Direct Cu-Cu bonding in C2S applications using Cu-pillar with nanoporous-Cu caps

Students: Ramón A. Sosa, Kashyap Mohan
Faculty: Vanessa Smet, Antonia Antoniou

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1. Outline

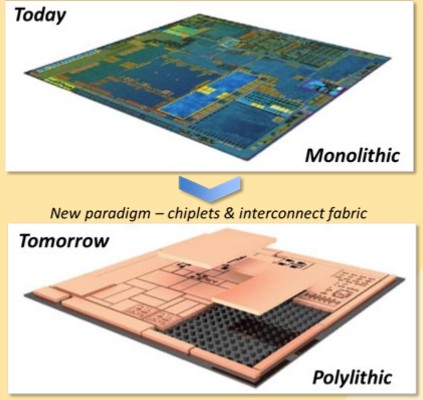
- ☐ Goals & Objectives
- ☐ Prior Work
- ☐ Technical Approach
- ☐ Results & Key Accomplishments
- ☐ Comparison with Prior Art
- ☐ Summary
- ☐ Schedule

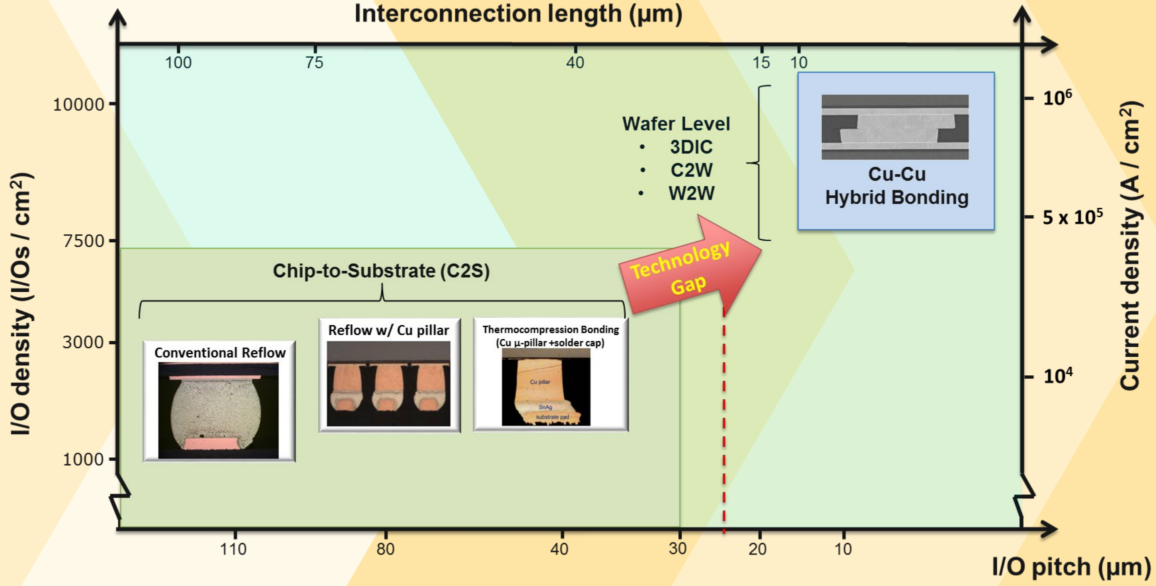
2. Goals and Objectives

Design and demonstration of novel all-Cu interconnections with solder-like compliance before assembly and Cu-like performance and reliability after assembly, for C2S application

Example in HPC / AI:
The "Chiplet Revolution"
→ C2S pitches <20µm by 2030

DARPA CHIPS Program Vision





- ☐ Solders are reaching their fundamental limits in **pitch scalability**, **power handling** capability and **fatigue resistance** – across applications (digital, analog, power, …)

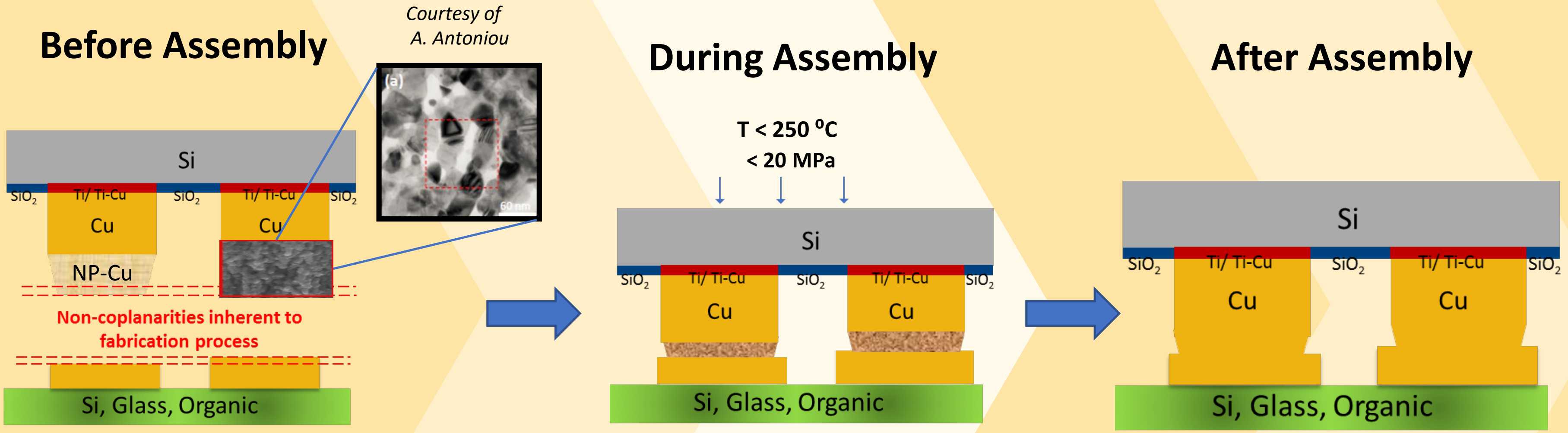
- ☐ **Direct Cu-Cu bonding** is predicted as the next interconnection node, but current technologies are not applicable at package level – the key bottleneck to developing a **universal** assembly solution: **non-coplanarities**

3. Prior Work

- ☐ Developed new process flow for seed layer etching that allows for the fabrication of daisy chain structures
- ☐ Stabilized electroplating bath chemistry to improve the composition uniformity of plated Cu-Zn structures
- ☐ Preliminary characterization of parts assembled using nanoporous-Cu caps as bonding interface

4. Technical Approach

Introducing nanoporous-Cu (NP-Cu) as a replacement to solder caps to form all-Cu C2S interconnections:



Before Assembly

Courtesy of A. Antoniou

Non-coplanarities inherent to fabrication process

During Assembly

T < 250 °C
< 20 MPa

After Assembly

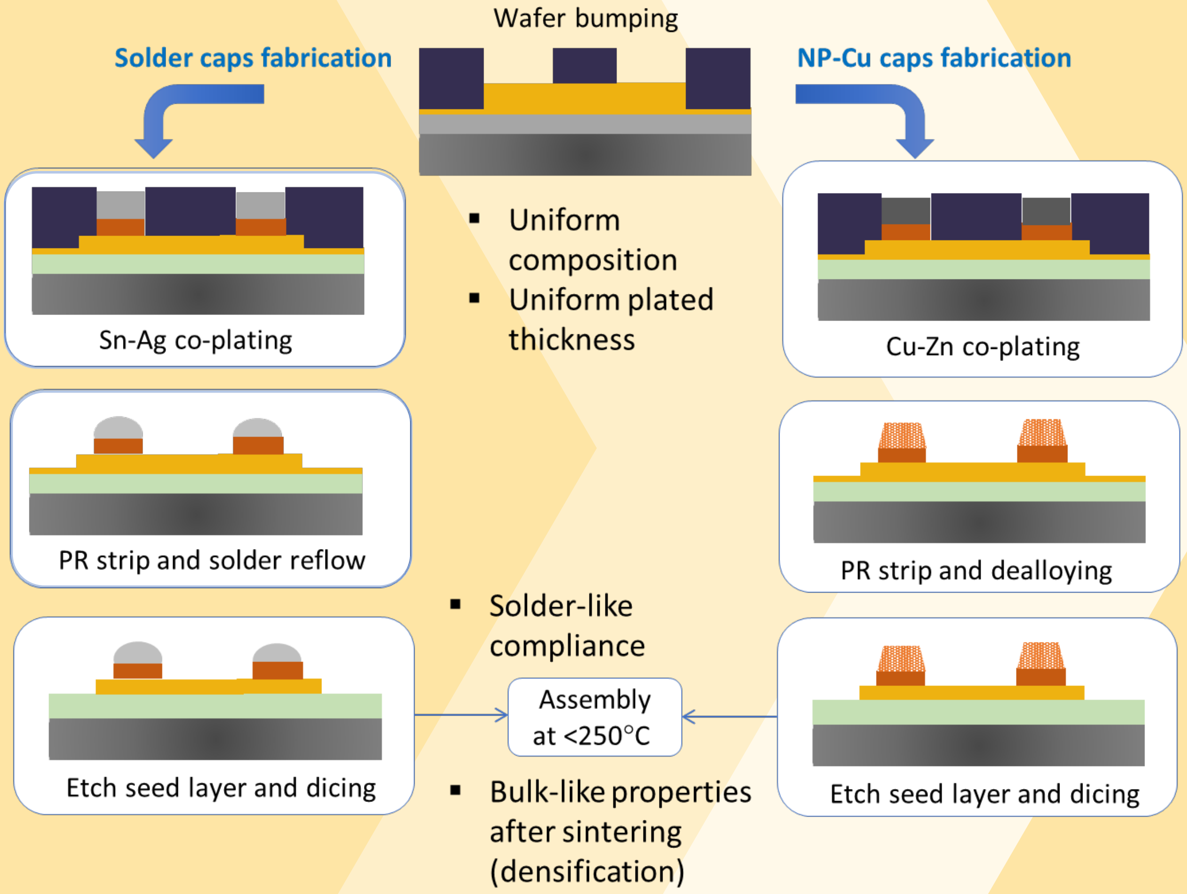
- Compliant, low-modulus
- Solid-state, non-discrete and organics free
- Compatible with semi-additive wafer bumping process

Low modulus NP-Cu deforms, accommodating mesoscale and microscale non-coplanarities

Highly reactive NP-Cu then densifies due to sintering, yielding all-Cu interconnections with void free bonded interfaces

4. Technical Approach

Comparison to solder technology



Wafer bumping

- Uniform composition
- Uniform plated thickness

Solder caps fabrication

Sn-Ag co-plating

PR strip and solder reflow

Etch seed layer and dicing

NP-Cu caps fabrication

Cu-Zn co-plating

PR strip and dealloying

Etch seed layer and dicing

- Solder-like compliance

Assembly at <250°C

- Bulk-like properties after sintering (densification)

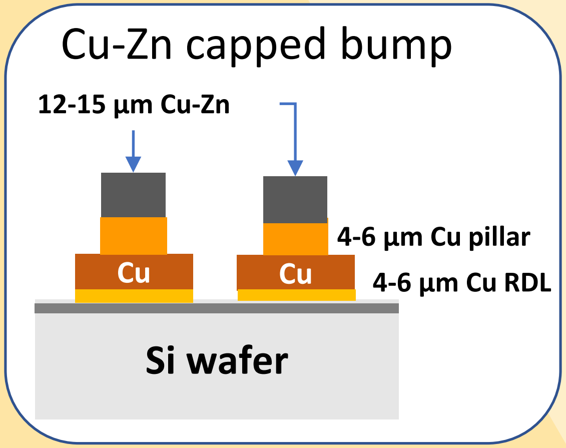
Maintaining compatibility with existing industry infrastructure is key to scaling to manufacturability

Proposed fabrication process is compatible with existing industry semi-additive processes, promising high precision and throughput

5. Results and Key Accomplishments

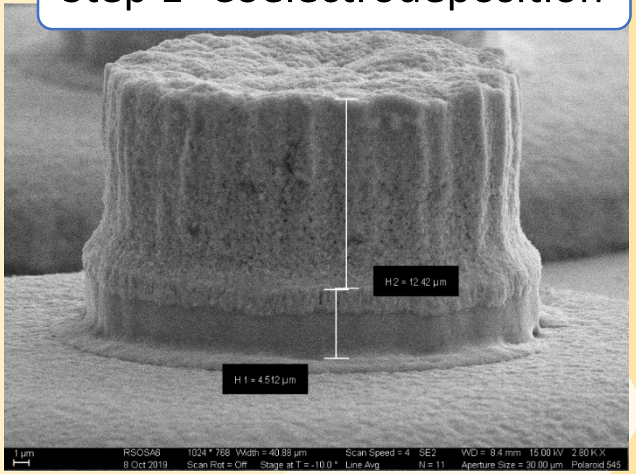
5.1 Understanding how to optimize the fabrication of a NP-Cu cap

Cu-Zn capped bump



- Properties of nanoporous metals are heavily dependent on fabrication
- Focus has been on determining how different process parameters influence the properties of the NP-Cu cap

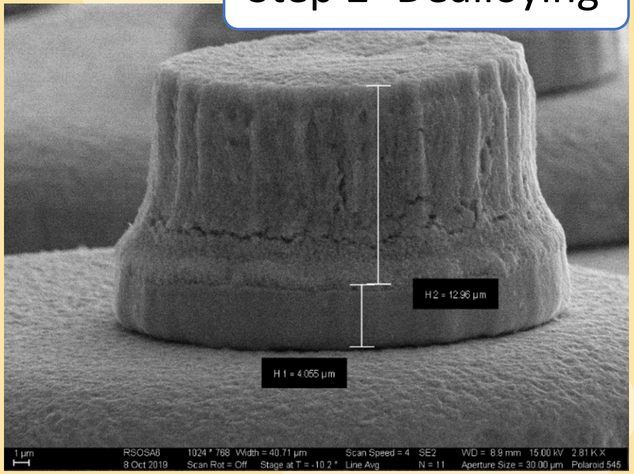
Step 1- Coelectrodeposition



Composition of the plating bath and plating potential primarily influence Cu-Zn composition, also:

- Plating rate
- WIP, WID, WIW uniformity
- Phases present in structure
- Grain structure
- <u>Residual stresses</u>

Step 2- Dealloying



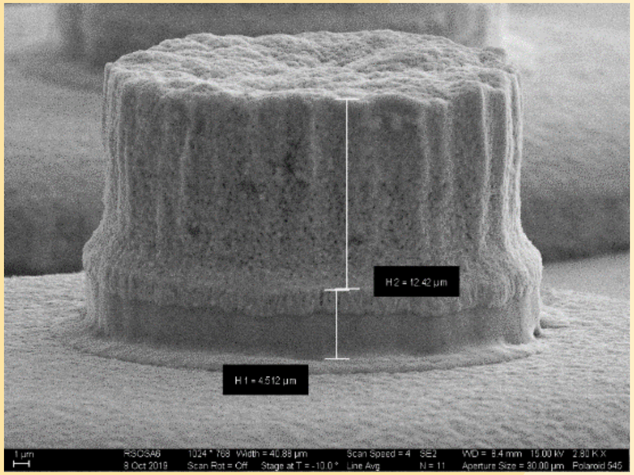
Dealloying controlled primarily by acid concentration and dealloying time but also on plated properties

- Modulus
- <u>Residual Zn%</u>
- Ligament morphology
- Cap shape
- <u>Cracking</u>

5. Results and Key Accomplishments

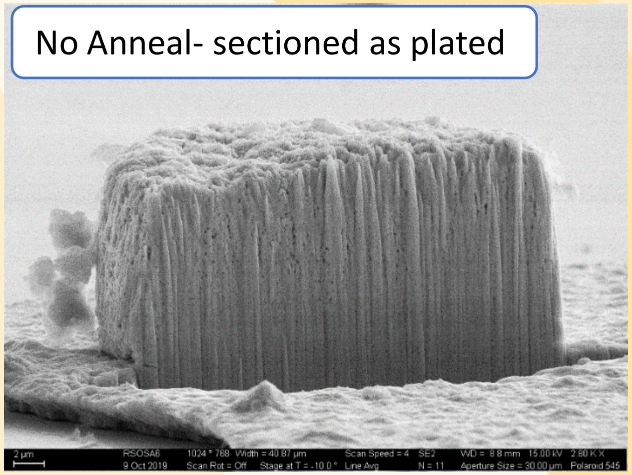
5.2 Effect of annealing on the properties of plated Cu-Zn

Cu-Zn on Bumps
Plated at -1.50 V for 45 min
~25:75 Cu:Zn initially



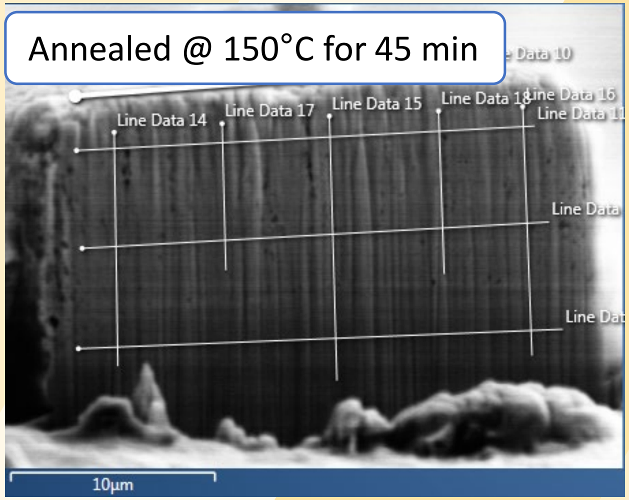
- Annealing shown to reduce tensile residual stresses induced during plating
- FIB milling and EDX line scans used to explore changes within the bump as a result of annealing

No Anneal- sectioned as plated



Average 23.36% Cu, σ=.82%

Annealed @ 150°C for 45 min



Average 26.02 % Cu, σ=3.12 %

Key Insights:

- Increase in Cu within Cu-Zn pillar-likely diffusion from underlying metallization
- More variation in composition throughout the Cu-Zn pillar- possibly from development of different phases

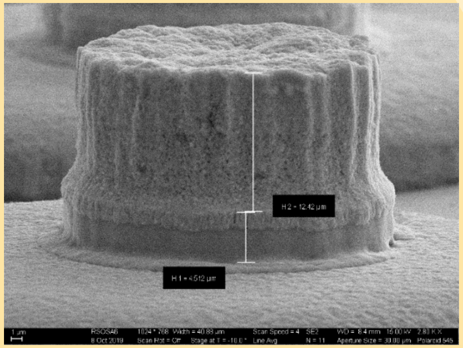
Need to be mindful of how comp. variance affects dealloying!

FIB X-Section Courtesy of Timothy Ibru

5. Results and Key Accomplishments

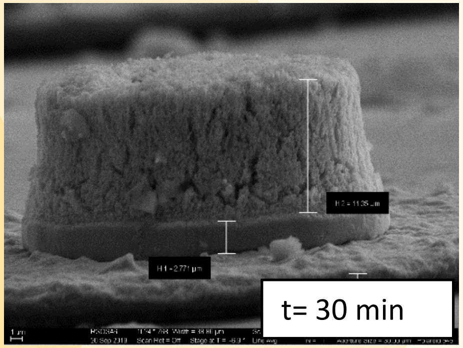
5.3 Effect of annealing on the dealloying process

Cu-Zn on Bumps
Plated at -1.50 V for 45 min
~25:75 Cu:Zn Initially
Dealloyed in 0.3 wt% HCl

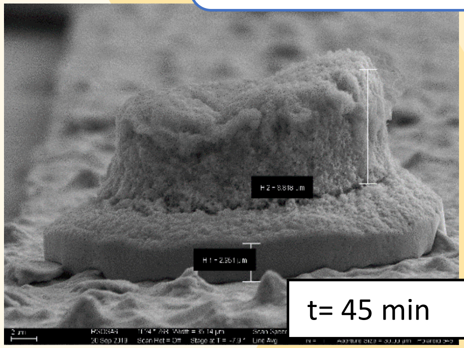


Same starting composition and structure…

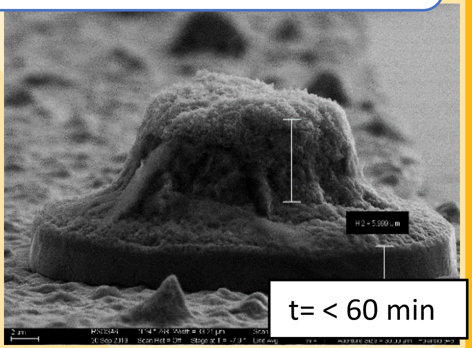
No Anneal- dealloyed as plated → Residual Zn decreases rapidly, but at the expense of bump integrity



t= 30 min

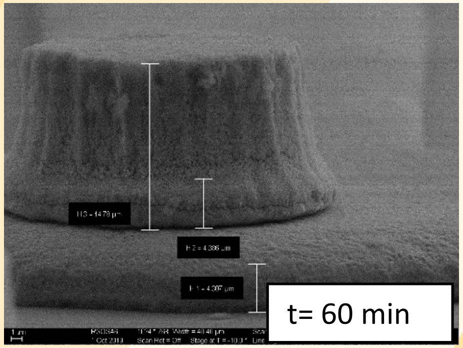


t= 45 min

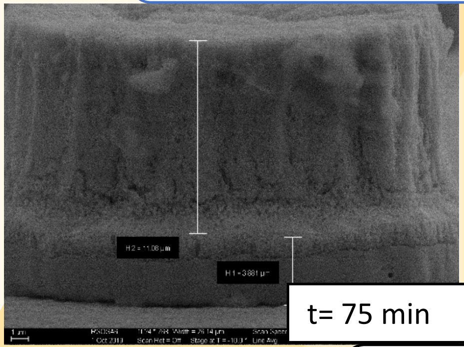


t= < 60 min

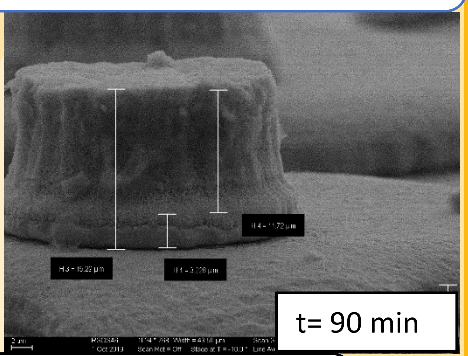
Annealed @ 180°C for 2 hrs → Dealloying rate slows considerably, but bump more stable



t= 60 min



t= 75 min

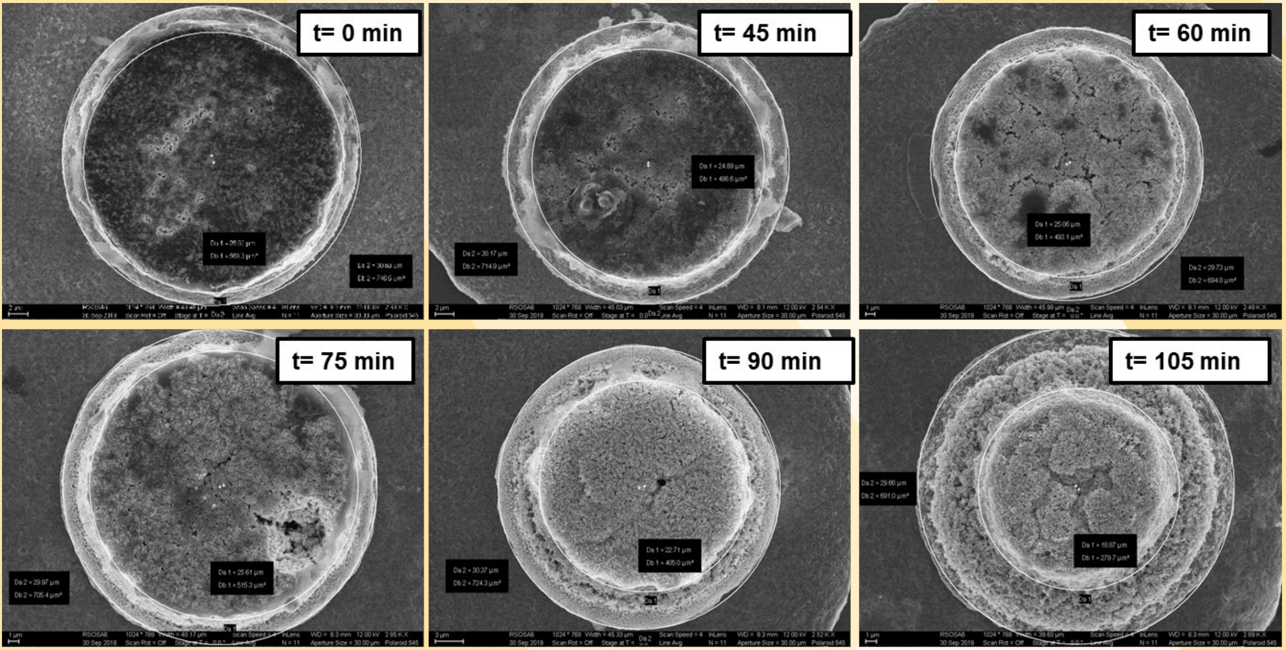


t= 90 min

…different behavior influenced by processing

5. Results and Key Accomplishments

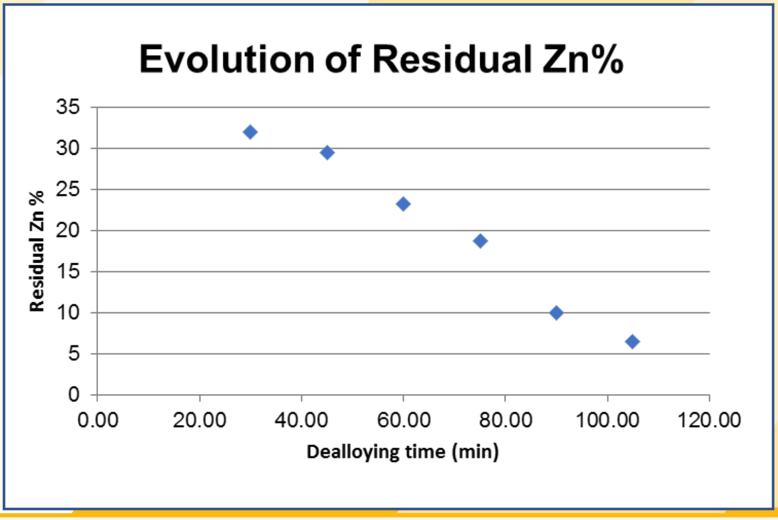
5.4 Effect of time on the dealloying process



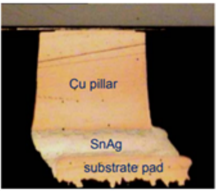
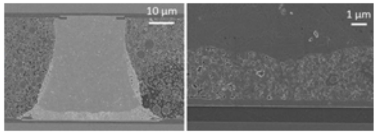
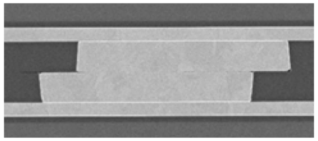
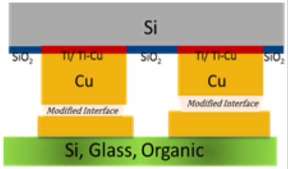
Cu-Zn on Bumps
Plated at -1.50 V for 45 min
~25:75 Cu:Zn Initially
Dealloyed in 0.3 wt% HCl

Change in **bump diameter** and increased **cracking** observed over time, as well as **coarsening** of NP-Cu- evaluating ways to reduce “delamination” and large cracks

Dealloying kinetics need to be better understood- trivial to remove Zn at first, but difficult to leech remainder without compromising on bump shape and NP-Cu morphology



6. Comparison with Prior Art

Parameters		State-of-the-art			Research objectives
		Lead-free solders (Cu µ-pillar TCB)	**Nanoparticle Systems (IBM Zurich)**	**Direct Cu-Cu bonding (Xperi Hybrid)**	
Package configuration					
		Universal	C2S	W2W	Universal
Pitch		Fine to large >35 µm	Fine to large >35 µm	Very fine <5 µm	Very fine <20 µm
Tolerance to non-coplanarities		High (>5 µm)	High (>3 µm)	Low (<<1 µm)	High (>5 µm)
Bonding parameters (Temp/pressure)		250°C 40 MPa	200°C 50.6 MPa	RT Oxide bond 200°C batch anneal	<250°C <20 MPa
Performance	Electromigration	$<10^4$ A/cm²	$<10^6$ A/cm²	10^6 A/cm²	10^6 A/cm²
	Thermomechanical Reliability	JEDEC standard JESD22-A104 thermal cycling at -55/125C, 1 cycle/h			

7. Summary and Future Plans

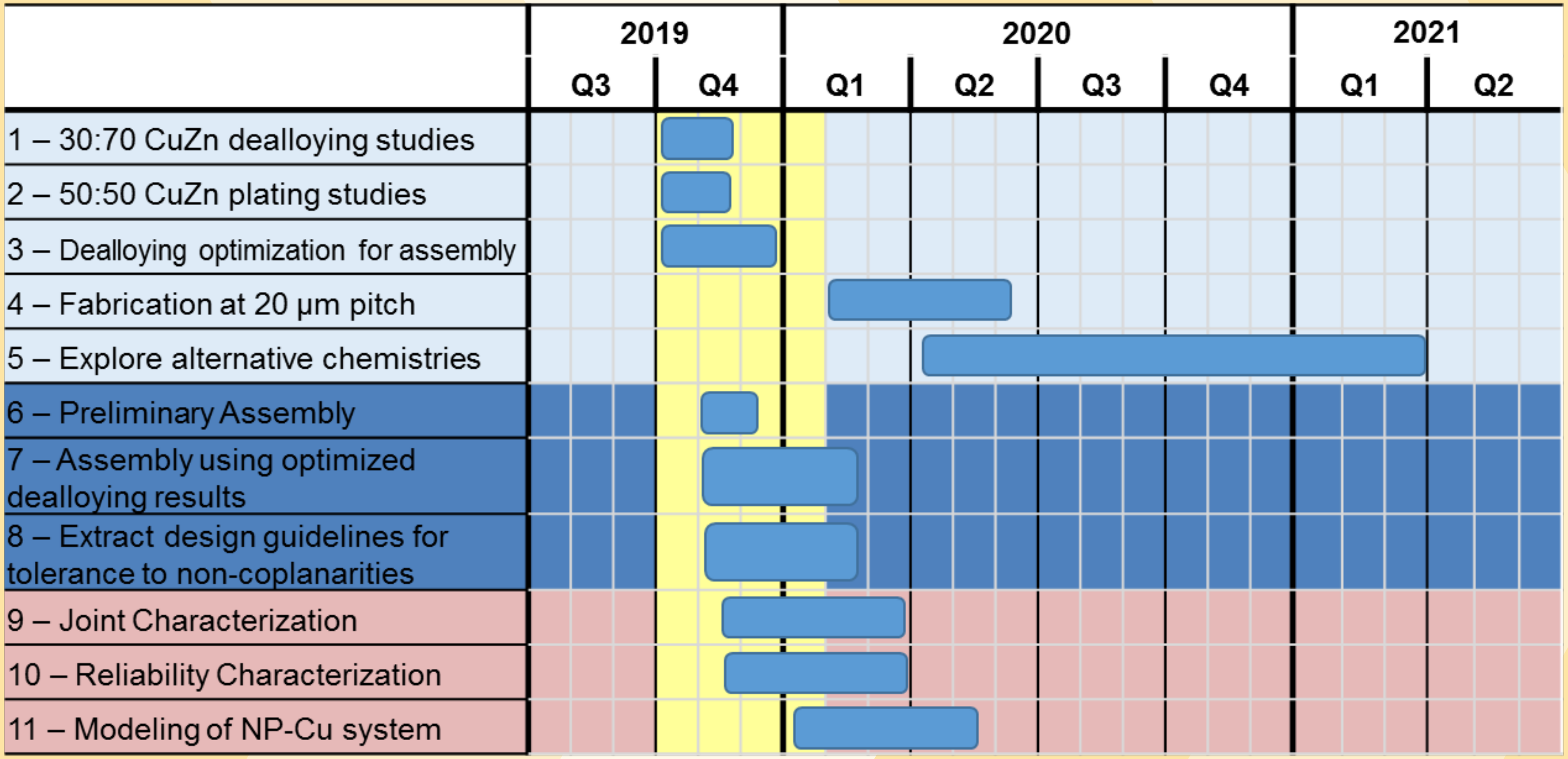
☐ Solving the problem of dealloying is non-trivial: yet to fully understand how the many input parameters contribute to the resultant structure of the NP-Cu

☐ Focus will be on identifying a preliminary candidate for full assembly characterization of system

☐ Exploring different regions of the phase diagram planned for future experiments (50:50 Cu:Zn seems promising based on preliminary results)

☐ Exploring different plating conditions and dealloying conditions to yield better NP-Cu

8. Schedule



	2019		2020				2021	
	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2
1 – 30:70 CuZn dealloying studies		■						
2 – 50:50 CuZn plating studies		■						
3 – Dealloying optimization for assembly		■						
4 – Fabrication at 20 µm pitch			■	■				
5 – Explore alternative chemistries				■	■	■	■	
6 – Preliminary Assembly		■						
7 – Assembly using optimized dealloying results		■	■					
8 – Extract design guidelines for tolerance to non-coplanarities		■	■					
9 – Joint Characterization		■	■					
10 – Reliability Characterization		■	■					
11 – Modeling of NP-Cu system			■	■				

Light blue: Fabrication tasks
Dark blue: Assembly tasks
Light red: Reliability characterization
Light Yellow: Current time window