Key Enabling Materials for 3D-IC Fabrication and Device Performance

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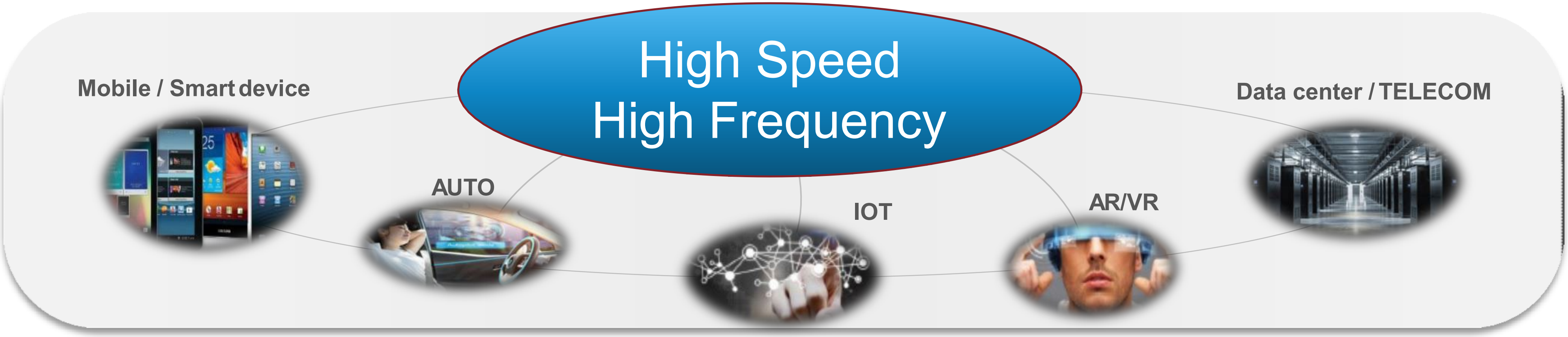
Global Market Trend for Devices and Packaging



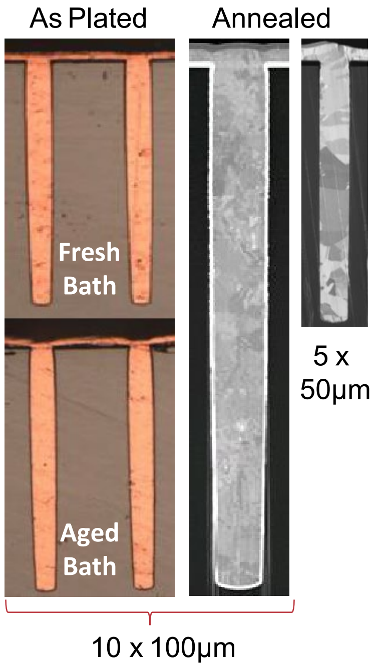
Faster | **Thinner** | **Denser** | **Lower Power**

Bump Pitch
Bump Diameter

>80um | 40-80um | 20-40um | <20um

Key Challenges to Enabling 3D-IC and Hybrid Bonding

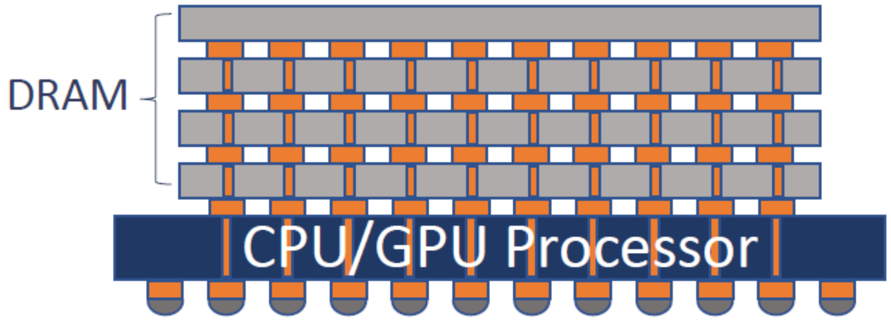
- TSV formation (Via Middle)
  - Photoresists with good resolution and superior etch selectivity
  - Cu plating with fast plating rate, minimal overburden, and long bath life
- Copper pillar and RDL plating
  - Chemical stability of photoresists to plating baths and pattern resolution,
  - EP Cu pillar with copper purity, crystallite size and grain orientation
- **Polymer adhesive layer**
  - Planar coating and polymer reflow over topography
  - Rheology modified after soft cure: non-tacky at RT for CMP and good flow at bonding temperature
  - Controlled removal rate of both polymer and copper
- Hybrid Bonding process
  - Low temperature for Cu-Cu joining and polymer bonding
  - No reaction of polymer with gas phase (formic acid) and liquid no residue fluxing agents
  - Use conventional Flip Chip bonding processes



Achieving Reliable 3D-IC and Cu-Cu Hybrid Bonding

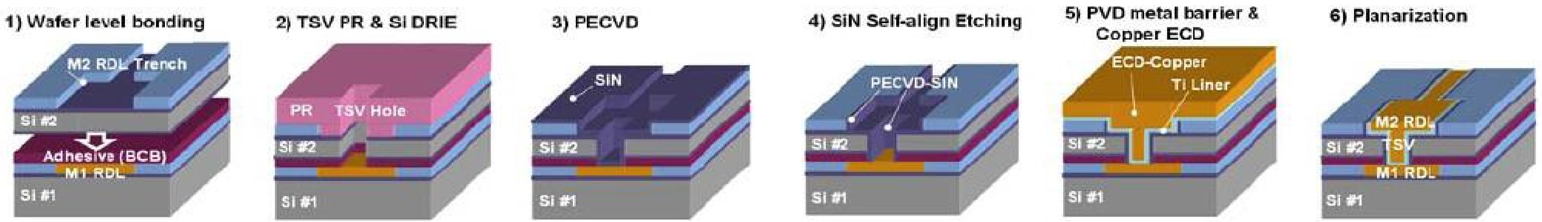
- Micro Electro-Mechanical & Micro Optical devices are currently the two most important applications driving permanent bonding applications.
- 3D-IC will be the driver for market growth in permanent bonding as designers continues to shrink devices to improve performance.
- 3D-IC Bonding Requirements
  - Controlled Rheology and Thermal Stability
  - Alignment Accuracy and Tool Throughput
  - Planar Surfaces and Copper-Copper Bonding
  - High Yield / Lower CoO
- Bonding Approaches
  - Anodic / Si Direct / Eutectic / **Adhesive /Hybrid**
- Adhesive Bonding Advantages
  - Low Bonding Temperature / High Bond Strength
  - CMP Planarization / Adhesive Reflow / Lower CoO

3D-IC Structure

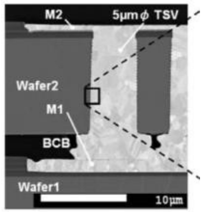


Proposed Integration Schemes for C2C / C2W / W2W Bonding

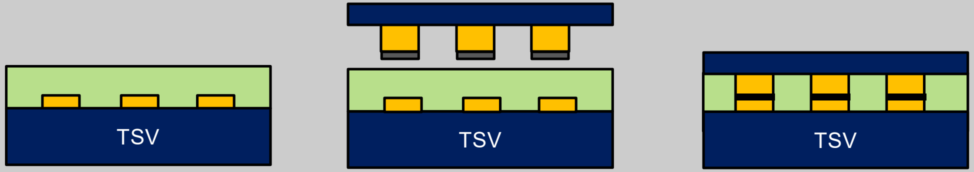
Via Last Process: WoW Consortium IITC 2012



5µm TSV

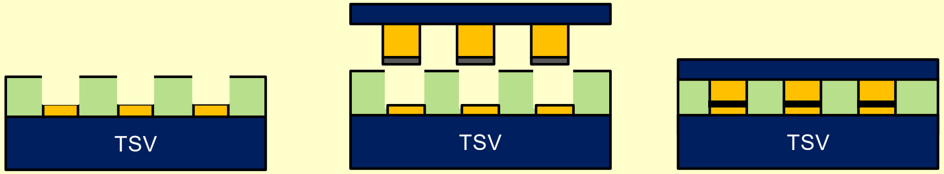


NCP/NCF Process



1) Coating — 2) Alignment — 3) Bonding

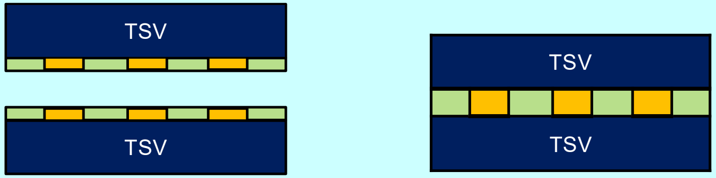
Photo Patterned



1) Photopattern Dielectric — 2) Plasma Clean — 3) Align and Bond

Hybrid Bonding
Cu-Cu or Cu-Sn and Polymer Adhesive

1) Coating — 2) CMP Planarization

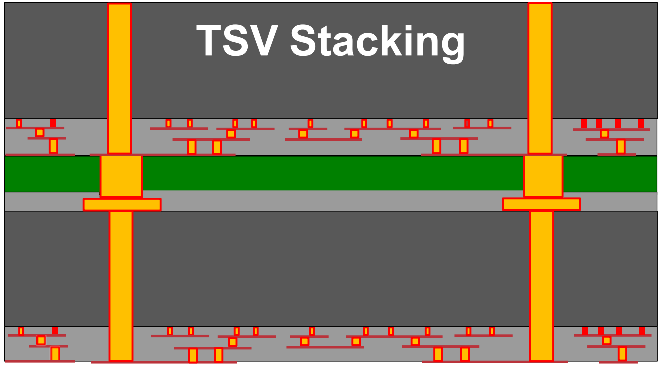


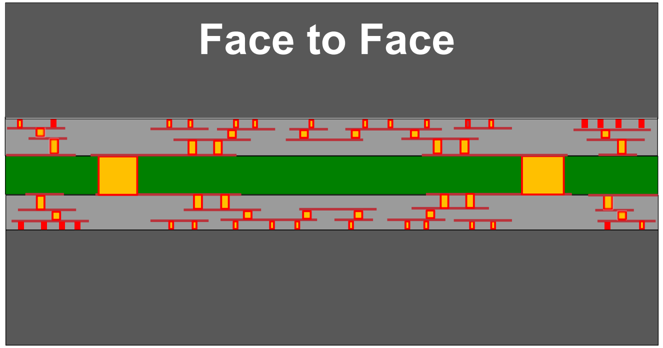
3) Alignment & Flux — 4) Bonding

DuPont E&I Materials that Enable 3D-IC and Hybrid Bonding

CMP Consumables
- CMP Pads
- Copper Selective Slurries
- Dielectric Slurries
- CMP Cleaning Solutions

Copper Plating
- Cu TSV Plating
- Cu RDL and Pillar Plating
- Sn/Ag, Pure Sn and In Plating
- ENIG and EP Ni Barrier

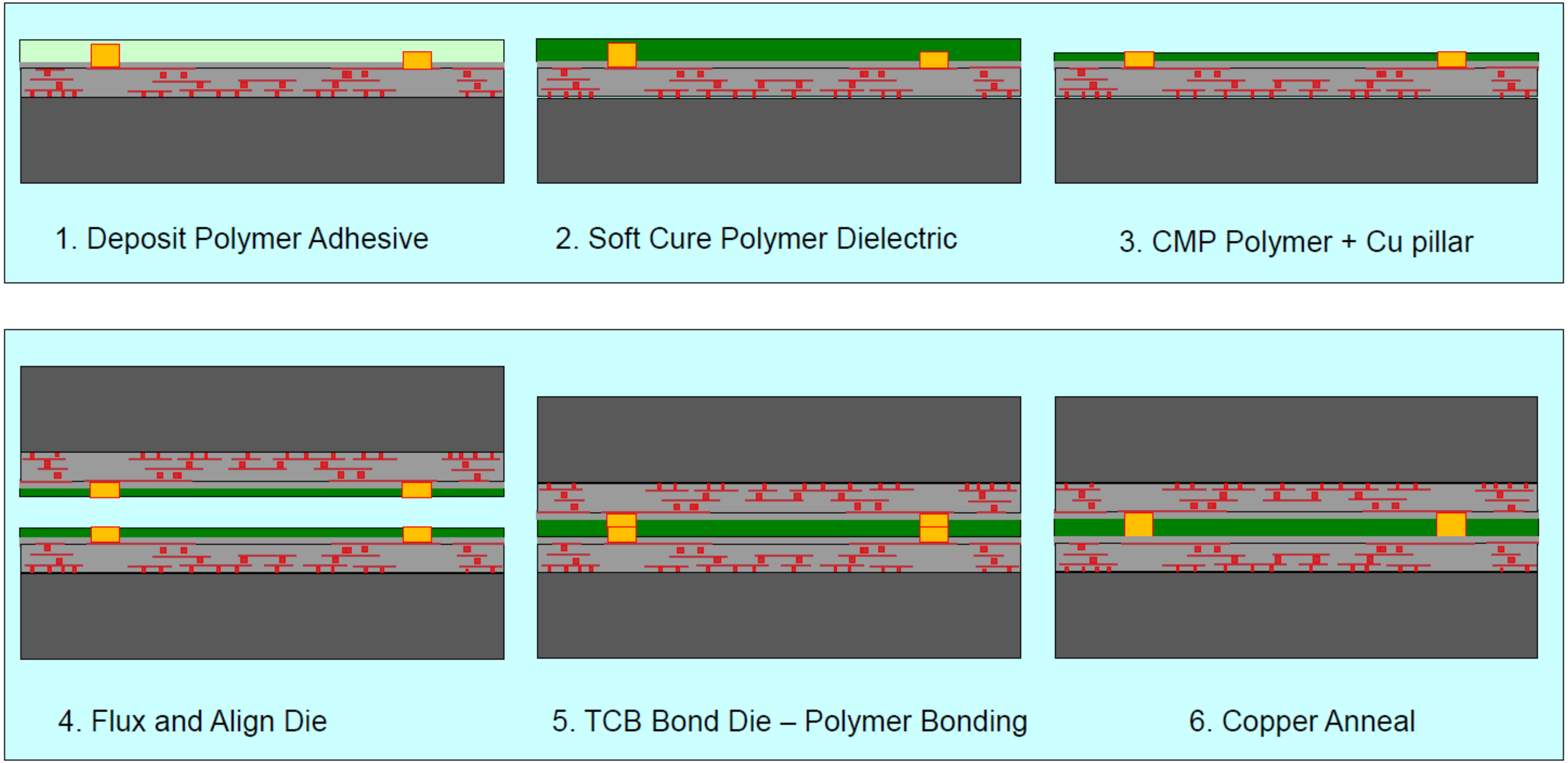




Plating Photoresists
- Spin-on Photoresists
- Dry Film Photoresists
- Chem Amp i-Line

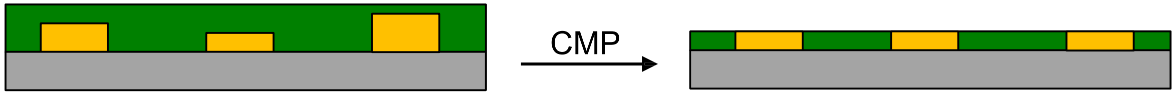
Dielectric Materials
- Polymer Adhesives
- Spin-on Photodielectric
- Dry Film Photodielectrics
- Adhesion Promoters

3D-IC Hybrid Bonding – Integration Process Flow



Uniformity Critical for Hybrid Bonding

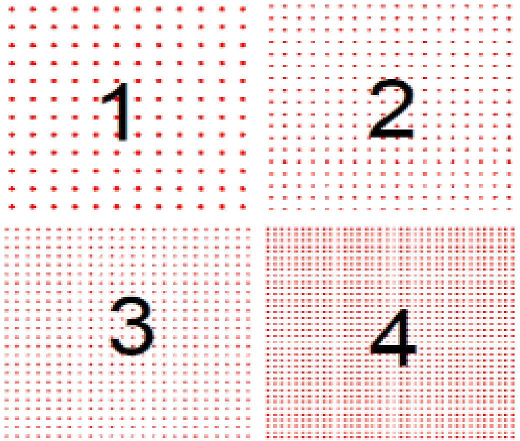
- Very good WID uniformity for pillar height is obtained for each die type with range of 0.3μm or 1.4% total height.
- While range in pillar height was quite low, it is still too large for successful Cu-Cujoining
- *CMP is required to achieve the desired height variance for Cu-Cu joining and polymer bonding*



IMAT BTP1C(200mm)	Quadrant			
Quadrant	1	2	3	4
Bump diameter (μm)	150	100	75	50
Pitch (μm)	600	400	300	200
Bump array (200mm)	12x12	18x18	24x34	36x36
Placement	Lattice	Lattice	Lattice	Lattice
Bump area (%)	4.5%	4.5%	4.5%	4.5%
Avg Cu Pillar Ht (μm)	10.0	10.0	9.8	9.6
Range (μm)	0.3	0.3	0.3	0.3
WID Uniformity	1.4%	1.4%	1.4%	1.5%
Copper pillar plating was performed in Cheonan Applications Lab				

Targeted 10 μm

plating thickness

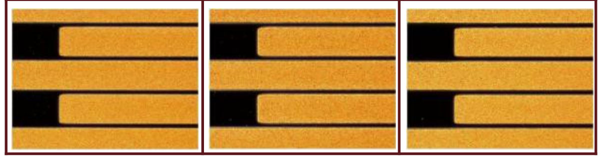


Critical Properties for Polymer Dielectrics

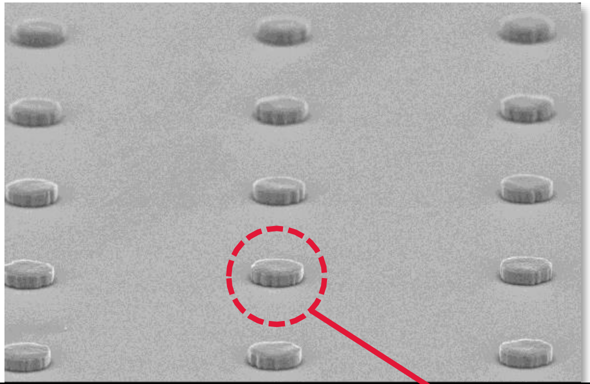
- Good planarization and reflow for coating
- Controllable rheology for CMP using soft cure
- Thermal stability of 350°C stable to PE-CVD
- No outgassing during cure, <1%wt loss/hr at 300°C
- Low dielectric constant, 2.55, tan δ, 0.0014 @ 40GHz
- Low water uptake, <0.2% @ 20°C/85%RH
- Low Cu migration, $<10^8$ ions/cm^2 @200°C
- Stable to gas phase (formic acid) fluxing
- Compatible with Au:Au and Cu:Cu fusion processes

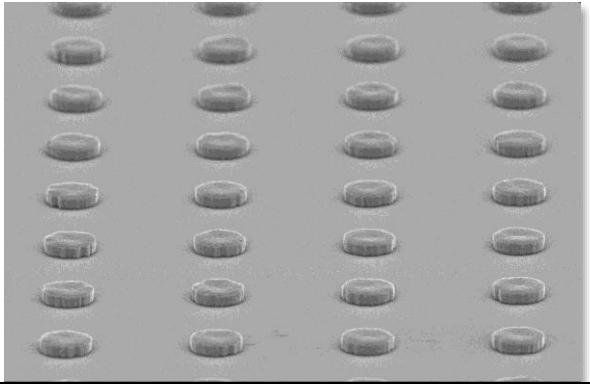
Copper Electromigration

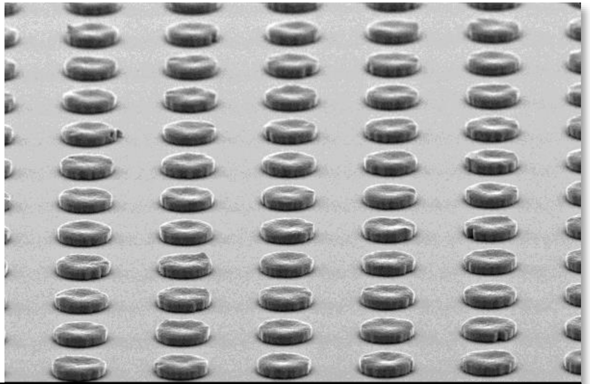
Biased HAST 130°C/85%RH	Bias V	Resistance ohm	
		Initial	After HAST
Polymer Dielectric	3	>1E+12	>1E+12
	5	>1E+12	>1E+12
	15	>1E+12	>1E+12



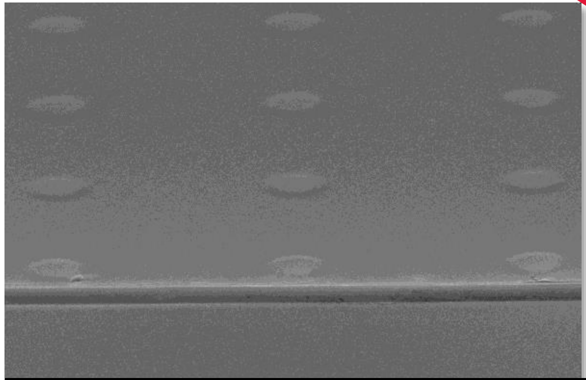
Planar Coating of Polymer Dielectric over Copper Pillars

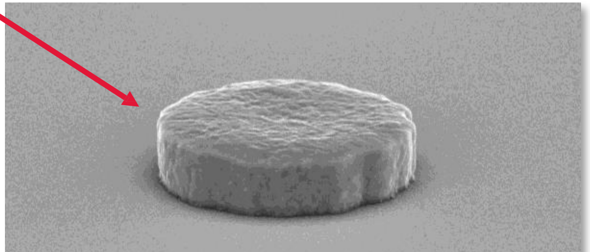




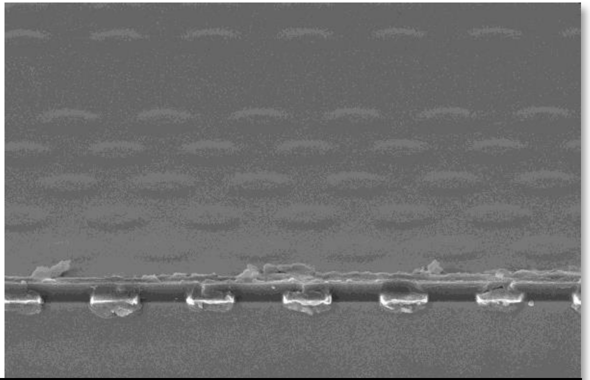


1:4 | 20µm diameter Cu pillar with different pitches | 1:1





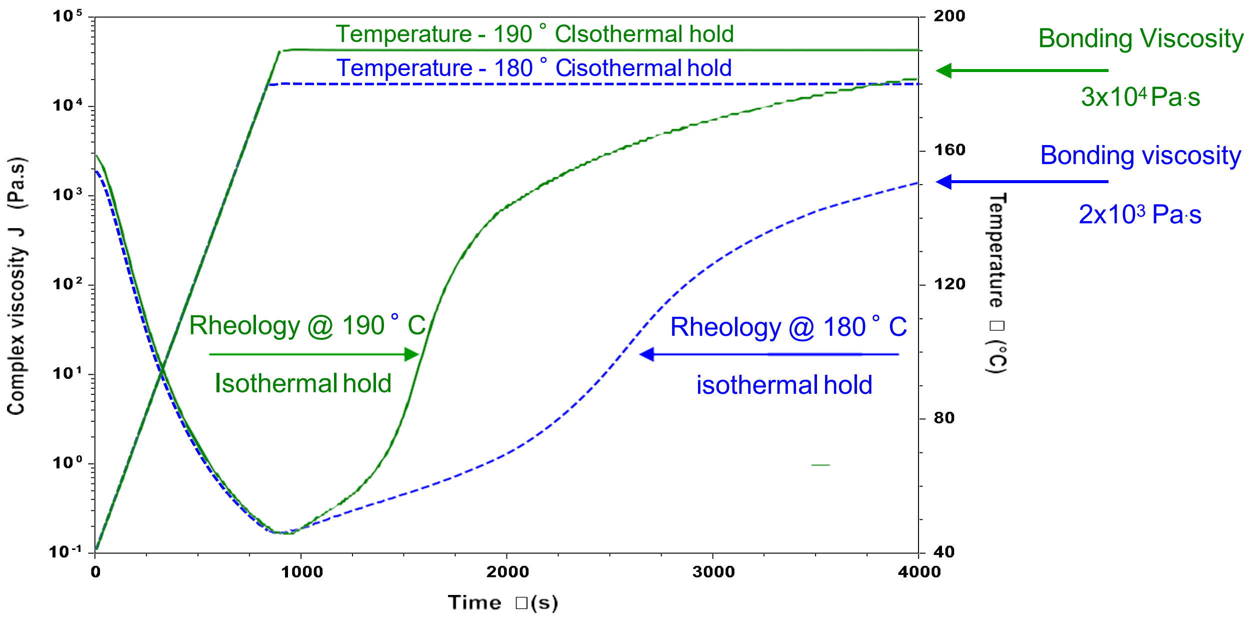
20µm diameter, 5µm height



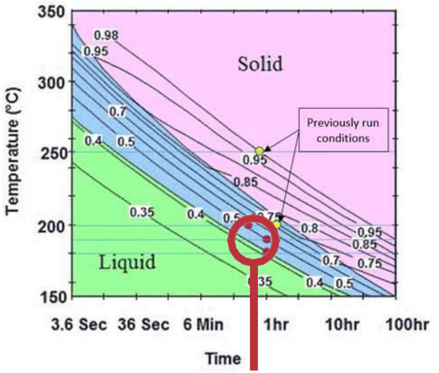
Polymer on less dense Cu Pillar ⟵ Excellent conforming on Cu Pillar ⟶ Polymer on dense Cu Pillar

Adjusting Hardness while Maintaining Flow Enables CMP

- Low viscosity polymer adhesive allows good coating uniformity and planarization over topography
- Soft curing (B-staging) polymer adhesive increases the modulus and hardness at RT to allow CMP
- Partial cured polymer dielectric has viscosity at bonding of 10^3 - 10^5 Pa·s



TTT Diagram
for Polymer Adhesive



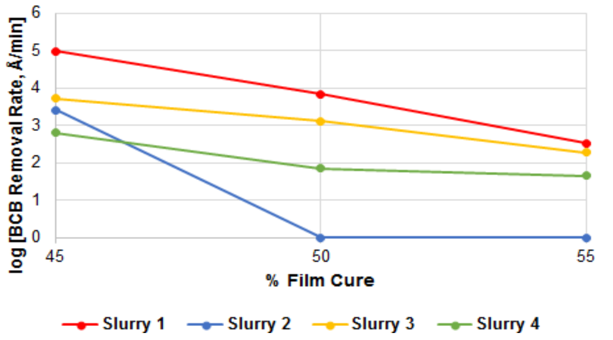
Conditions selected for testing

Removal Rate of Polymer Dielectric Controlled by Soft Cure

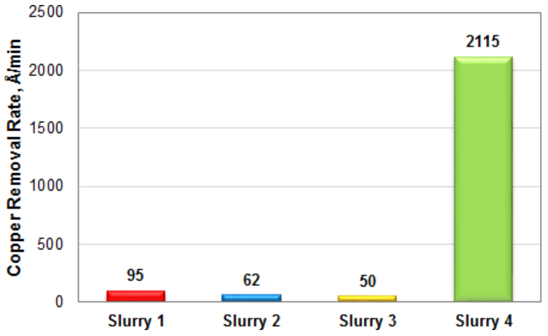
Formulation	Material Removal Rate, Å/min			
	Polymer Dielectric			Copper
Soft Cure Condition	***180°C/60min***	***190°C/60min***	***200°C/45min***	–
Degree of Cure	45%	50%	55%	
Viscosity at Temperature	$2x10^3$ @ 180°C	$3x10^4$ @ 190°C	$>10^5$ @ 200°C	
Slurry 1	97580	6788	335	95
Slurry 2	2575	1	1	62
Slurry 3	5166	1283	192	50
Cu Slurry 4	637	72	45	2115

Strasbaugh 6EC 200 mm R&D polisher; IC1010™ pad; 2 psi; 93/87 rpm table/carrier speeds; 200 mL/min slurry flow; Saesol 8031C1 disk, 7 lbf

- Removal rate is controlled by both CMP processing conditions and soft cure temperature

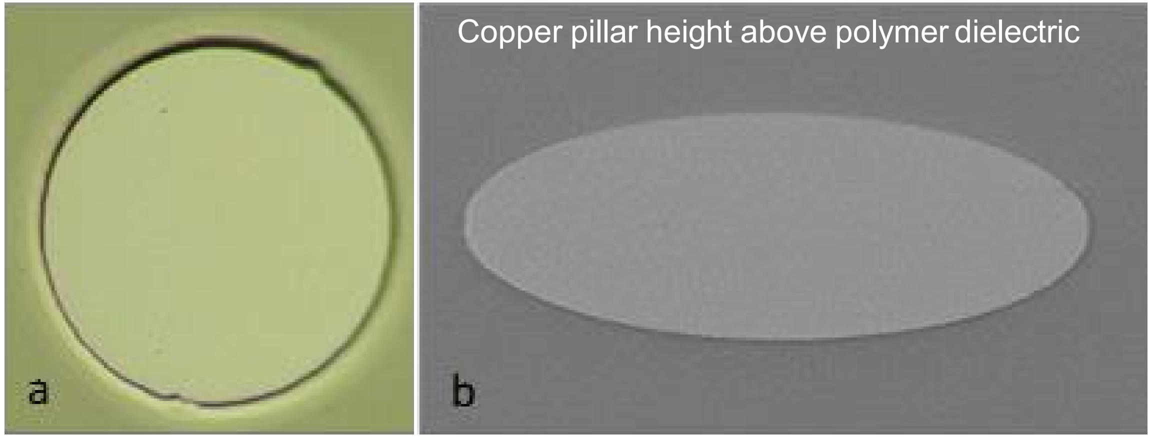


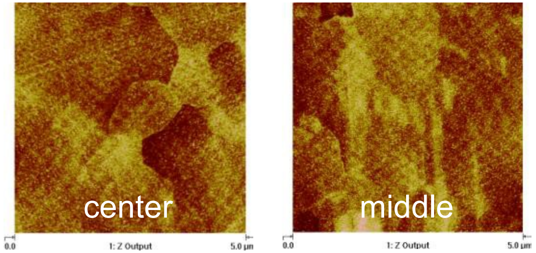
Non-selective copper and polymer removal process is under development



Optimization of CMP Required for 3D-IC Hybrid Bonding

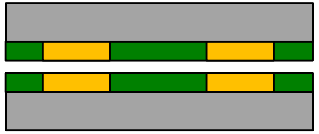
- Process adjustments and slurry design facilitated controlled polymer dielectric and copper removal on blanket films and in copper pillar/polymer structured wafers
- Excellent uniformity across the wafer and across copper pillars can be achieved
- Due to thermal expansion mismatch between Cu and polymer, Cu pillar is left exposed by ~10-20 nm
- A ***strong collaboration between CMP and APT businesses*** enabled material, formulation and process tuning to achieve topography control of patterned copper pillar/polymer structures





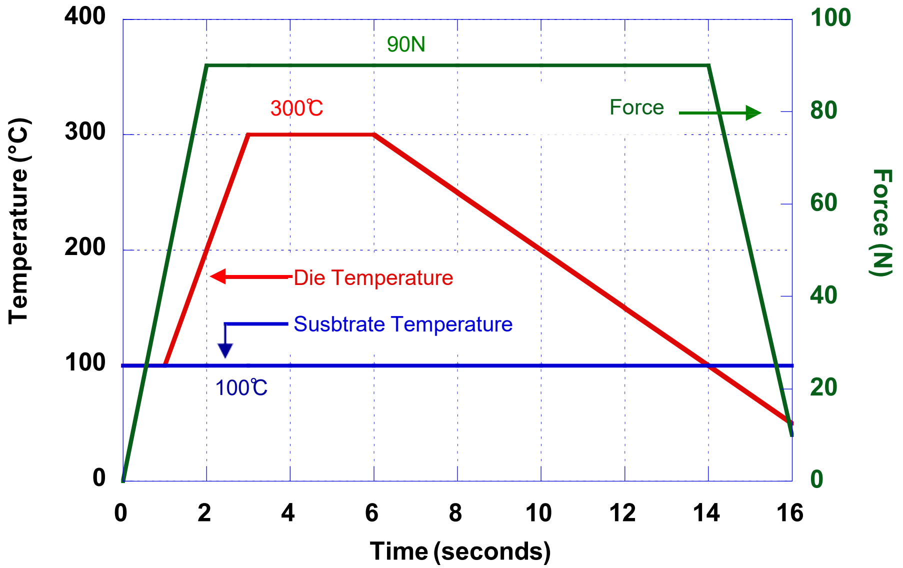
Location	R_a (Å)	R_q (Å)	R_{max} (Å)
Center	6.5	8.4	120
Middle	6.9	8.9	117
Edge	7.4	10.1	100

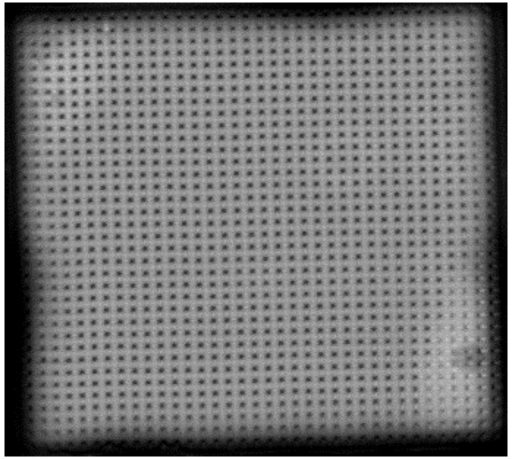
TCB Bonding Process Used to Achieve Cu-Cu Joining



Typical TCB Process: *Toray FC3000S*

- Bring die in contact Cu-Cu only 90N force @ 100°C
- Ramp top die from 100°C→300°C 90N in 2 sec
- **Hold top die at 300°C / 90N for 4 sec**
- Cool top die to 100°C / 10N
- Release bond head



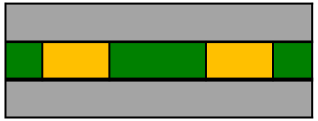


Good Cu-Cu joining (dark areas)

No voiding seen in the field area

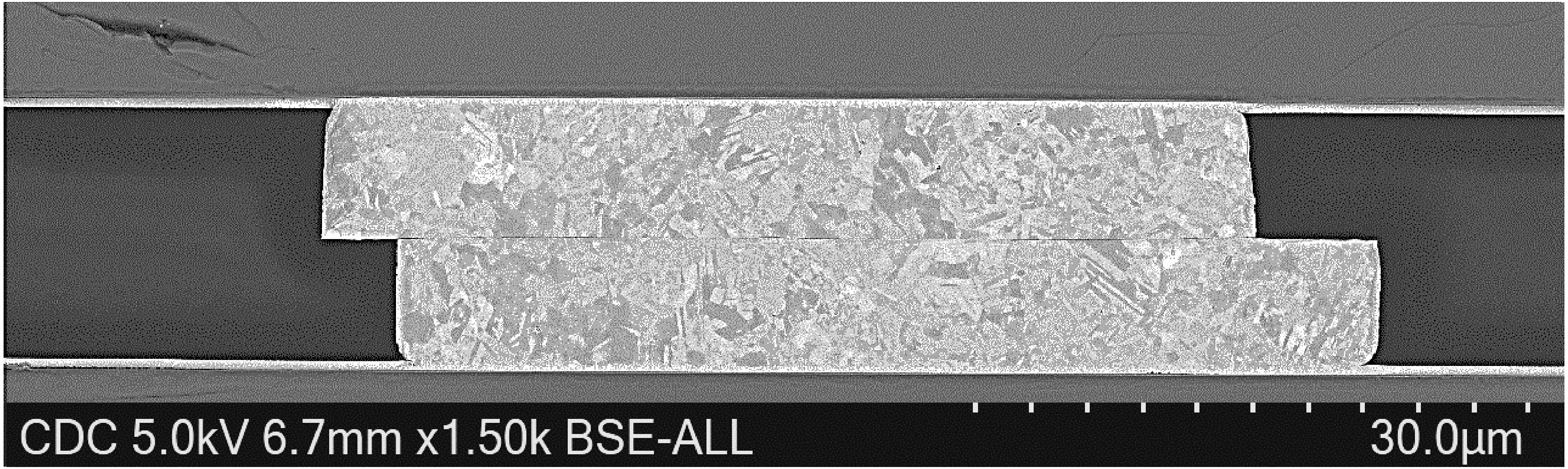
CSAM - 100 MHz transducer

Cu-Cu Joining and Polymer Bonding Results

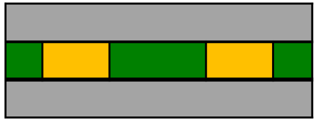


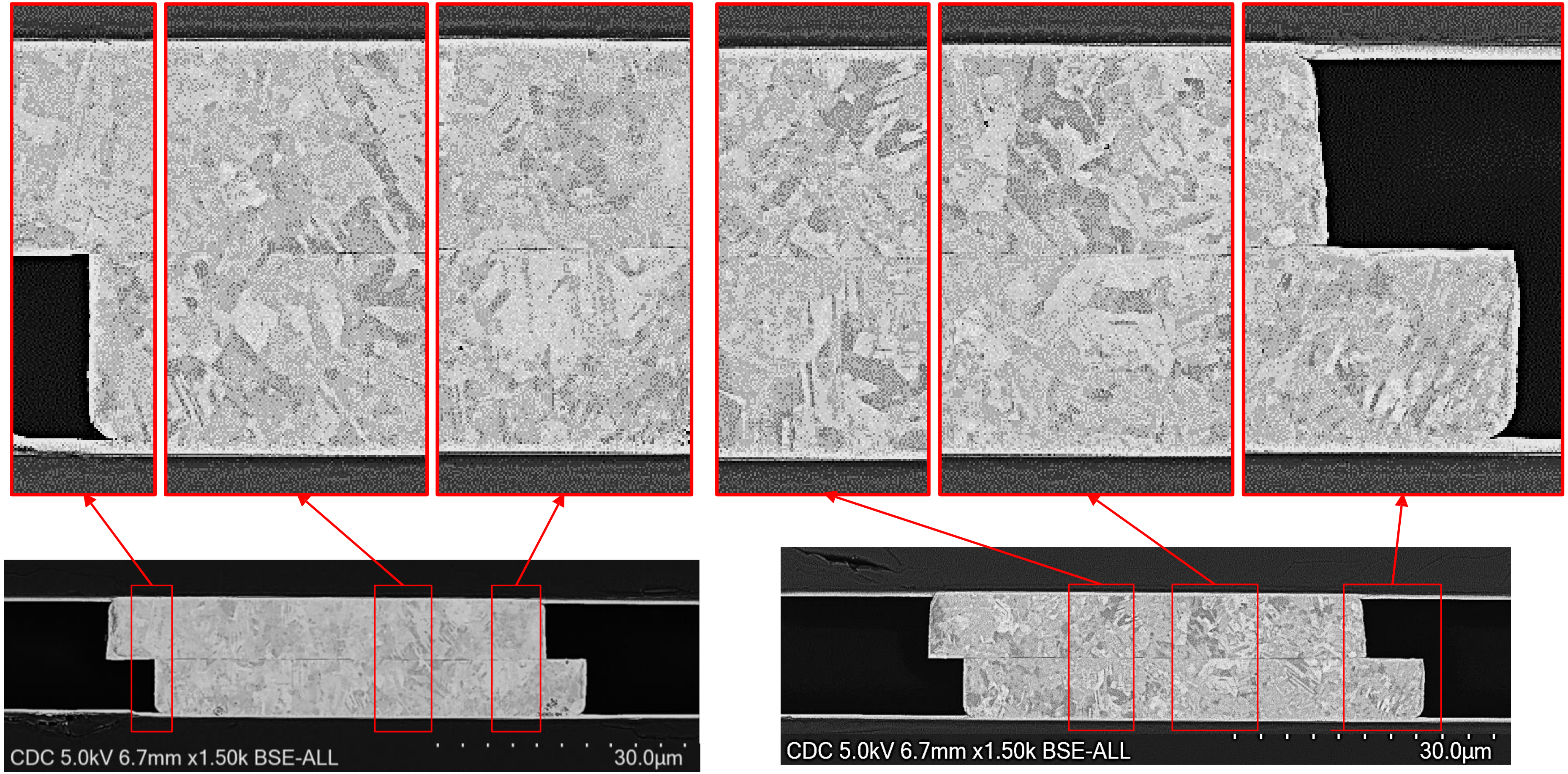
Join/Bond processing improvements

- Cu–Cu Joining observed and good Polymer Dielectric bonding with no voiding
- Gas phase fluxing will remove copper oxide without impacting polymer bonding
- TCB process optimization will focus on temperature and pressure profile

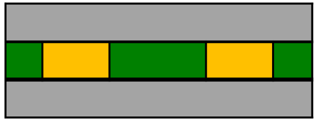


Achieving Copper-Copper Joining and Polymer Bonding





Summary of Current Work

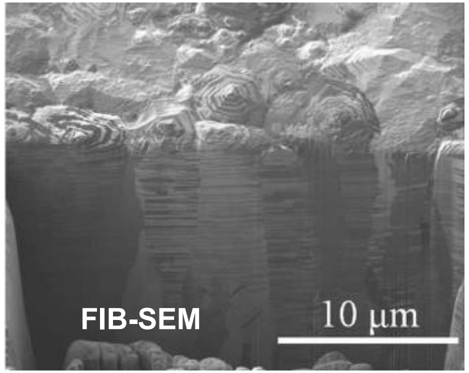


- ✓ Copper pillar plating delivers pillar of uniform height with high purity and small crystallite size
- ✓ Polymer dielectrics provide planar coatings and the controllable rheology for both CMP and bonding
- ✓ CMP slurry selection and process variables allow planarization of both Cu and polymer dielectric
- ✓ Cu-Cu joining demonstrated using a TCB bond tool using 90N of force and <4 sec bond time
- ✓ Low temperature bonding conditions were used, 300°C on the top die and 100°C on the bottom die

- ✓ Successful hybrid bonding results were demonstrated using polymer resin, copper grain structure and selective CMP processes developed across **DuPont Electronics & Imaging** business portfolio.
- ✓ This will enable broader and faster adoption of 3D-IC technology

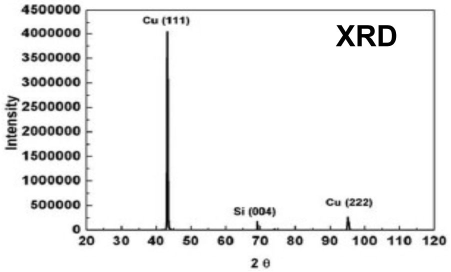
Plating Cu with Higher Diffusion for Low Temp. Joining

- Lower temperature processing required for DRAM and advanced node devices to minimize damage
- Surface diffusion of Cu ions across bonding interface is essential for reliable join
- Copper (111) can be plated with commercial EP Cu chemistry
- Different orientations of Cu provide widely different Cu diffusion rates:
- Cu (111) also has lowest Cu oxidation rate of all planes



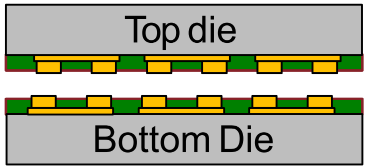
Temperature	Cu (111)	Cu (100)	Cu (110)
150°C	6.85×10^{-6}	2.15×10^{-10}	6.61×10^{-12}
200°C	9.42×10^{-6}	1.19×10^{-9}	5.98×10^{-11}
250°C	1.22×10^{-5}	4.74×10^{-9}	3.56×10^{-10}
300°C	1.51×10^{-5}	1.48×10^{-8}	1.55×10^{-9}

Liu et. al., Scientific Reports, 2015　　*Surface Diffusivity, D (cm^2/sec)*



Next Steps for 3D-IC Cu-Cu Joining and Polymer Bonding

- Copper pillar structures featuring sub 20 micron pillars at 1:1 pitch
  - Segment plate copper pillars, e.g. Cu(111)
  - Coat polymer adhesives, e.g. low temp cure
  - CMP segments using different process conditions
  - Dice segments and TCB bond
  - Reliability testing and failure analysis



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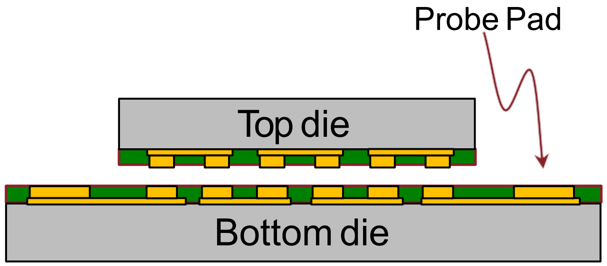
- Via chain structure featuring sub 20 micron pillars and pads at 1:1 pitch
  - Repeat DOE with electrically testable segments
  - Validate bonding based on resistance measurement
  - Reliability testing and failure analysis



Thank You