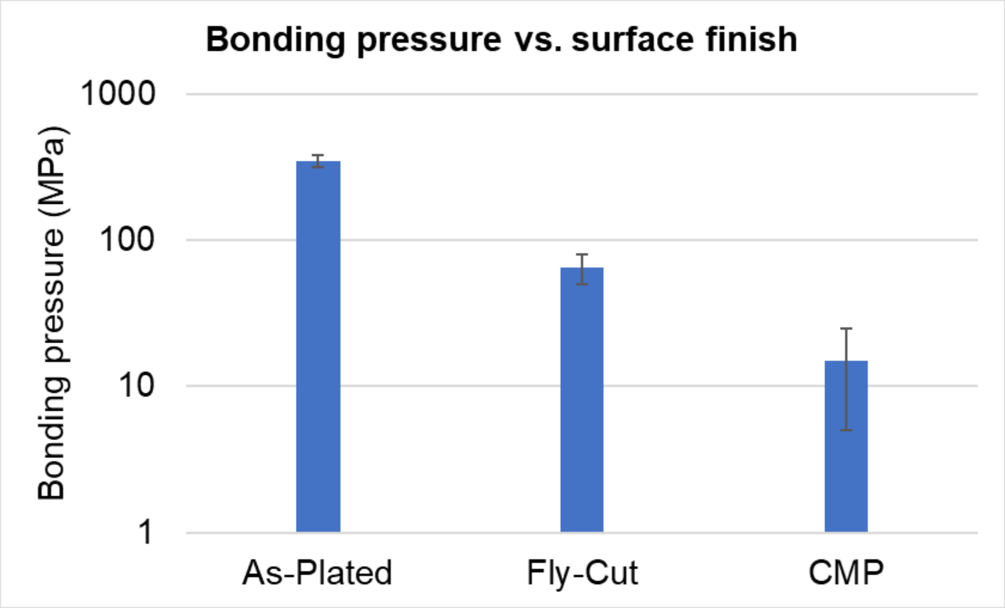
1 MegaPascal (MPa) = 1 Newton per Square Millimeter

Role of Cu-pillar surface roughness

- Bonding pressure and surface roughness are important factor for successful bonds.
  - APTURA™ bonder force limit: 500N
- Example applications of bonding pressure vs bump size and pitch for an 8×8mm² die

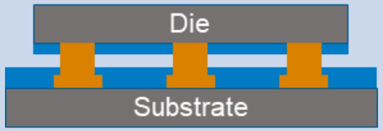
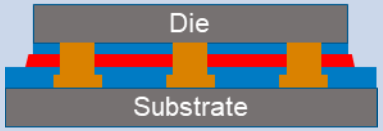
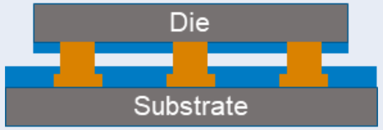
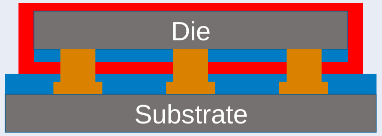
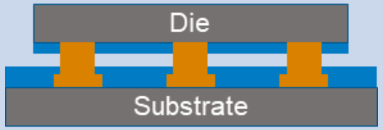
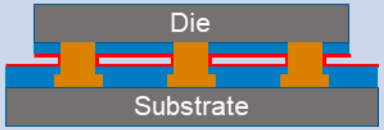
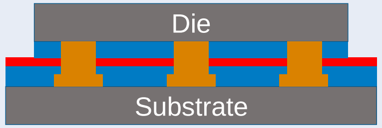
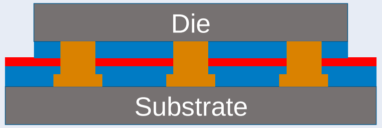
	Pressure (MPa)	No. of bumps	Pitch (µm)	Bump dia (µm)	Cu coverage
As-plated	390	2608	157	25	2%
Fly-cut	80	36217	42	15	10%
CMP	25	318310	14	8	25%
CMP-2	20	1018592	8	4	20%





Underfill Options for Cu to Cu Reliability

- Strong Cu to Cu bonds do not need underfill for package strength only moisture protection

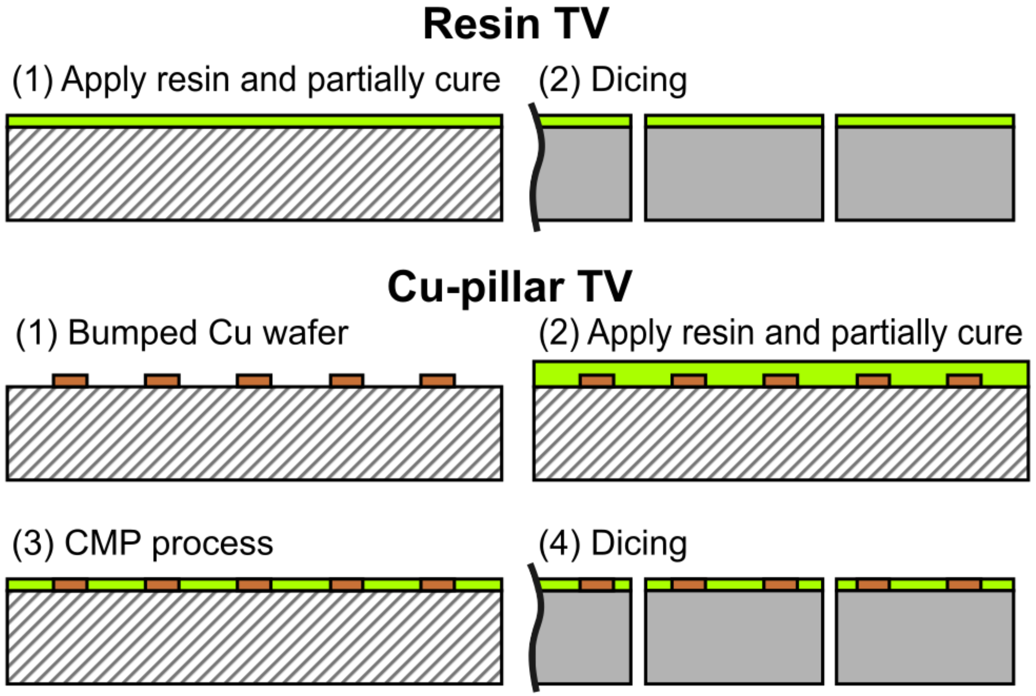
Option	Comments	As Bonded State	After Downstream Processing
Capillary Underfill (CUF)	Limited capability to flow into narrow gaps – new underfills being developed		
Mold Underfill (MUF)	Limited capability to flow into narrow gaps		
Passivation (e.g. ALD)	Provides environmental protection		
Organic Dielectric	**Promising solution and the focus of the paper**		

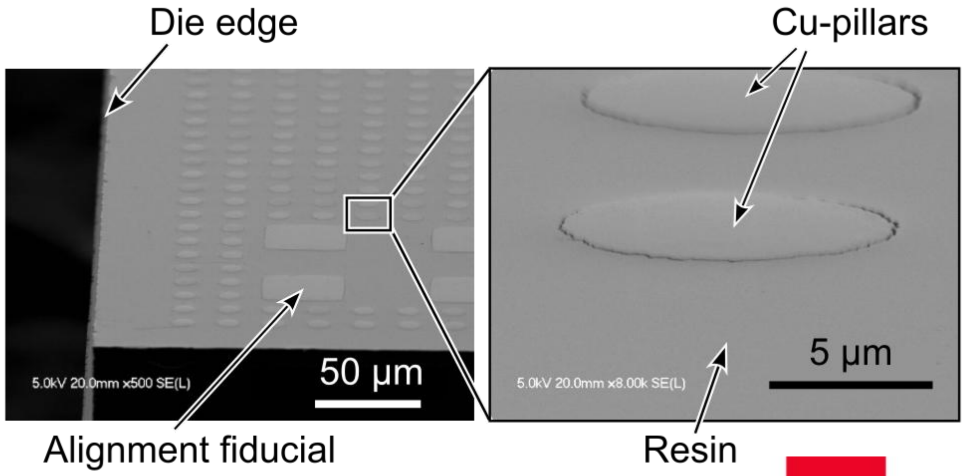
Material preparation

- Pre-applied underfill (Resonac corporation):
  - Partially cured resin (LB-2110)
  - CTE: 33ppm/K || Full-cure temperature: 250°C
  - Resin thickness on test vehicles: 4µm

Test vehicles

1. Resin-Resin bonding characterization
   - Die size: 4×4mm^2 die
2. Cu-pillars with pre-applied underfill (resin)
   - Die size: 5.1×5.1mm^2
   - Pillar diameter: 10µm || Pitch: 20µm
   - Surface is CMP to obtain low roughness ($R_a \approx 0.5$nm)
   - Cu-pillar height: 5µm || Post-CMP protrusion: ~30nm

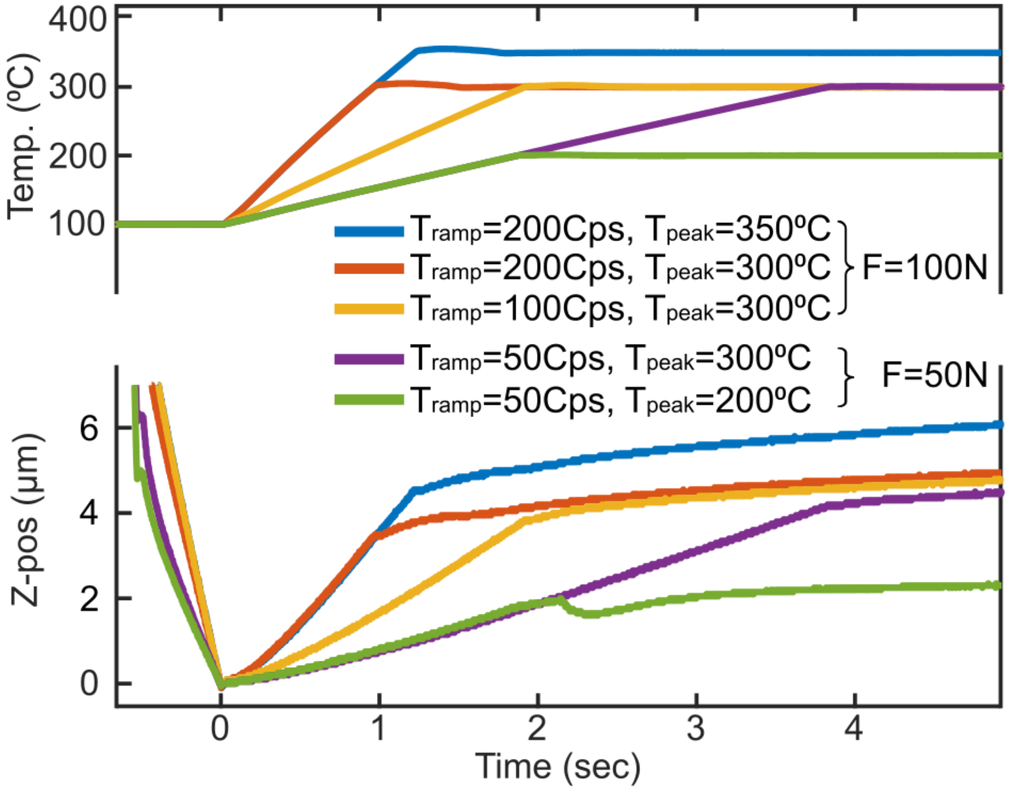


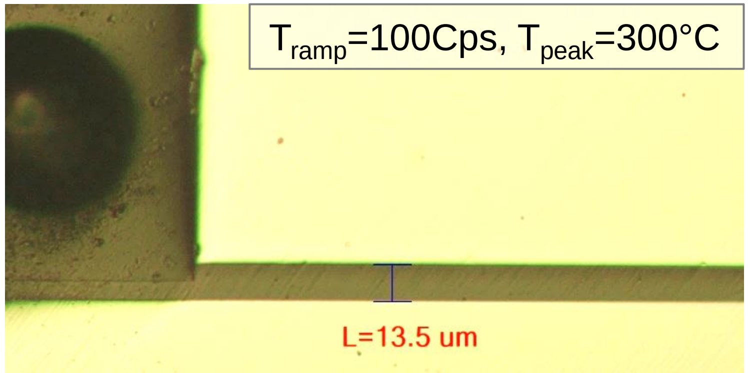


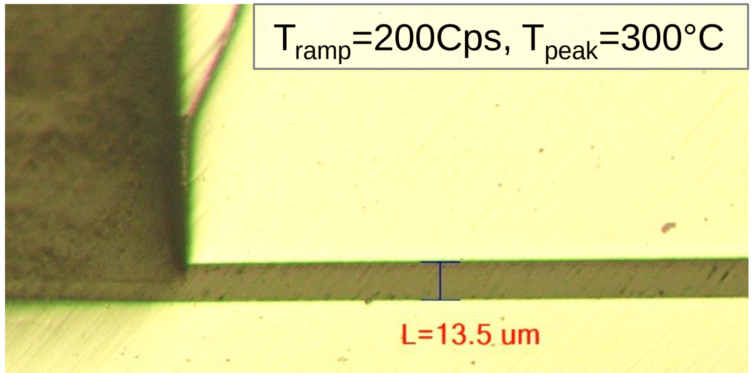
Underfill-only bonding results

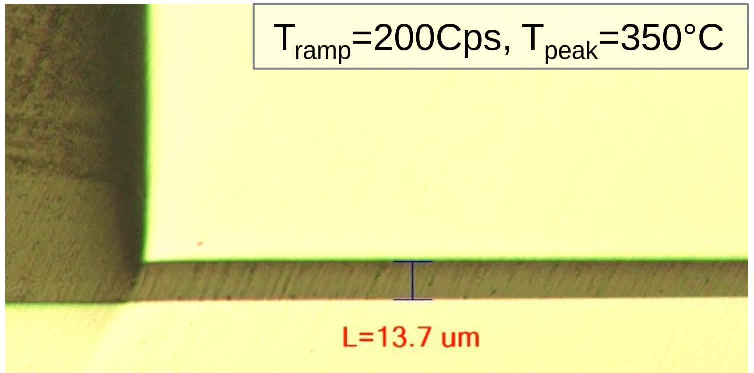
- Variable parameters for bonding DOEs
  - Temperature ramp
  - Peak temperature
  - Force (Bonding pressure)

- Bond profiles characterize resin expansion
  - Required during Cu-Cu bonding to close the gap as protrusion of Cu-pillars is ~30nm





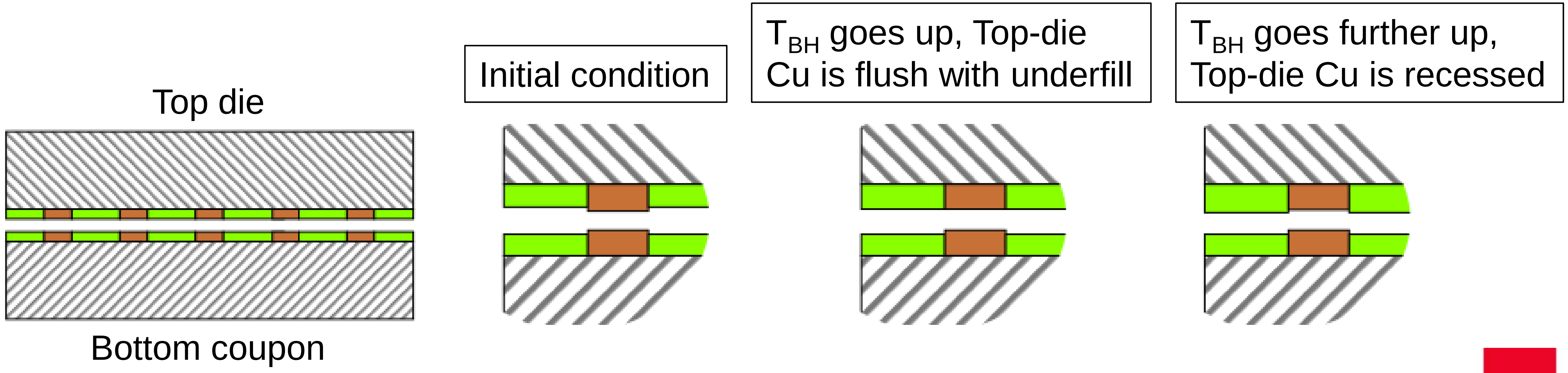




Cu-Cu TC bonding

- Objective
  - Attach the resin and the Cu pillars in a single step
  - Ensure no gap in the bonded interface

- Mechanism of single step bonding
  - Apply sufficient pressure to squeeze out any variation in the Cu-pillars or possible foreign particle
  - Adjust the temperature such that the resin and Cu-pillars of die can mate with those on the coupon

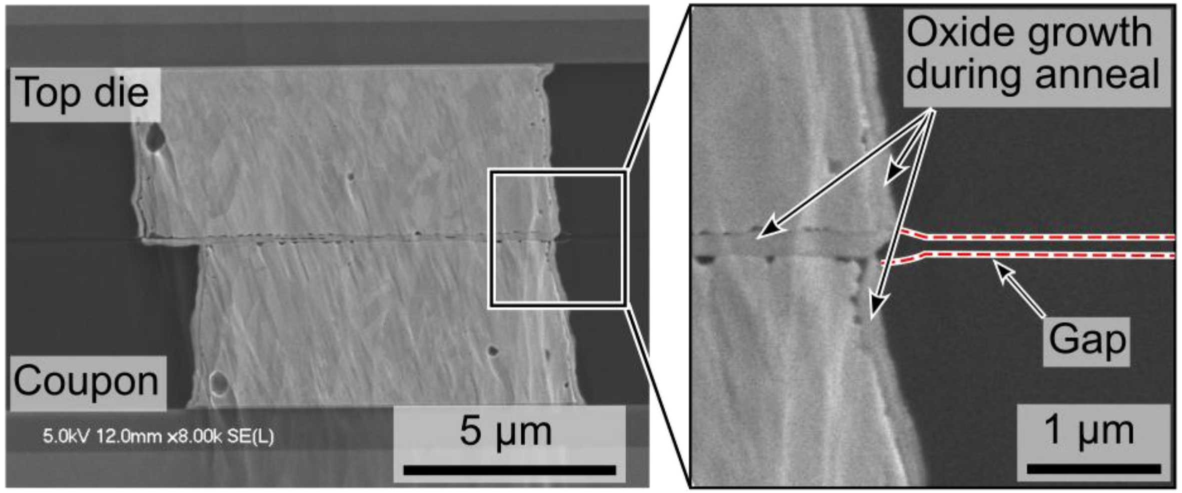


Cu-Cu TC bonding results

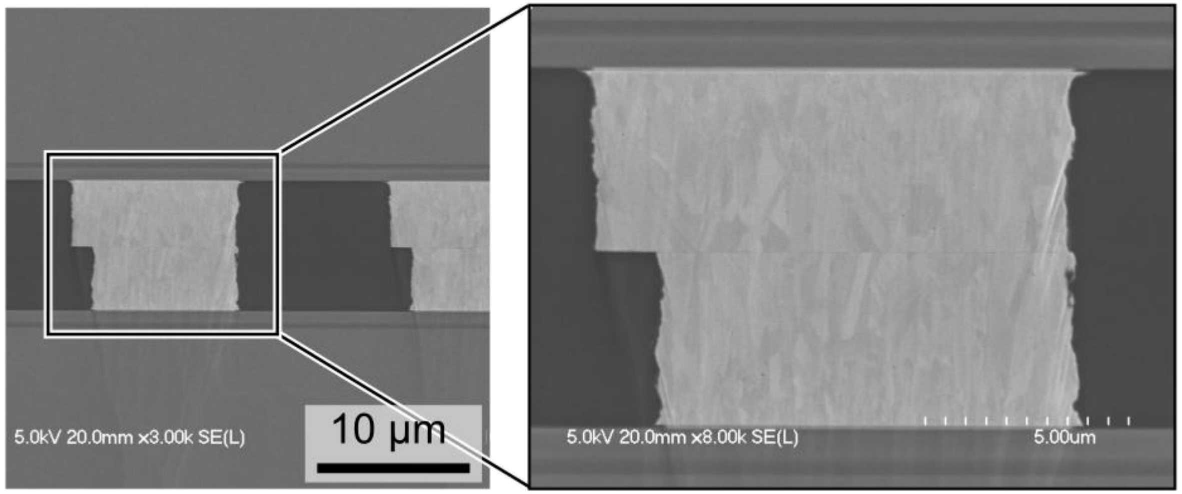
- DOE legs with different bond chuck temperatures
  - 120°C → hairline gap remains in the resin allowing oxygen to enter and form CuO
  - 160°C → no gap visible, both pillars and resin are attached
  - 180°C → prominent gap in the Cu-pillars

- These samples annealed for 2 hrs at 250°C after bonding

T_{stage}=120°C

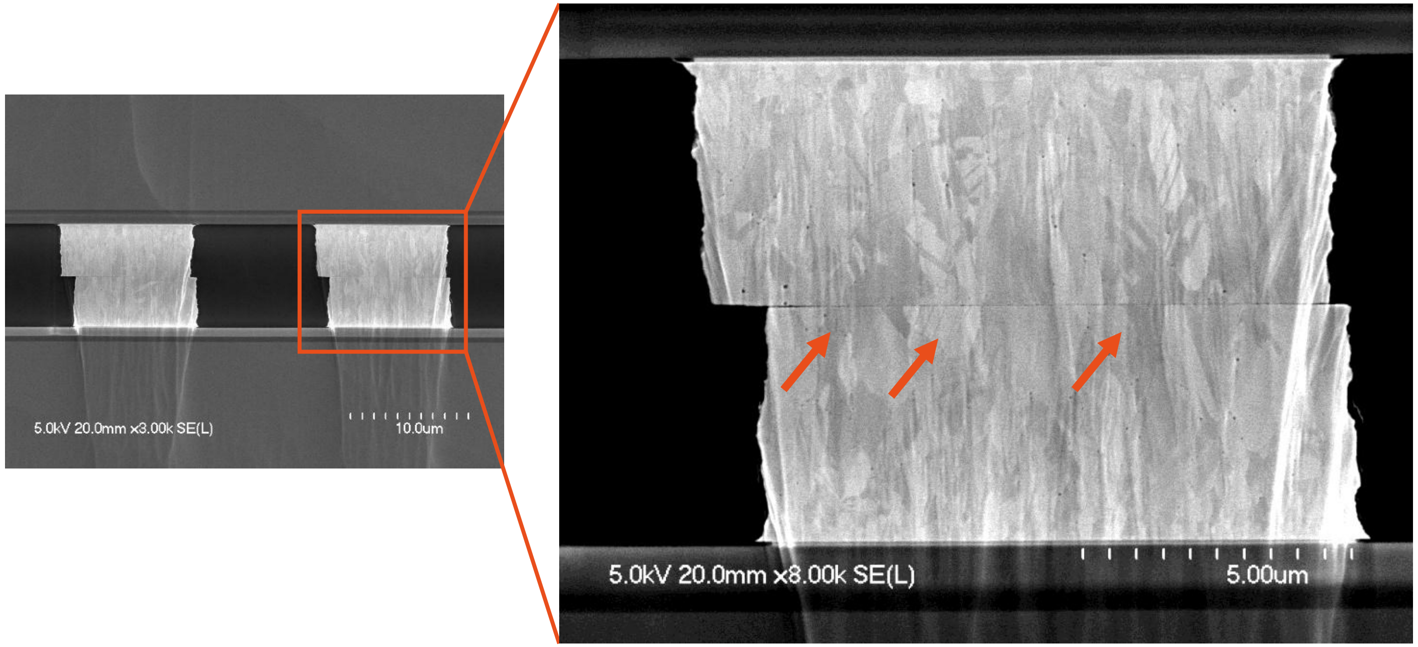


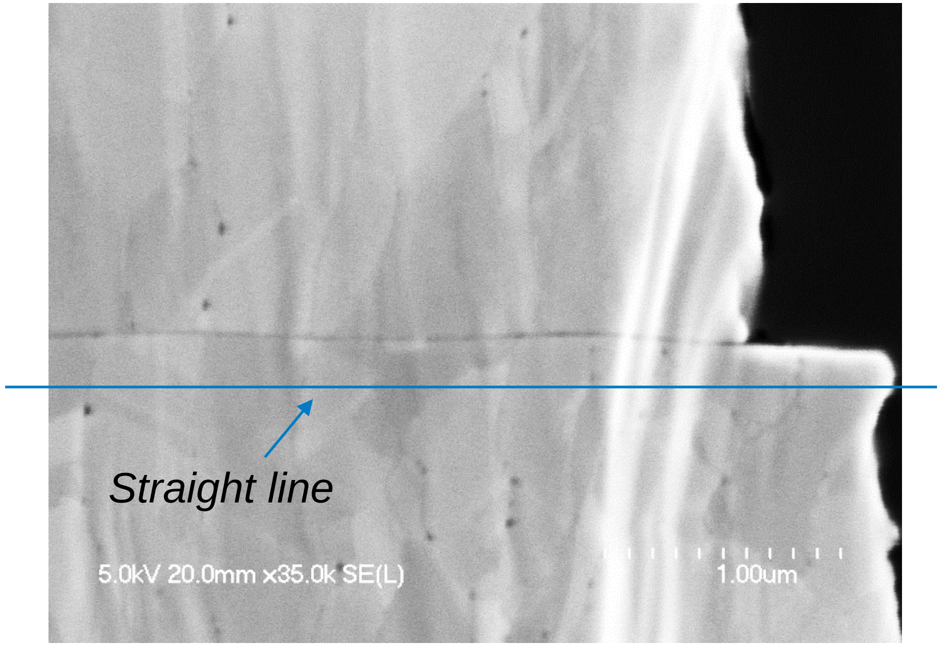
T_{stage}=160°C



Cu-Cu TC bonding results

- Longer anneal process → 250°C for 8hrs
  - Pillars show **grain-growth** across the bonded interface
  - The **wavy interface** is a confirmation of good joint
  - No signs of resin degradation after annealing

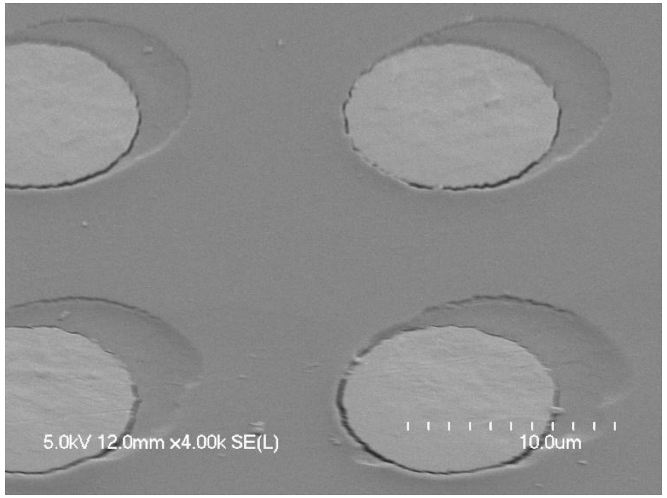




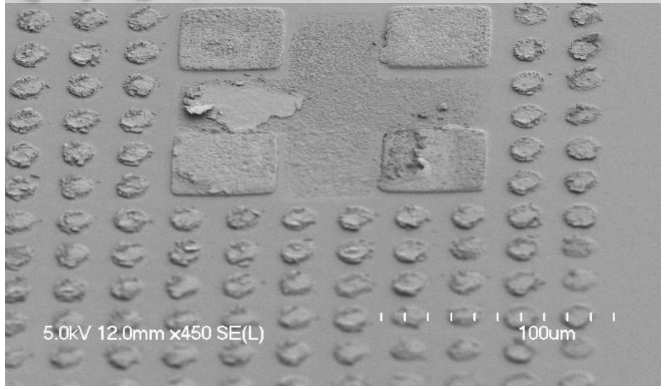
Post-bond shear testing

- Non-annealed samples sheared at the Cu-Cu interface
- Annealed samples broke into pieces

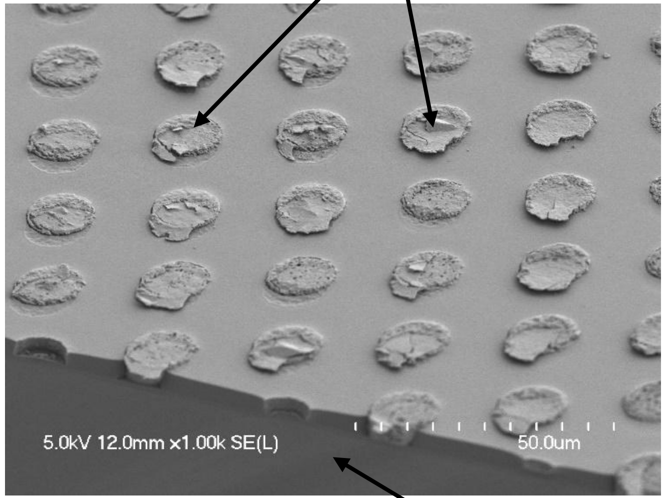
Top die sheared before annealing



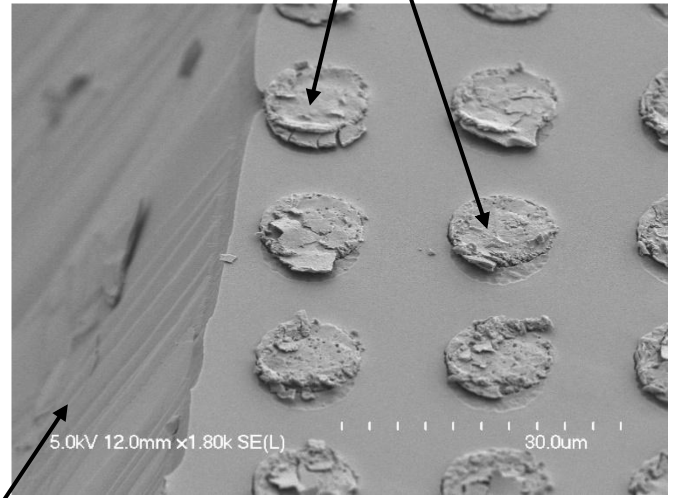
Remaining part of the annealed bottom coupon (top right corner)



Sheared Cu joints



Sheared Cu joints



Broken edge of the die

Summary

- Fluxless in-situ Formic acid vapor-based oxide reduction is in high volume manufacturing for Sn – Sn and Sn-Cu at pitches down to 25 um (with POCs down to 12 um)
- This process is readily applicable to Cu-Cu TCB with no equipment modifications
- TC bonders developed by K&S can extend fluxless TCB to < 10 um pitch Cu to Cu applications, thanks to the high placement accuracy
- There are various methods of protecting the Cu interconnects for rel test
- Pre-applied underfills that also create a bonded interface such as the materials from Resonac are being developed for this application
- This work demonstrates successful Cu-Cu interconnections using pre-applied underfills
- Cu to Cu TCB offers a low cost alternative to Hybrid bonding and can extend advanced packaging technology to consumer applications

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