Sintered Nanoporous Copper Die-Attach Interconnections for High-Power, High-Temperature Applications

Students: Kashyap Mohan, Ramon Sosa
Faculty: Dr. Vanessa Smet, Prof. Antonia Antoniou, Prof. Rao Tummala

Acknowledgements

- This work is sponsored by SRC's "Global Research Collaboration" under task 2661.01-02 (project ended Feb 2019). We are thankful to SRC industry liaisons Dr. Luu Nguyen and Sadia Khan from Texas Instruments, and Dr. Ravi Mahajan from Intel.

- PRC's Industry consortium's "Interconnections & Assembly" program. We acknowledge YY Tan and Denise Theinpoint from On Semiconductor for their technical feedback.

Research Objectives

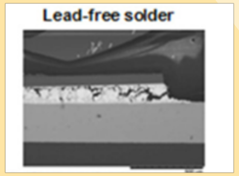
Model, design, fabricate and demonstrate low-cost, all-Cu die-attach interconnections with enhanced processability, by low-temperature (<250 ℃), low-pressure (<5MPa) sintering, for superior electrical, thermal and reliability performances as compared to silver sintering under high operating temperatures (>250 ℃) and power densities.

		Parameters		Target	Sintered joints			Technical challenges (TC)	Research Tasks
					Ag paste	Ag films	Cu paste (Research)		
1	Before assembly	Novel Cu die-attach material system capable of low-temperature, low-pressure assembly	Fabrication	**Preforms, directly on wafer**	Printing	Preforms	Printing	**High reactivity → difficult to stabilize material, oxidation**	**Design and demonstration of nanoscale, solid-state, low-modulus organics-free Cu interconnection material**
			Thickness	**Easily tailorable 5-50um**	Multiple printings	Tailorable	Multiple printings		
2	After assembly	**Superior electrical and thermal performance joints**	Thermal conductivity 3-layer stack	**>200 W/m-K**	60-160	~200 (Alpha)	<100	**Incomplete and uncontrolled densification after sintering, voids at interfaces**	**Material and assembly process design for very high densification to achieve bulk-Cu properties by understanding sintering kinetics**
3		**High thermo-mechanical reliability of joints**	Shrinkage	**<20%**	>50%	-	>50%	**Decrease in stress relaxation capability with higher modulus of sintered joints**	**Design of interconnection material and assembly process to reduce modulus/provide compliance in axial plane**
			Modulus - assembly	**60-100 GPa**	10-70GPa (porosity dependent)	High	High		
			TCT	**-55/200C, 1000 cycles**	Henkel – SSP 2020 -55/175C, 750 cycles- delam	Data NA			

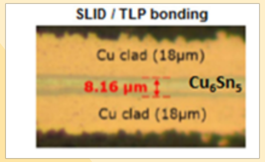
Prior Art

High-Pb solders

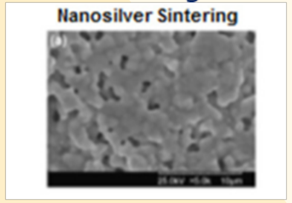
Pb-free solders



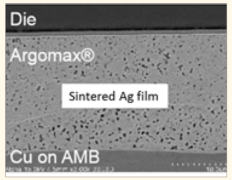
Diffusion soldering



Ag nanopaste sintering



Ag nanofilm sintering



Higher current density and heat dissipation

Toxic, RoHS guidelines

-Low-melting temp
-Limited performance

- High-melting temp
- High modulus
- Low electrical and thermal

-Good performance for high temperature and reliability
-High cost limiting adoption
-High modulus

?

- Evolution of die attach technologies has been primarily guided by increase in thermal and electrical performances and high-temperature stability.
- **Ag nanopastes sintering is the current state of the art solution.**

Can Ag nanopastes sintered die-attach joints meet the needs of emerging power conversion applications?

Technology	Advantages	Challenges
Ag nanopastes sintering	• Operating T>250°C • Excellent electrical and thermal performances • Sintering temperatures <250°C	• Organics →voids after densification. • Organics → high-shrinkage → warpage after assembly • High modulus joints as compared to solders • High cost and poor ECM

Nanoporous Copper (NP-Cu) Sintered Die-Attach

Going beyond Ag Nanopastes Sintering

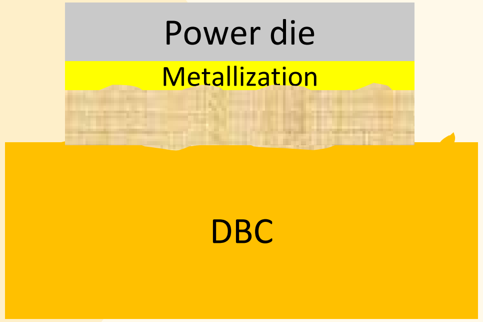
Before assembly

NP-Cu film die-attach

- Solid-state nanoscale reactive interface
- <20GPa modulus
- Can be fabricated directly on wafer/substrate or as a insert/preform

During assembly

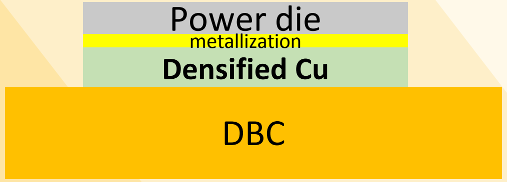
Film sintering
T< 250°C
Low pressure, short cycle time



- Low modulus brings adequate "wettability" to accommodate for non-coplanarities and surface roughness and form a strong, void-free bond
- Much reduced shrinkage during assembly as compared to pastes

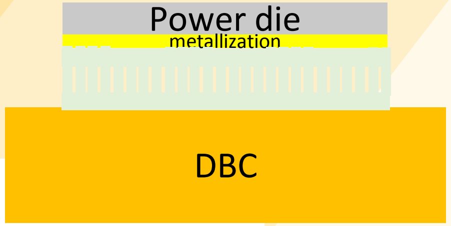
After assembly

Small die sizes
High densification >90%



- All-Cu highly densified joints
- High electrical and thermal performances

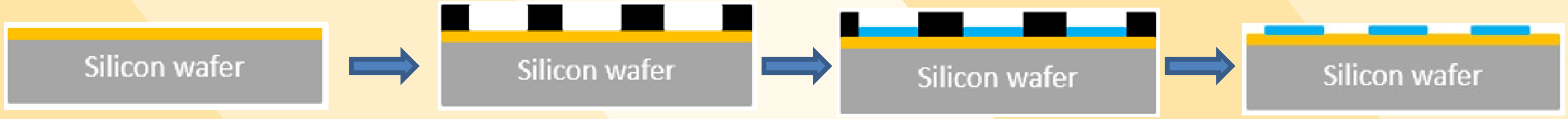
Large die sizes
Novel joint: anisotropic densification



Tailorable modulus with no drop in electrical and thermal for superior reliability

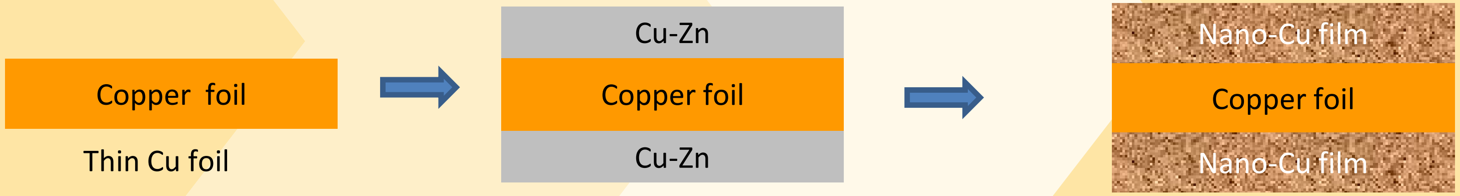
Versatility in Implementation

Patterned NP-Cu on substrate/device



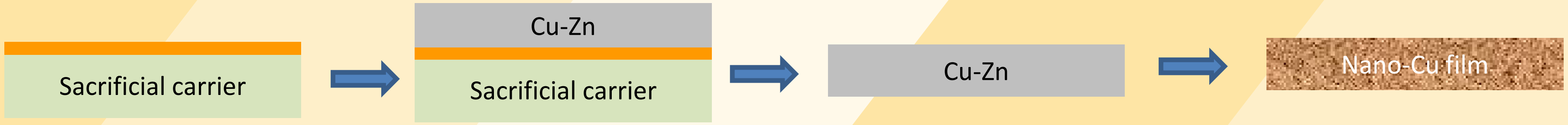
Sputter oxide and Ti/Cu seed layer on Si wafer → Photoresist lamination and patterning → Deposit Cu-Zn alloy layer 5 – 10 µm thick → Lift-off photoresist, etch Ti/Cu seed and dealloy

NP-Cu film with a Cu core



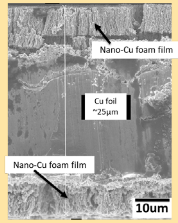
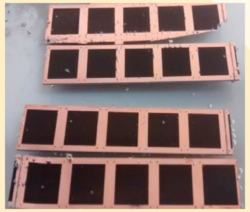
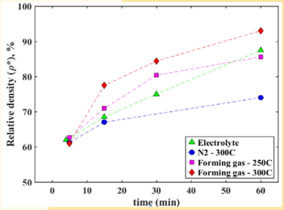
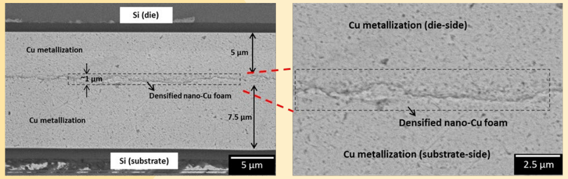
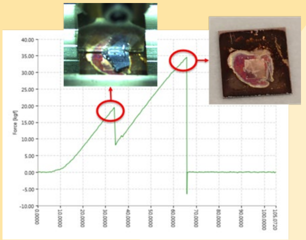
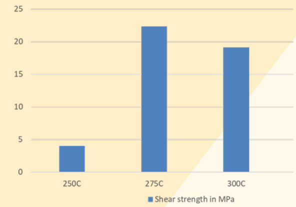
Thin Cu foil → Deposit Cu-Zn alloy layer 5-30 µm thick → After dealloying

Standalone NP-Cu films



Sacrificial carrier with a seed layer → Deposit Cu-X alloy layer 15–30 µm thick → Isolate the Cu-X film and dealloy

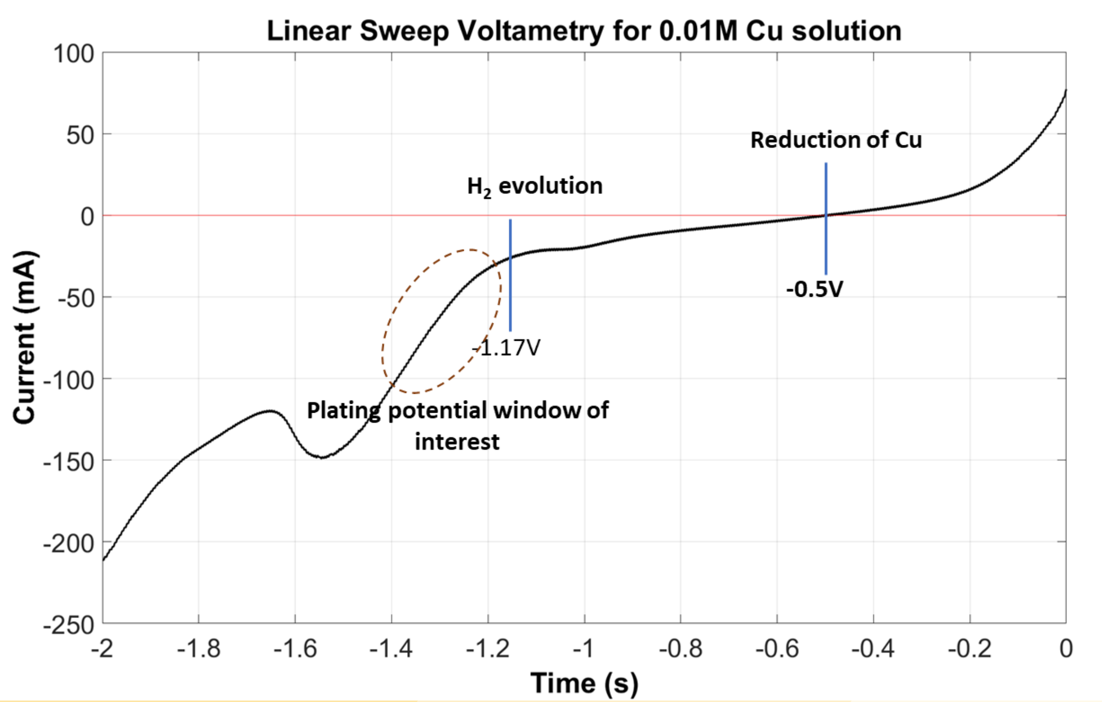
Key Research Tasks and Prior Work

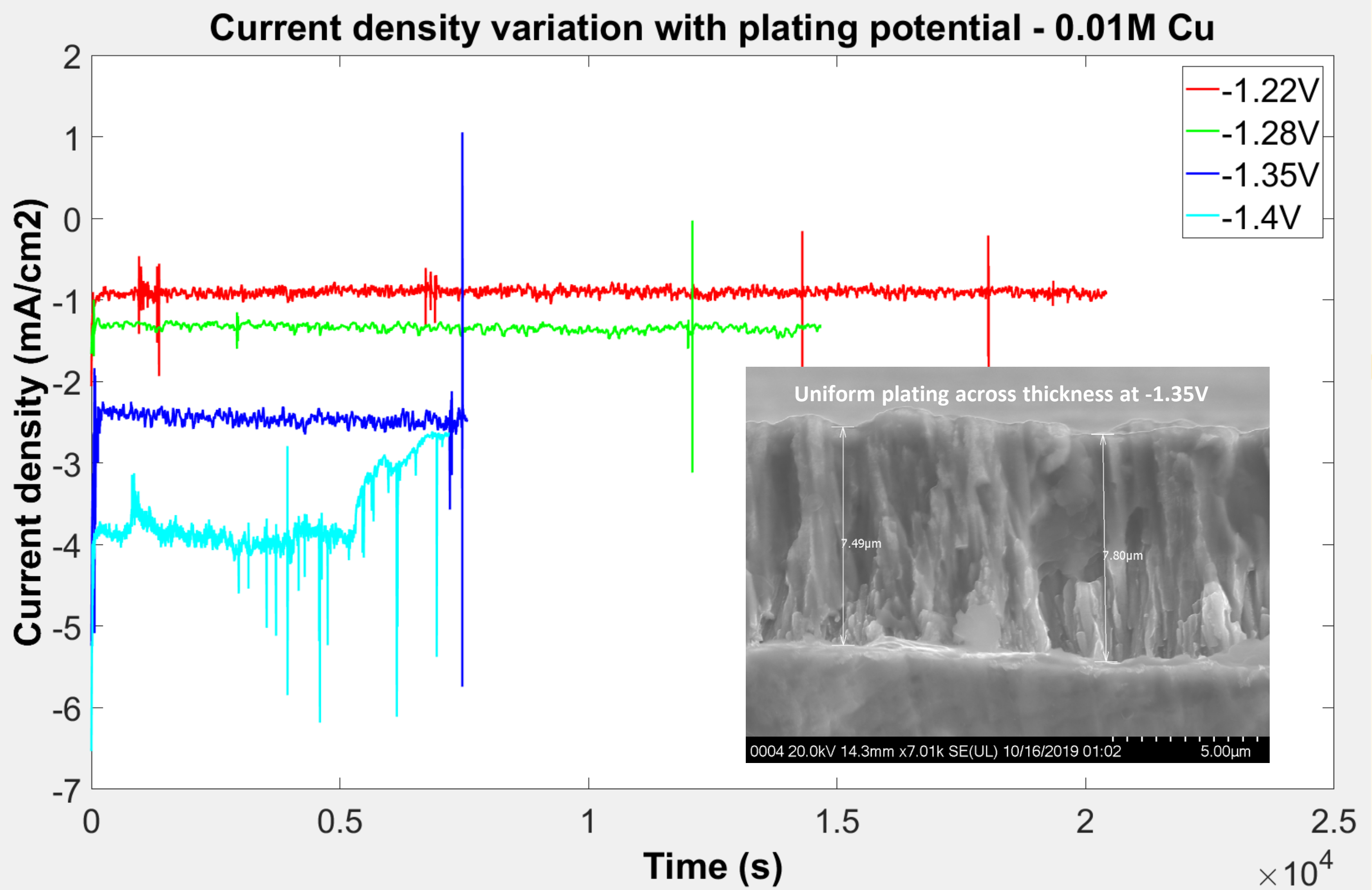
Research Tasks	Sub-tasks	Status	Prior Work
Fabrication of NP-Cu ***Focus of this presentation***	Cu-Zn co-plating development	●	 **NP-Cu with Cu core**  **Large-area patterned NP-Cu films**
	Dealloying of Cu-Zn alloy films	●	
	Process development for patterned NP-Cu	●	
Assembly demonstration using NP-Cu	Sintering kinetics of NP-Cu	●	 **>90% densification in forming gas @300C**  **All-Cu large area die-attach joints**
	Assembly on patterned NP-Cu ($9mm^2 – 25mm^2$ area)	●	
	Assembly on NP-Cu with Cu core ($9mm^2 – 25mm^2$ area)	●	
Reliability characterization of sintered NP-Cu joints	Shear strength with variation in assembly parameters	●	  **Variations in shear strength with assembly temperatures**
	Thermal conductivity (3-layer)	●	
	Thermal aging (200°C – until failure) Temperature cycling (-55C/200°C – until failure)	●	

Co-electrodeposition of Cu-Zn

Characterization of Plating Bath

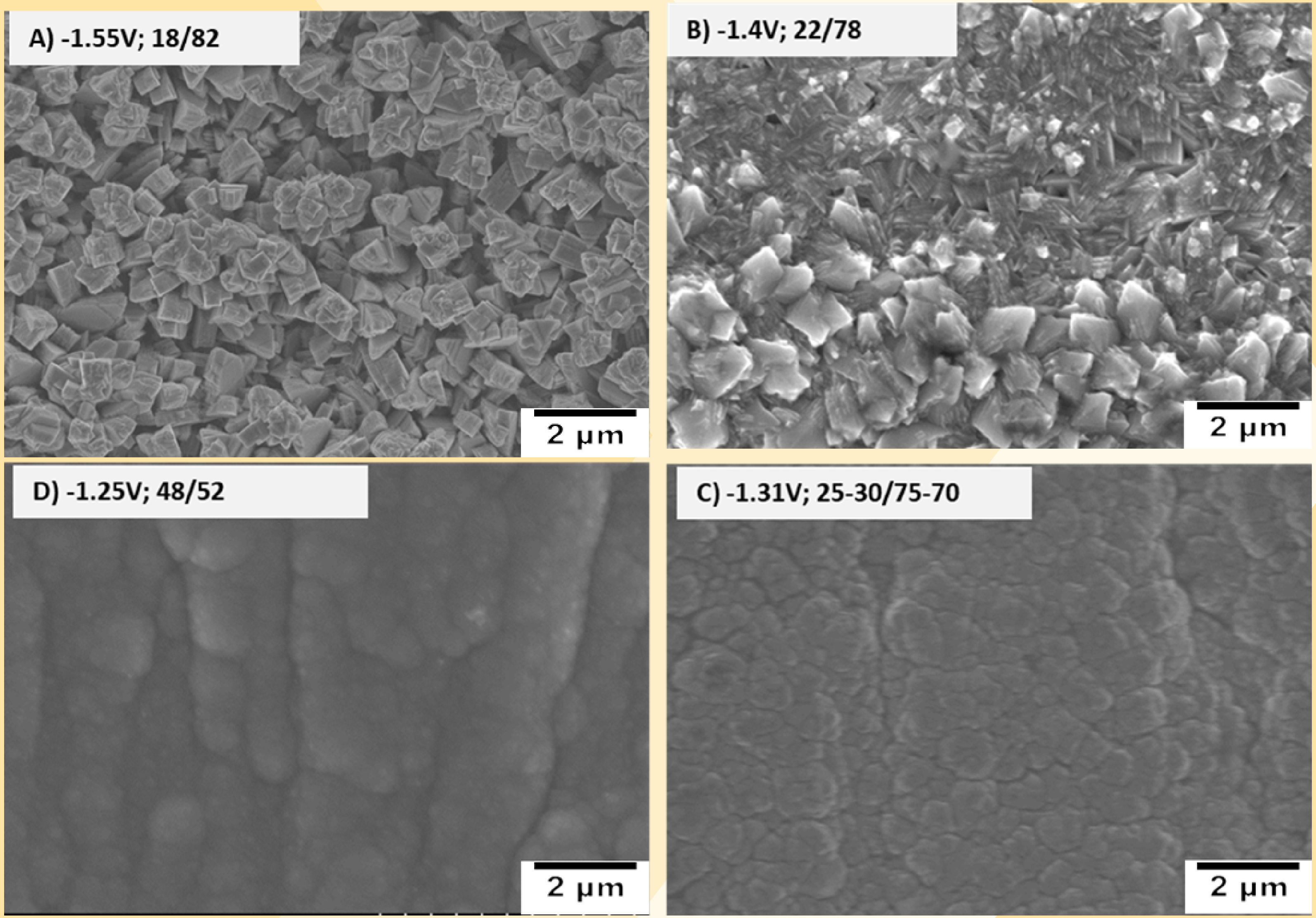
0.01M $CuSO_4$, 0.15M $ZnSO_4$, 0.32M Potassium pyrophosphate
Plating solution = 3L, Plating area = 18cm^2, Ref electrode: Ag/AgCl





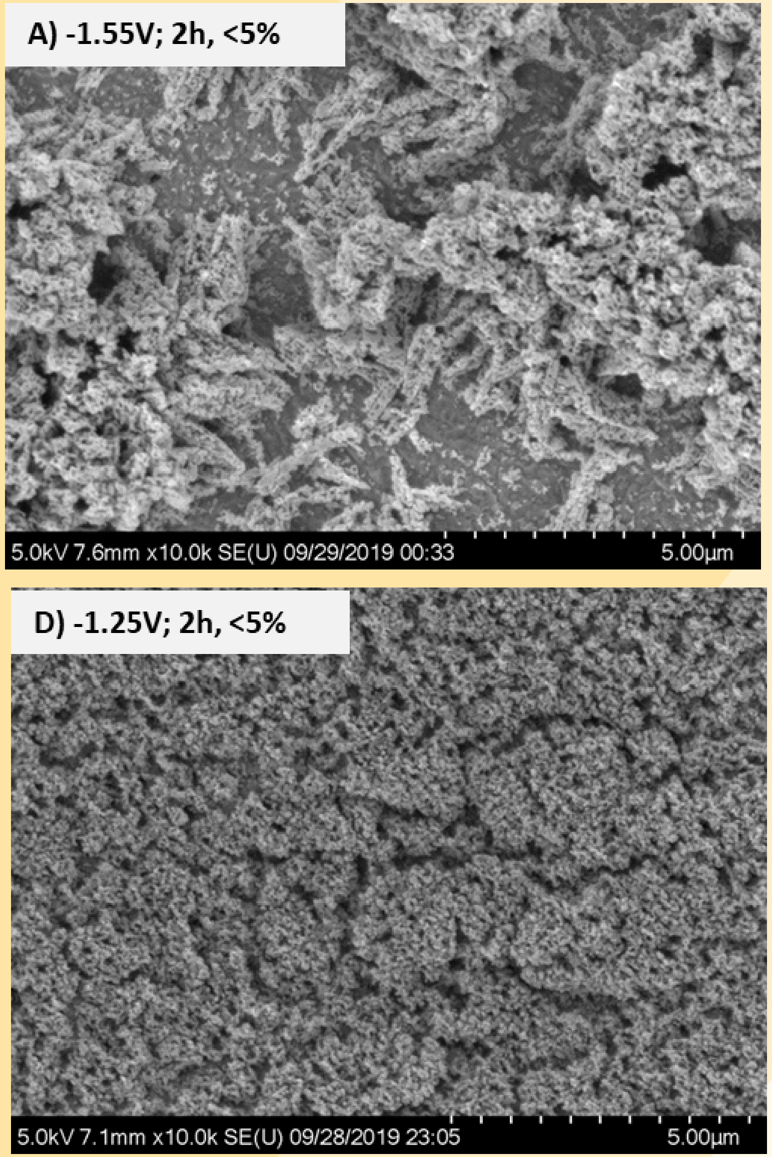
- Plating potential window from -1.2V to -1.35V based on both I-V and i-t measurements.

Effect of Plating Potential on Composition and Microstructure of Cu-Zn Alloys



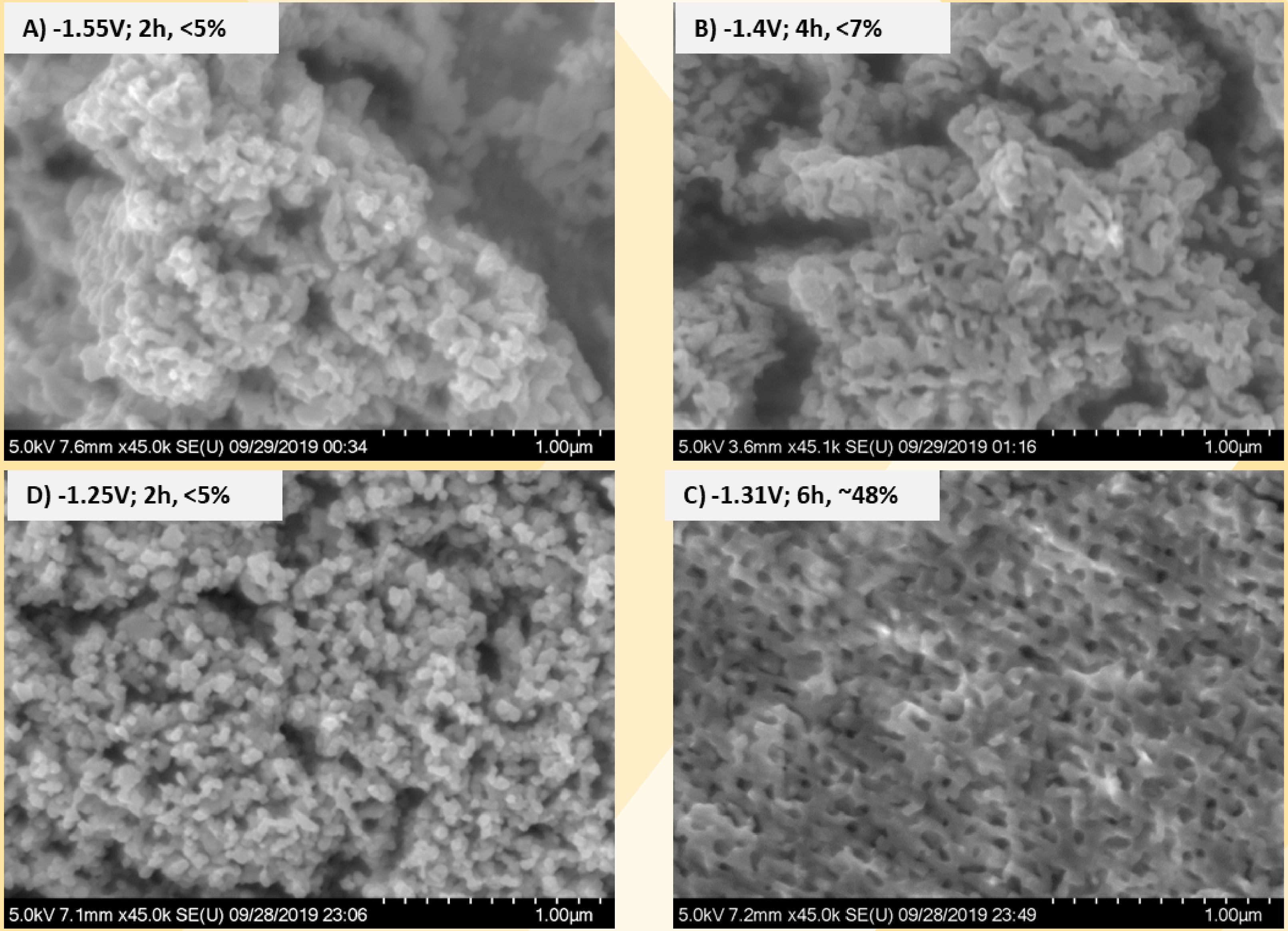
- Composition characterization carried out for plating potentials in the range of -1.25V to -1.55V.
- Increase in plating potential results in increase in Zn content.
- Zn > 75% gives hexagonal morphology Zn rich phases.
- Zn<75% gives with β + γ phases.

Dealloying of Different Cu-Zn Alloys in 1M HCl



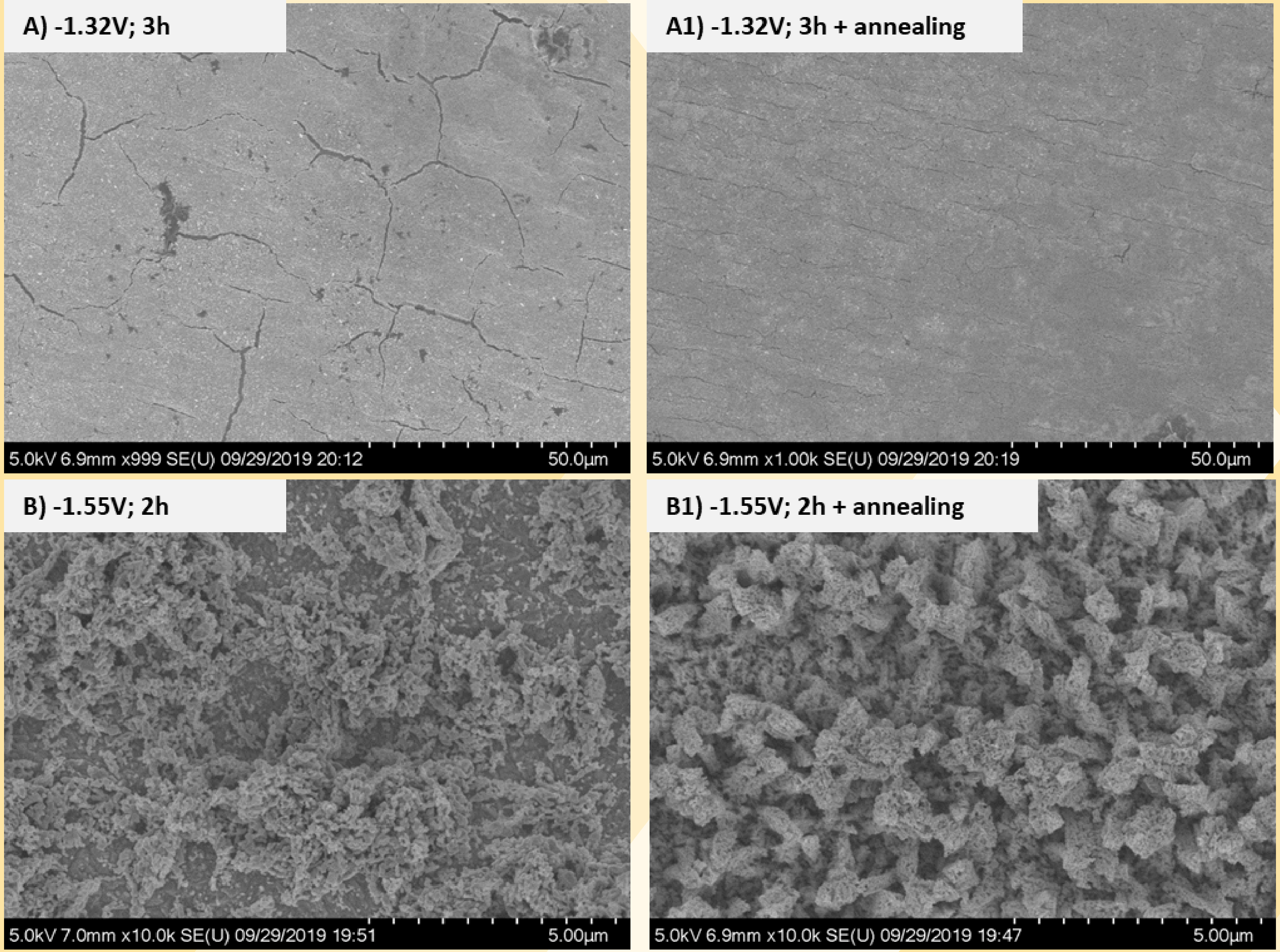
- Upon dealloying, the initial morphology of the precursor Cu-Zn alloy is preserved.
- The crack size increases at %age Zn increases in Cu-Zn.
- Residual Zn after dealloying needs more evaluation.

Dealloying of Different Cu-Zn alloys in 1M HCl - Magnified



- Different NP-Cu morphologies – particle like structures v/s structures with well-defined ligaments.
- Impact of different morphologies on NP-Cu properties?

Free Dealloying in 1M HCl after Annealing – 150°C/90min/N_2



- Annealing prior to dealloying results in significant reduction in cracks after dealloying.
- Further evaluation needed to understand the underlying mechanism.

Summary and Key Accomplishments

- Developed and demonstrated the protocol for fabrication of NP-Cu from Cu-Zn alloy films.
- In-depth characterization of co-electrodeposition of Cu-Zn with variable Zn content completed.
- Detailed study on the impact of Cu-Zn precursor alloy structure on morphology and residual Zn of NP-Cu also completed.
- Annealing of the plated Cu-Zn films was found to mitigate the cracks formed during dealloying.
- Based on results, Cu-Zn alloy films with Zn>85% and Zn~50% selected for sintering and assembly demonstration.

Timeline

Research Tasks	Status	Sub-tasks	2019		2020				2021	
			Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2
Fabrication of NP-Cu	Done	Cu-Zn co-electrodeposition process development								
	Done	Development of free dealloying protocol in dil. HCL								
	Ongoing	Dealloying Cu-Zn alloy films in different etchants								
	Ongoing	Electrochemical dealloying of Cu-Zn films								
	Ongoing	Process optimization for thickness scaling								
Assembly and reliability characterization	Ongoing	Sintering kinetics of NP-Cu – effect of morphology and temperature								
	Ongoing	Assembly round 1 and mechanical characterization								
		Thermal and reliability characterization on round 1 assembly								
		Assembly round 2 and mechanical characterization								
		Thermal and reliability characterization on round 2 assembly								
Phase -2, Sintered Cu with compliance in X-Y plane		Fabrication and assembly process design to provide compliance for stress-relaxation after assembly								

Fabrication of NP-Cu

Assembly and reliability characterization of NP-Cu die-attach joint

Phase 2, assembly and process design for in-built compliance in the die-attach joints

Current quarter