A Study of Dilute Cu Alloys for Dual-Damascene Interconnect Applications

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Objectives

Cu integration research is presently focused on the reduction of electromigration, stress migration and associated void formation along with inhibiting corrosion. As part of this effort, a set of Cu alloys is characterized to assess their performance.

Evaluated Alloys

- 6N Cu
- Cu-0.5at%Ag
- Cu-0.5at%Al
- Cu-0.5at%Sn
- Cu-0.5at%Ti

Target Properties

- Target hardness
- Target grain recovery
- Electrical resistivity
- Thermal conductivity
- CTE
- IV characteristics
- Deposition yield

PVD ECD Film Properties

- Electrical resistivity
- Reflectivity
- Stress
- Adhesion
- XRD orientation
- SIMS diffusion profile
- AFM microstructure
- Corrosion
- Leakage current, line resistance

Due to the memory constrains, only highlights are presented here. For details, please contact eal.lee@honeywell.com

Target Characterization Summary

- **Alloying addition increases hardness of forged alloys, but the increase becomes insignificant once exposed to elevated temperature (>350 C) after recrystallization.**

- **Ti increases electrical resistivity most and resistance to grain growth.**

- **Alloying addition increases electrical resistivity and decreases thermal conductivity.**

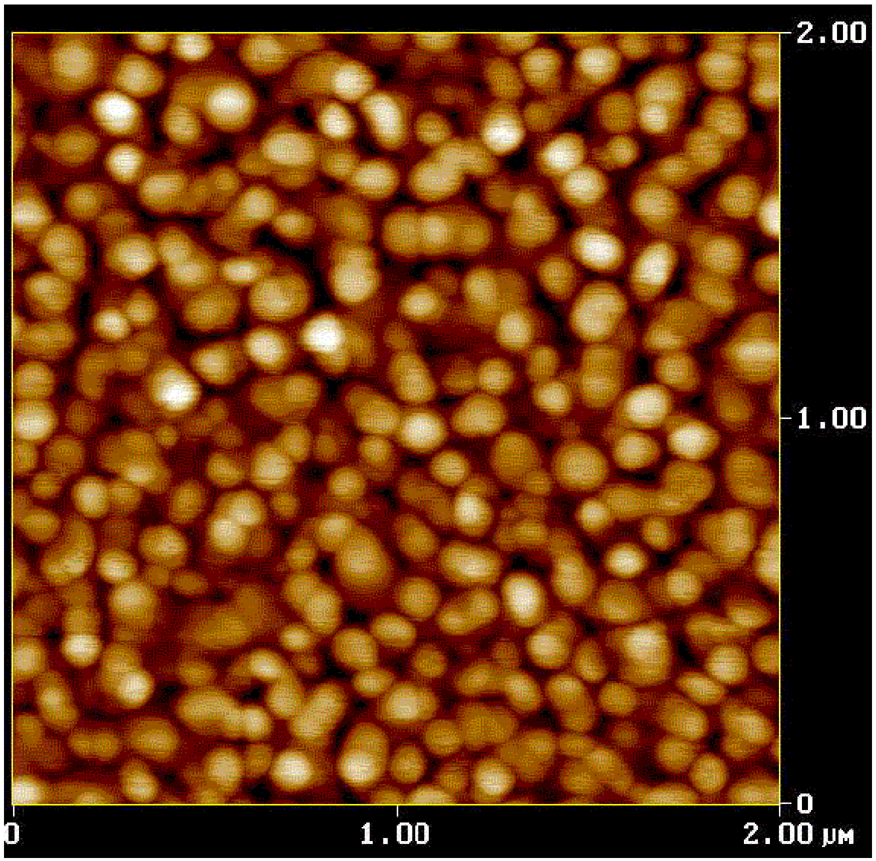
- **Ag produces the least increase in electrical resistivity and the lowest CTE.**

- **V vs. Power and I vs. Power show no significant difference in response regardless of alloy composition.**

- **Alloying addition refines grain size and improves deposition yield.**

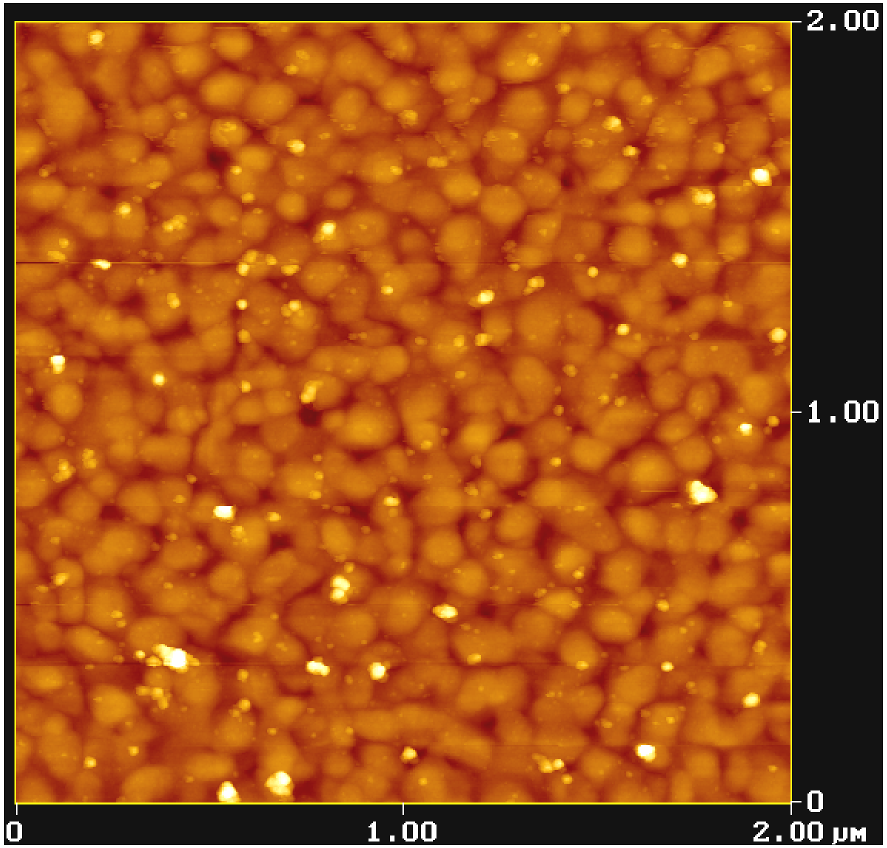
AFM Microstructure of PVD Cu-Seed Film

69Cu (Ra=2.2 nm)



Grain size 110 nm

Cu-Al (Ra=2.86 nm)



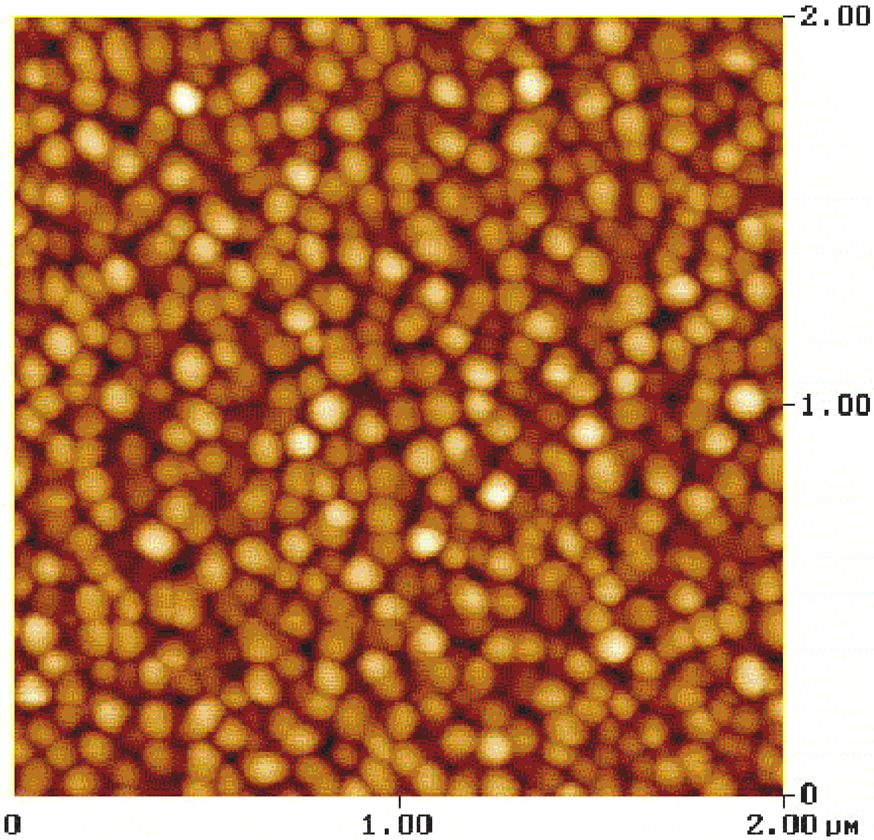
Grain size 115 nm

Al addition increased the grain size slightly.

Ra (surface roughness): Average of absolute values of the delta of all the height values from the mean (not rms)

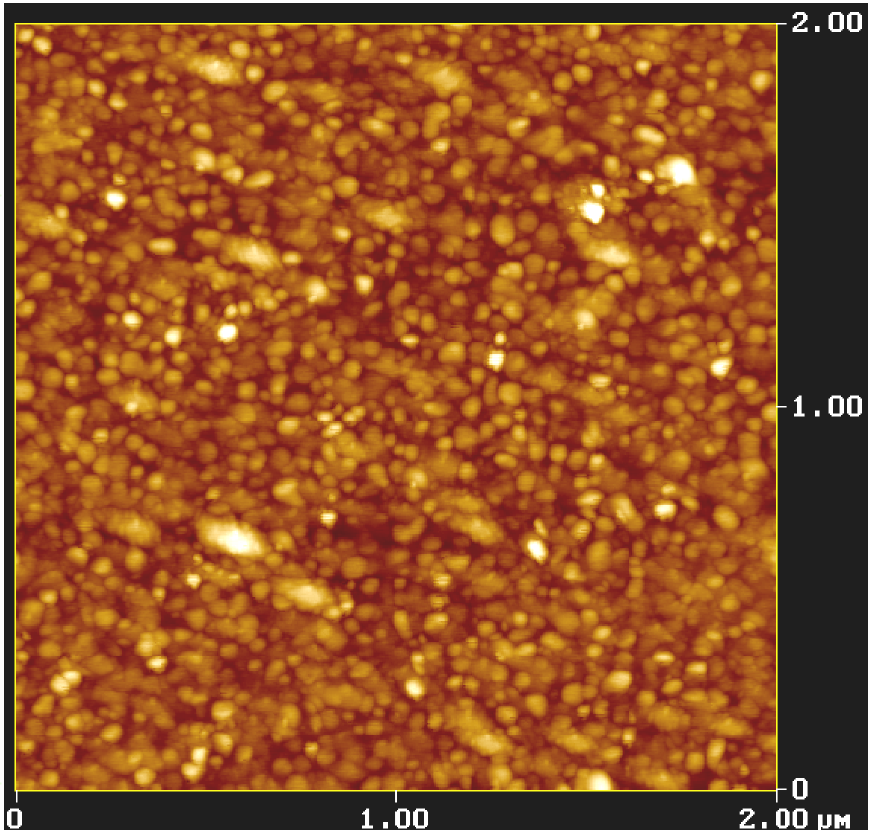
AFM Microstructure of PVD Cu-Seed Film

Cu-Ti (Ra=1.7 nm)



Grain size 86 nm

Cu-Sn (Ra=1.01 nm)

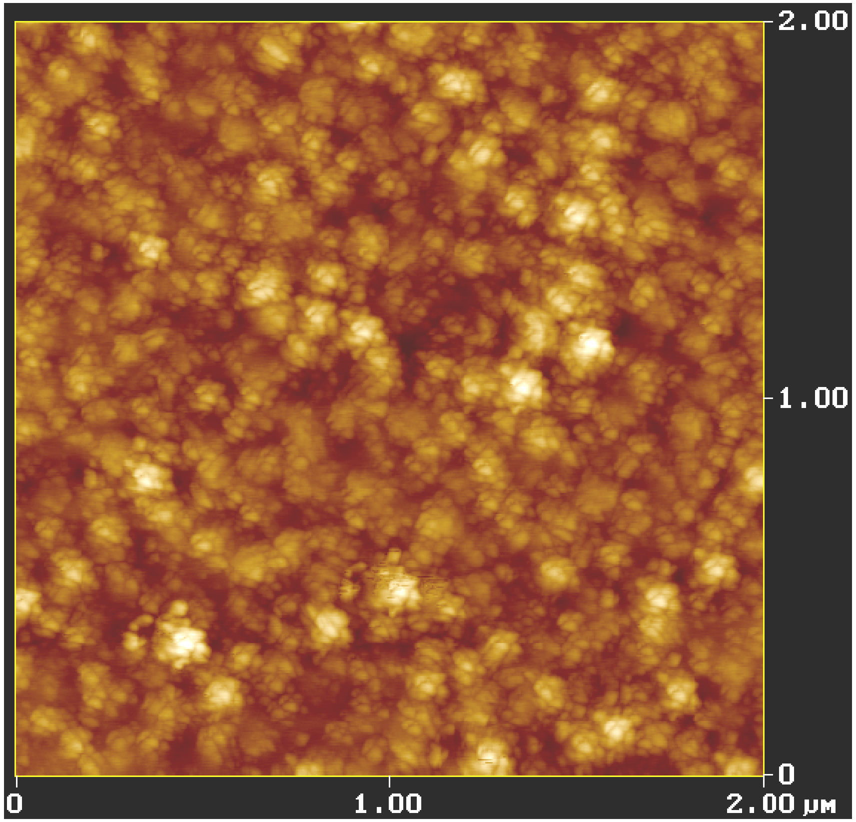


Grain size 57 nm

Ti and Sn addition produced finer grain sizes.

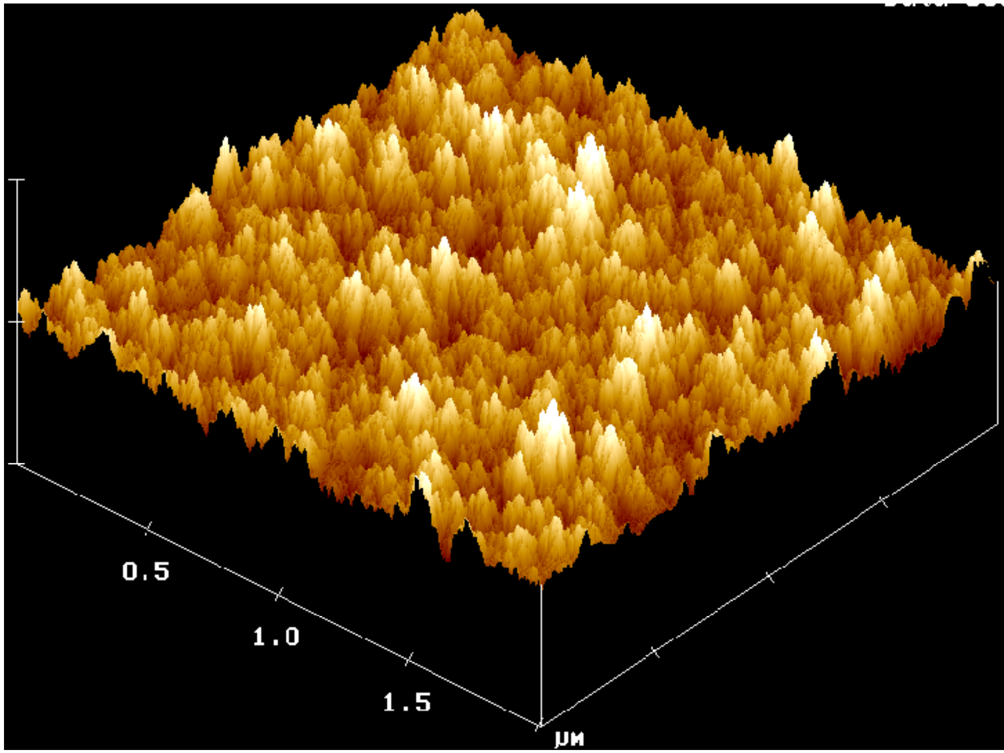
AFM Microstructure of PVD Cu-Seed Film

Cu-Ag (Ra=1.05 nm)



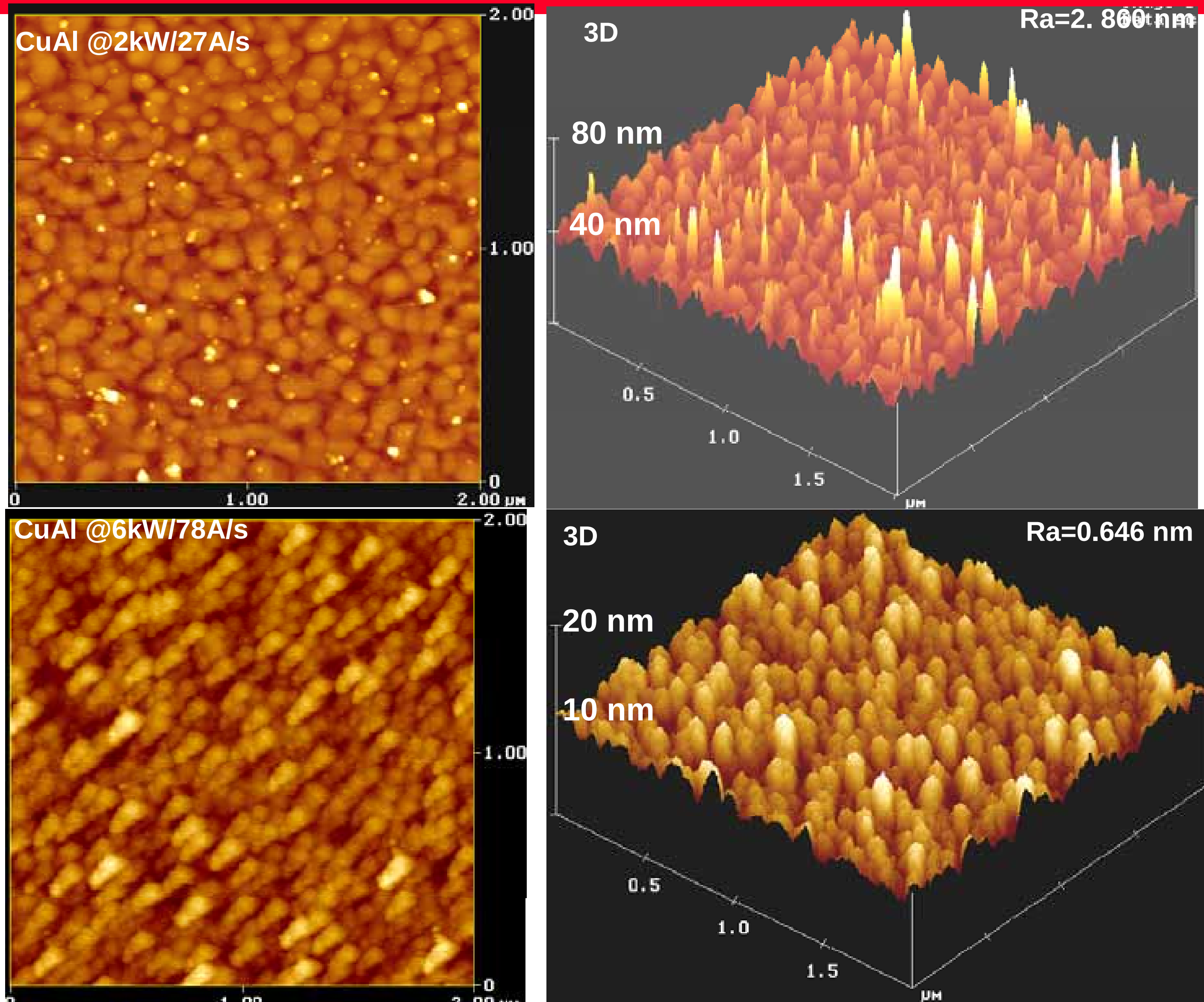
Grain size 25 nm

Angled View of Cu-Ag



Ag addition produced the finest grain sizes.

AFM topography of 1200A Cu-Al deposited @2 kW and 6kW at RT



High power deposition produces finer grain size and smoother surface due to enhanced nucleation rate.

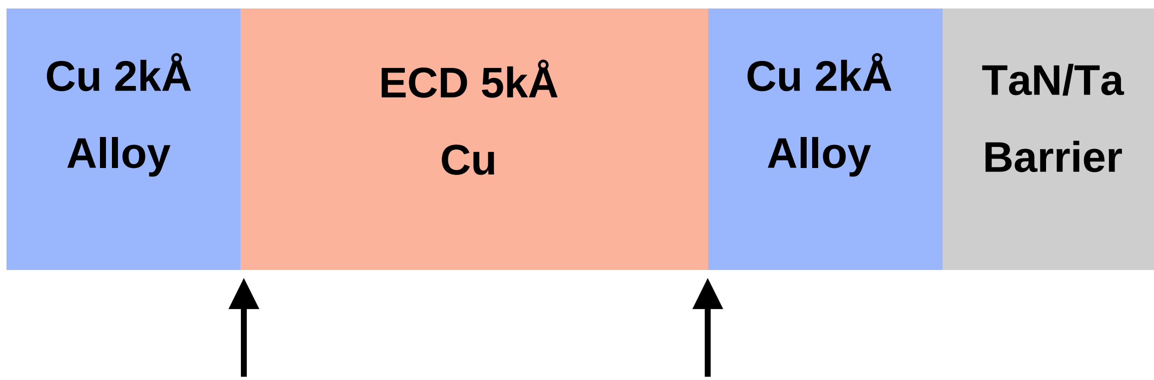
XRD characterization of Cu-0.5at.%X films

Film (350C/30 min)	XRD Integrated Peak Intensity (%)			
	<111>	<200>	<220>	<113>
6N Cu-Seed	100	0	0	0
6N Cu + ECD	85.1	4.8	3.1	6.9
CuSn-Seed	100	0	0	0
CuSn + ECD	82.2	8.2	4.0	5.6
CuAl-Seed	100	0	0	0
CuAl + ECD	64.8	18.0	7.3	10.0
CuAg-Seed	100	0	0	0
CuAg + ECD	56.0	21.9	10.2	11.9
CuTi-Seed	100	0	0	0
CuTi + ECD	80.7	6.8	3.5	9.0

Cu-seed showed predominantly <111> orientation for all alloying additions, but ECD Cu orientation varied with seed composition, 69Cu seed extending <111> orientation most.

SIMS Analysis Layer Structure

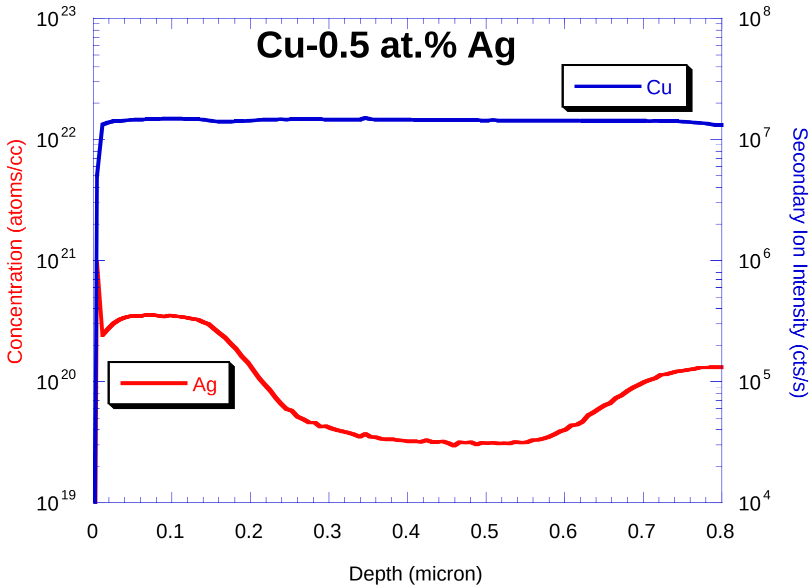
Annealed @ 400 ºC for 1 hour

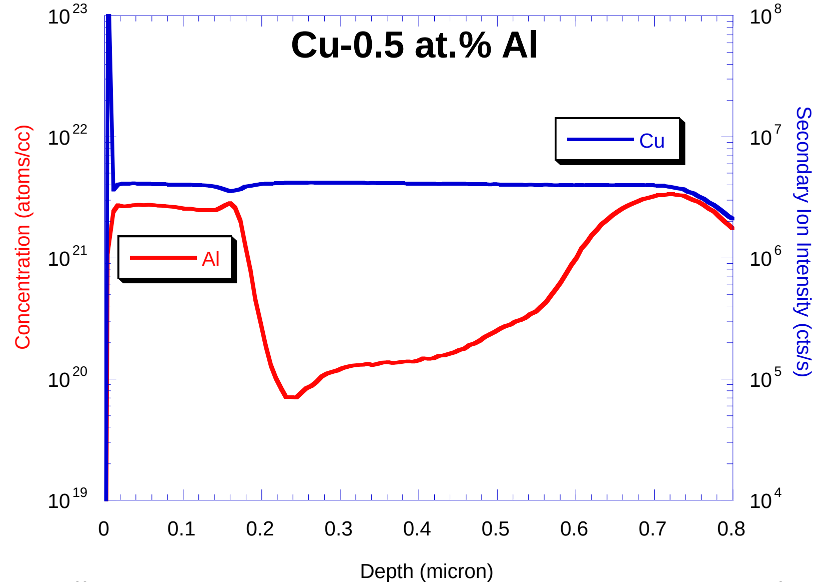


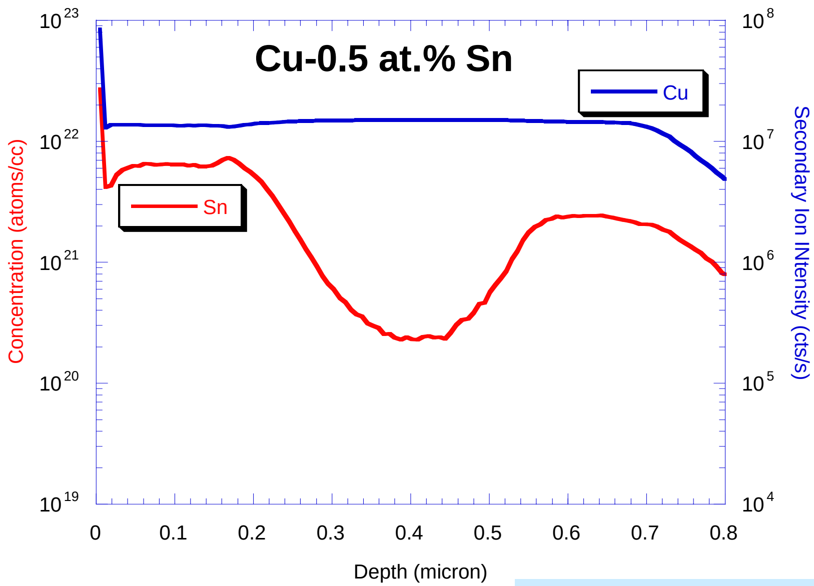
Oxide layer at this interface remains and may suppress the diffusion. This can cause non-symmetric SIMS profile.

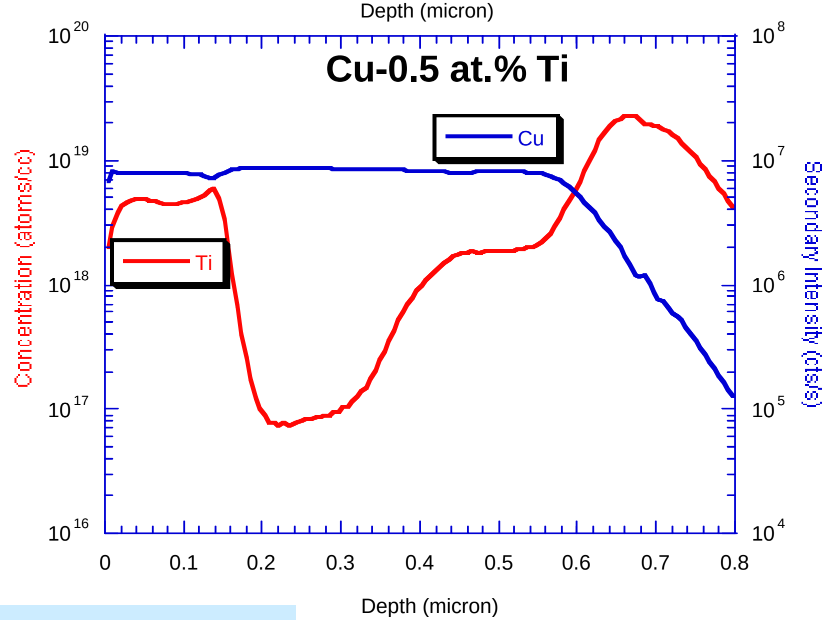
Oxide layer at this interface dissolves away during ECD.

SIMS diffusion profile of alloying elements after 400C/1 hr









Ag diffuses fastest followed by Sn.

Film Characterization Summary

•Reflectivity of Cu-seed layer varies strongly with annealing temperature, whereas that of ECD Cu shows little variation.

•Alloying addition imparts little effect on the grain size and electrical resistivity of ECD copper.

•Stress of seed layer is generally higher than those of ECD Cu, but imparts little effect on the stress of ECD film.

•All alloyed Cu-seed films show good adhesion to TaN/Ta barrier.

•All Cu-seed showed predominantly <111> orientation regardless of composition.

•SIMS analysis shows complete homogenization of Ag through ECD Cu, whereas Mg shows limited diffusion. Non-symmetric diffusion of Ti and Al SIMS indicates surface oxidation effect. Potential advantage or disadvantage of this diffusional behavior should be evaluated.

Electrical Testing Flow

Process flow

ILD deposition: $SiN\backslash SiO_2$

↓

Trench patterning: Litho, Etch, Ash

↓

Degas: 415C, 100 s
Barrier dep.: TaN\Ta
Cu seed dep.

↓

ECP Cu (10kA)

↓

Cu Anneal
200C/60min

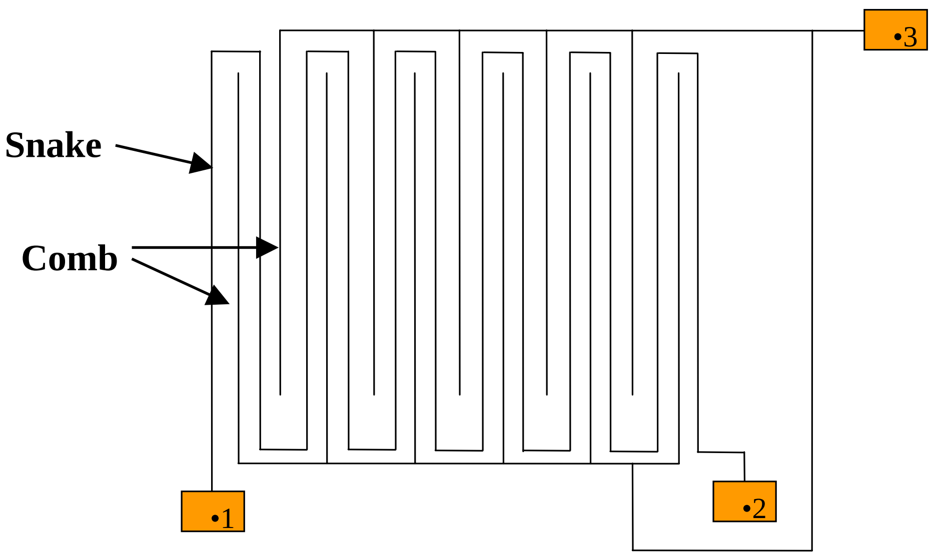
↓

CMP

↓

E-TEST

Test structure



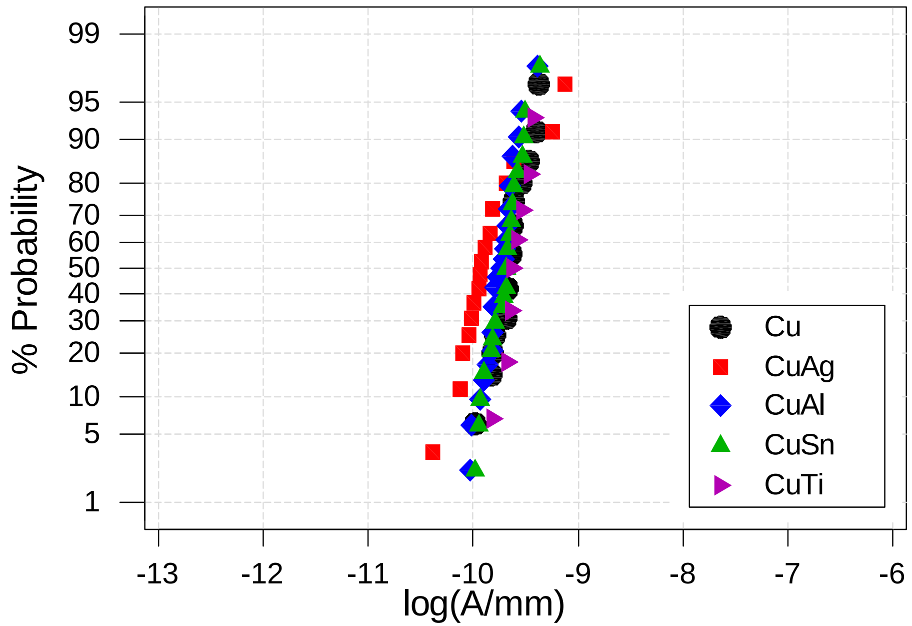
•Line-to-line leakage (also called comb leakage):
Apply voltage between Pads (1,2 shorted) and Pad (3)

•Snake resistance (also called Serpentine resistance):
Apply voltage between Pad 1 and Pad 2

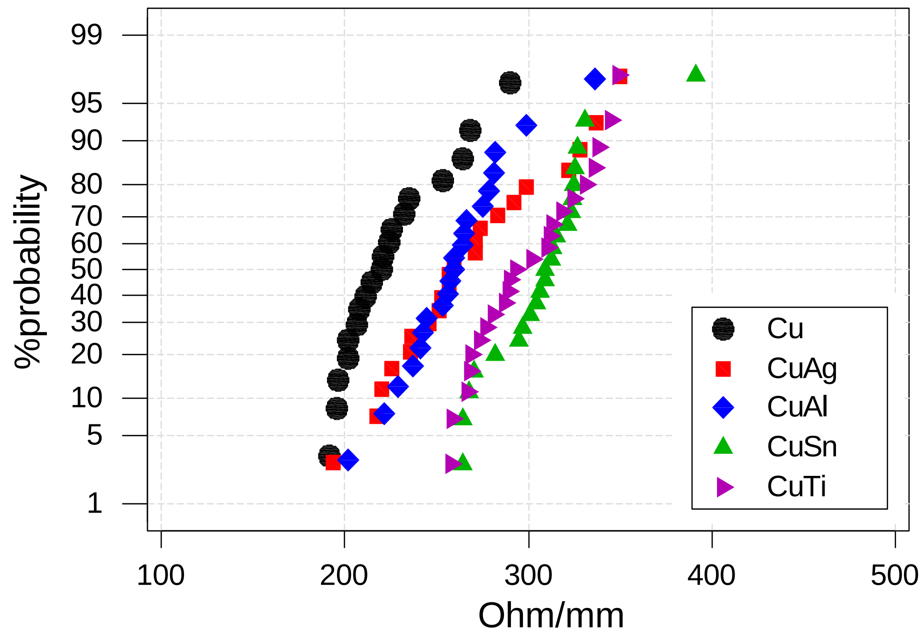
Comb Leakage Current and Serpentine Resistance

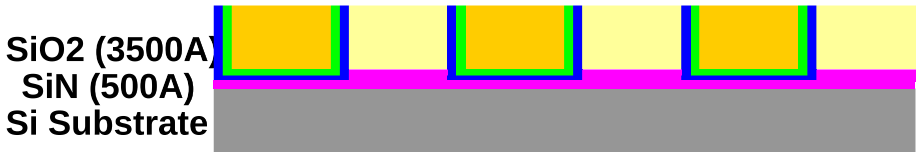
L/S = 0.32/0.32 μ

Comb Leakage current



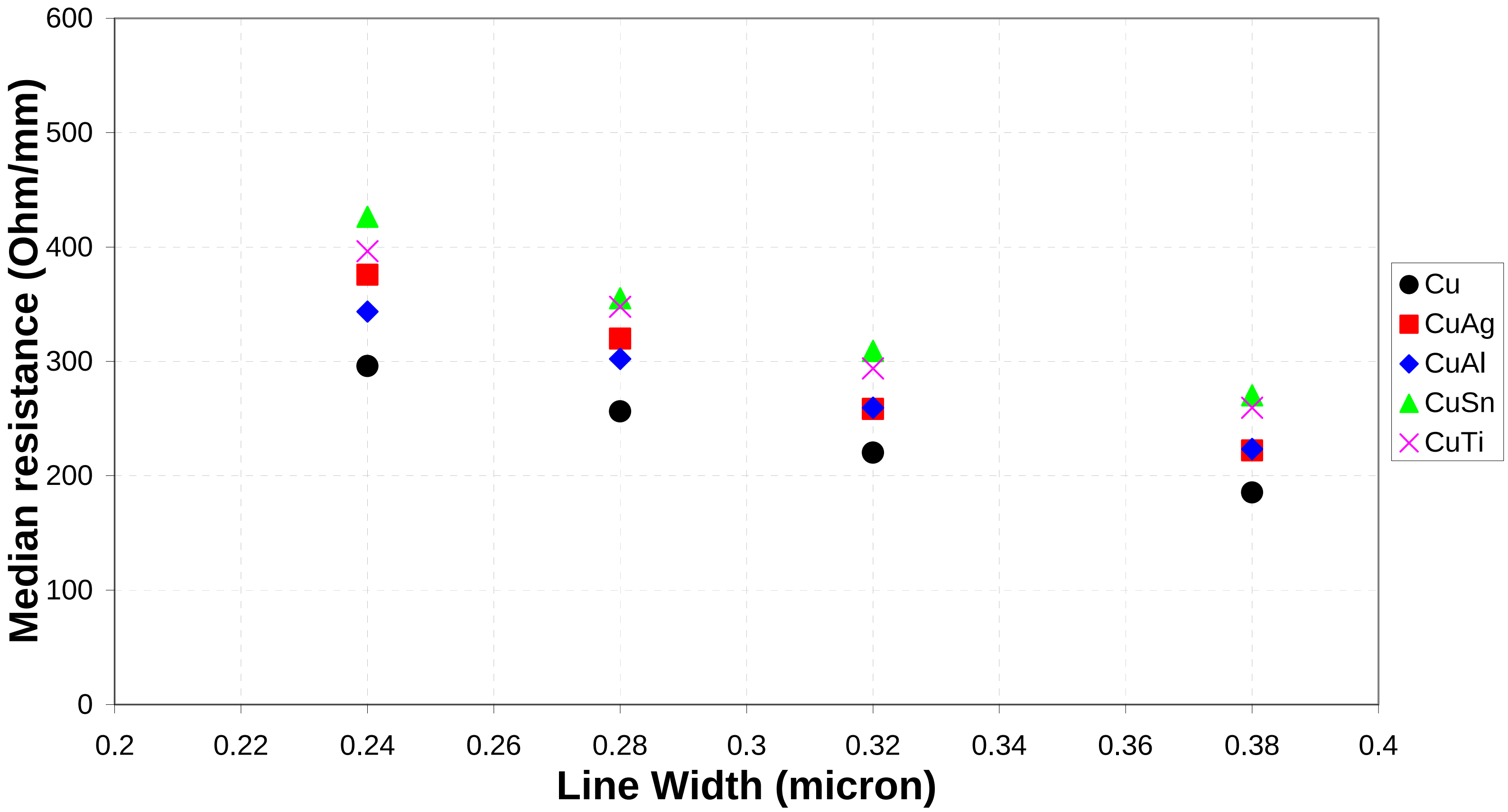
Serpentine resistance





- Cu alloy composition did not significantly affect comb leakage current
- Cu-Ag and Cu-Al show 10-15% higher serpentine resistance than 69Cu
- Cu-Ti and Cu-Sn show % higher serpentine resistance than 69Cu

Resistance vs. Line Width for Copper Alloys



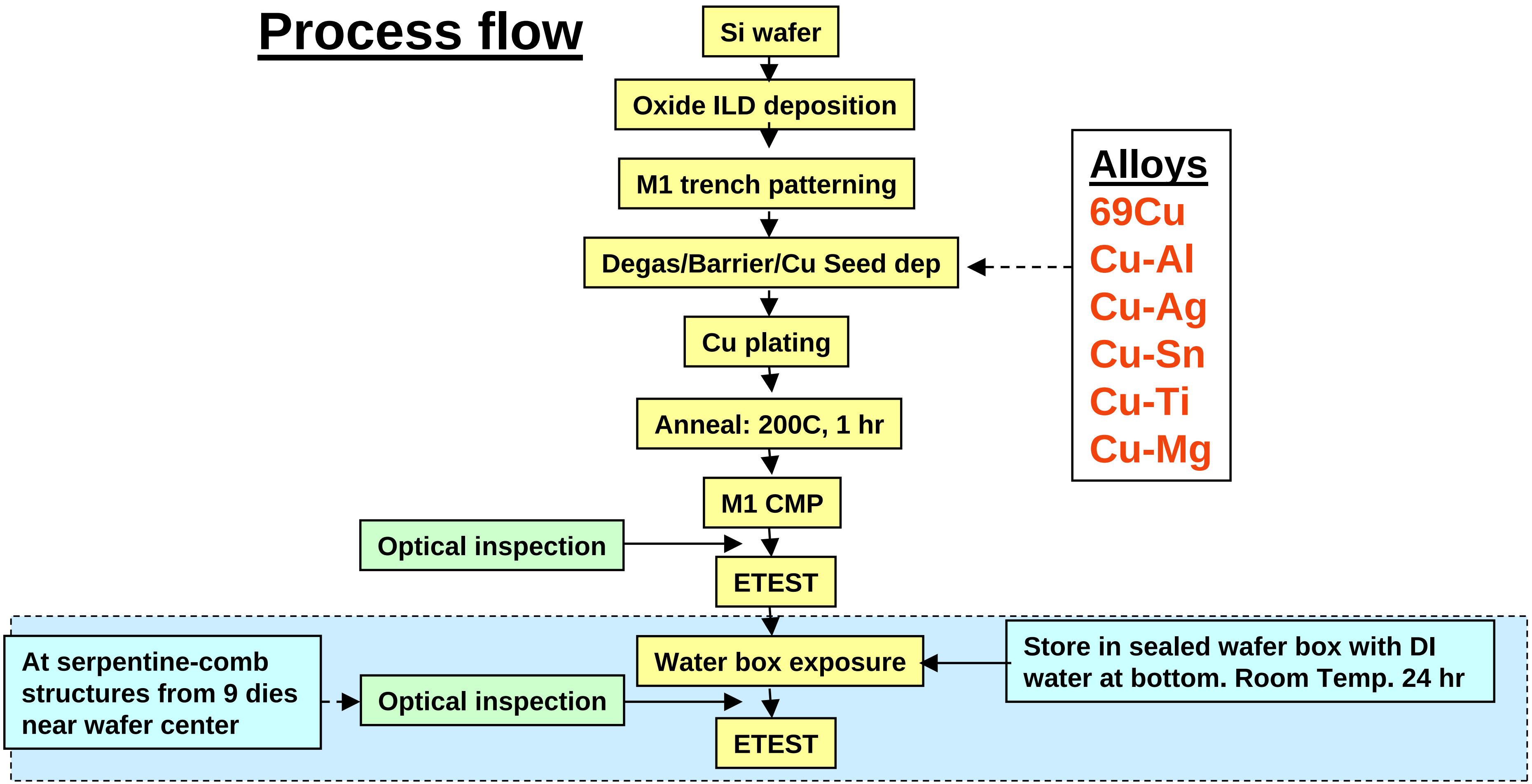
Serpentine resistance in the 0.24 – 0.38 micron line width range:

Line resistance decreases with line width because of reduced liner contribution

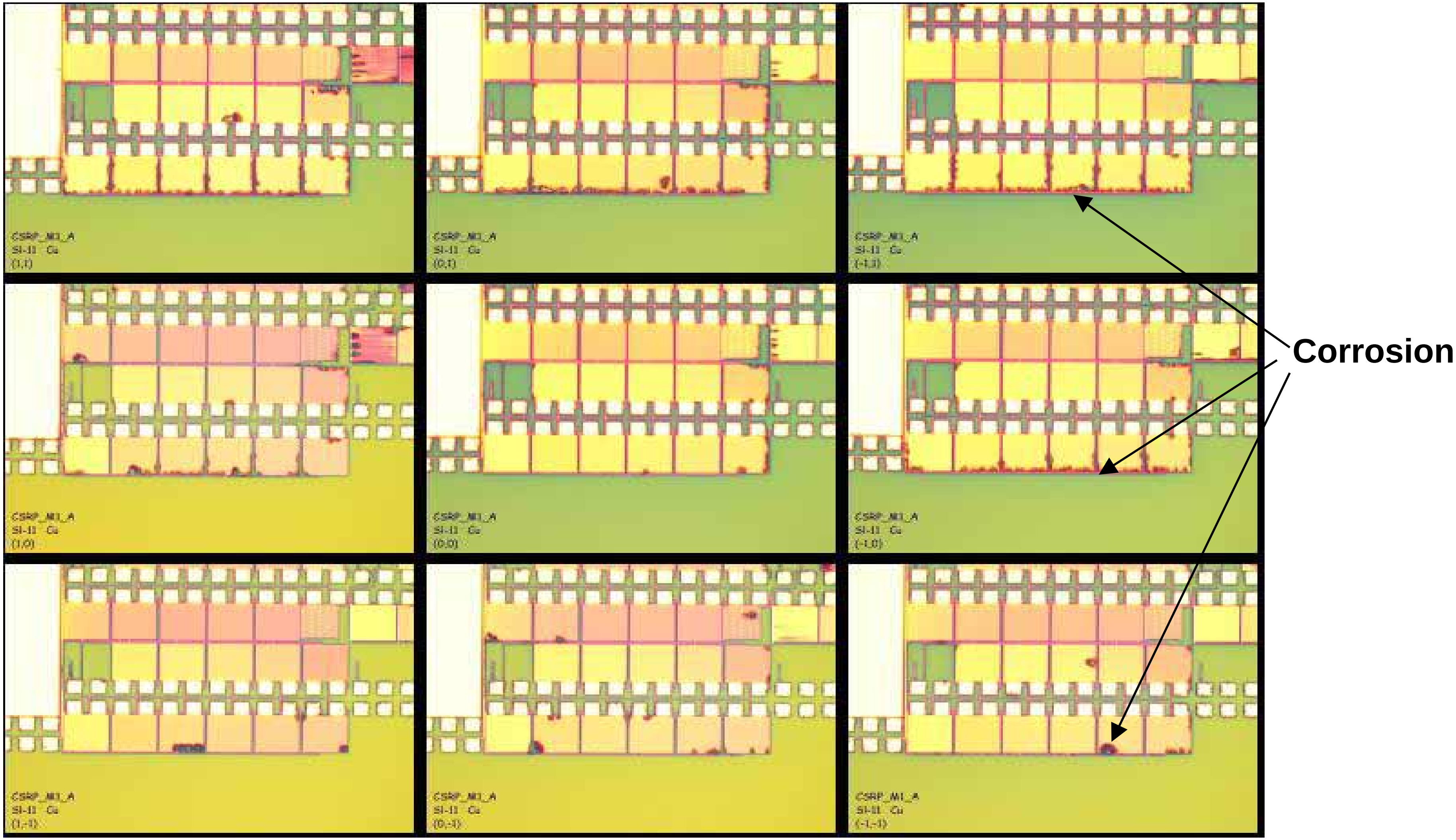
Alloying Effect: 69Cu **<** Cu-Al ~ Cu-Ag **<** Cu-Ti ~ Cu-Sn

Water Box Corrosion Test

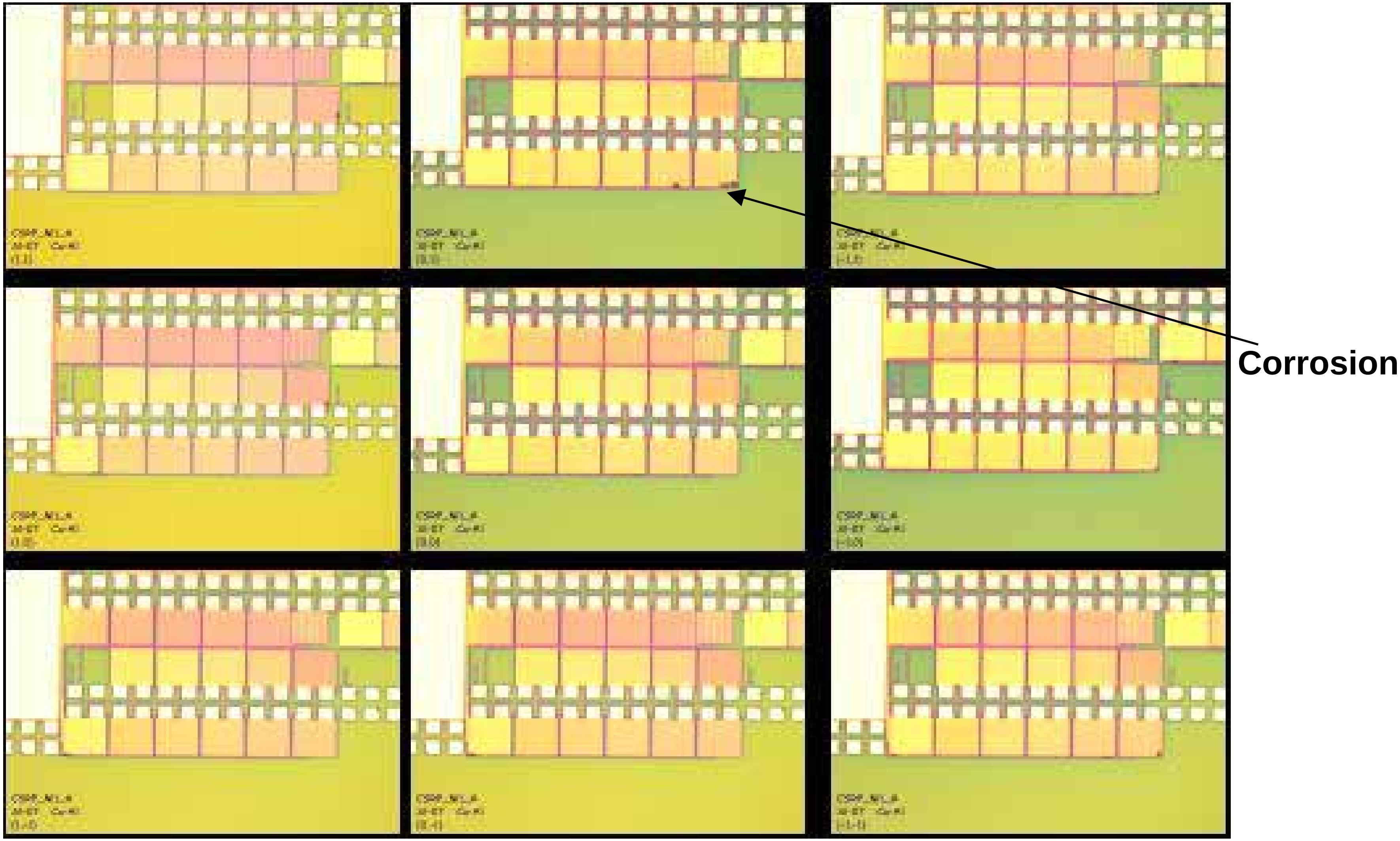
Process flow



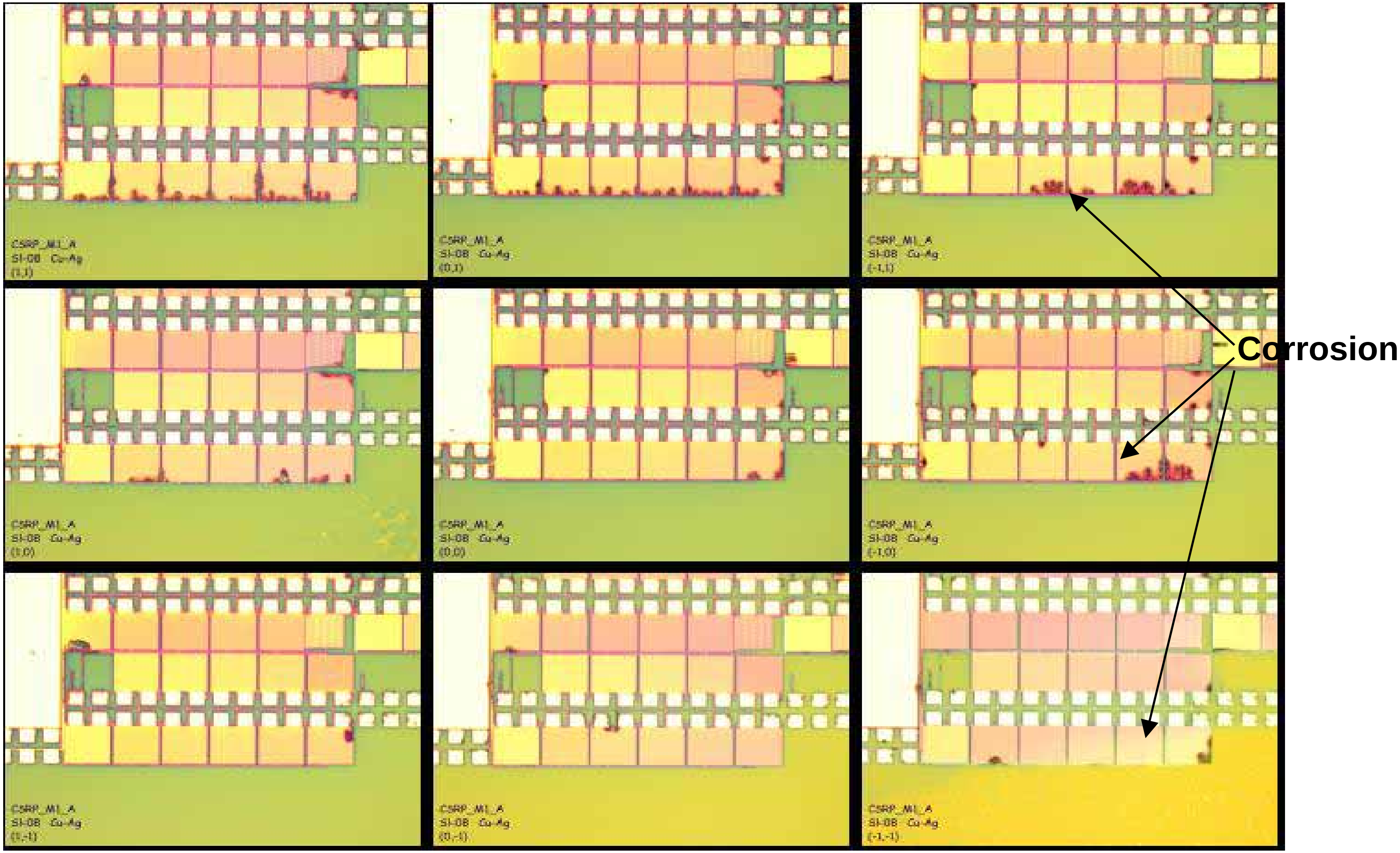
Optical Inspection of 69Cu



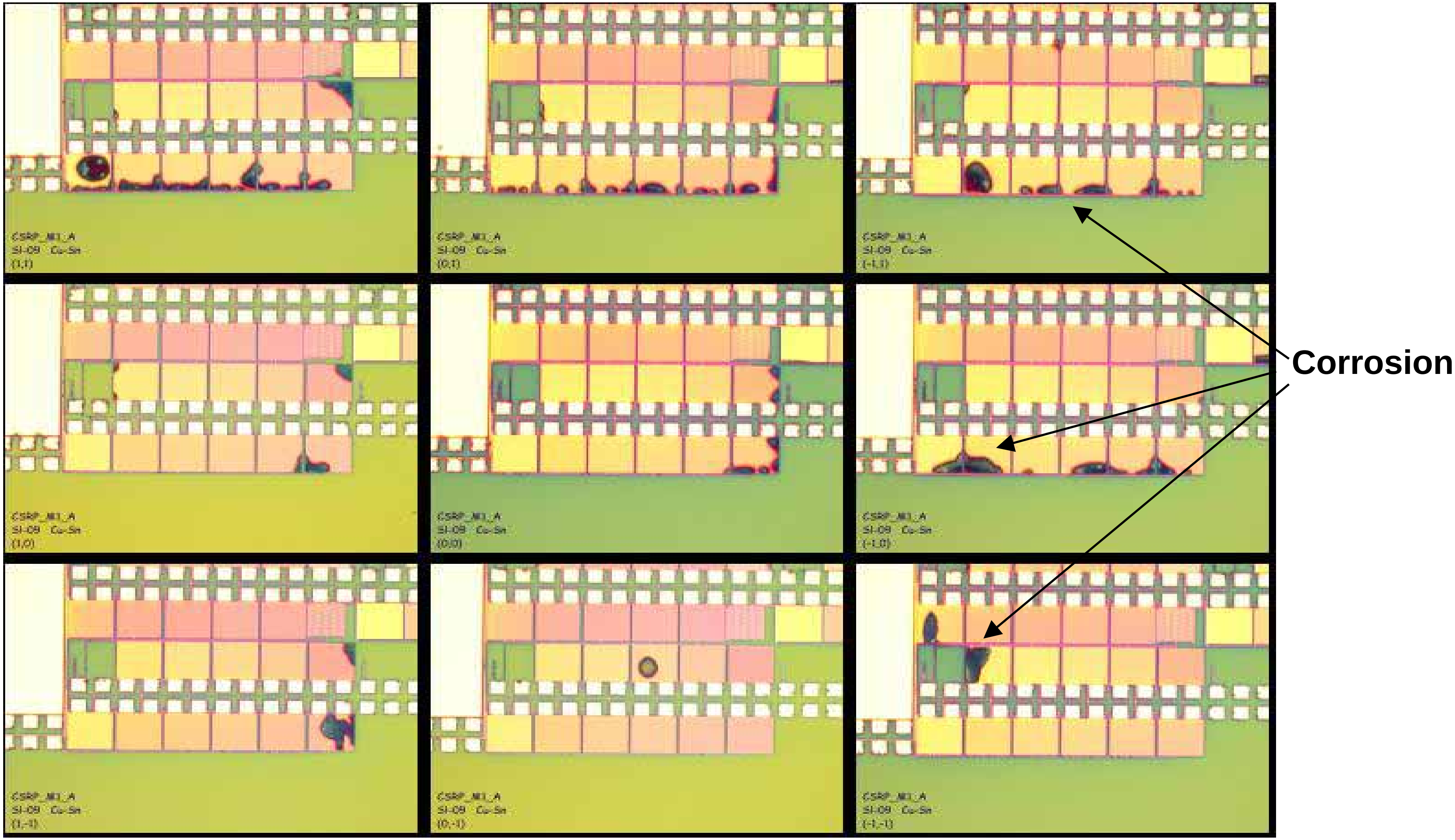
Optical Inspection of Cu-Al



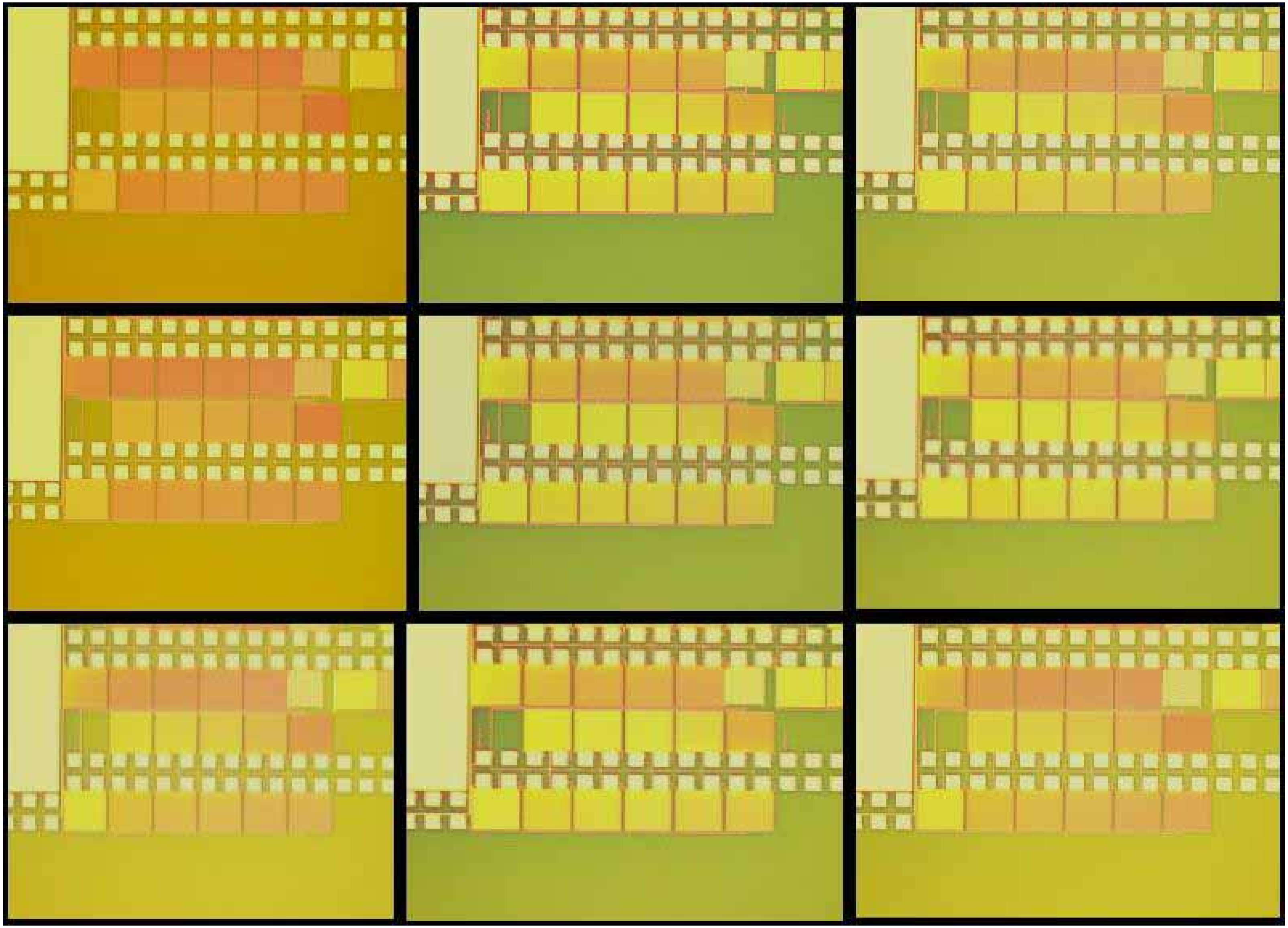
Optical Inspection of Cu-Ag



Optical Inspection of Cu-Sn

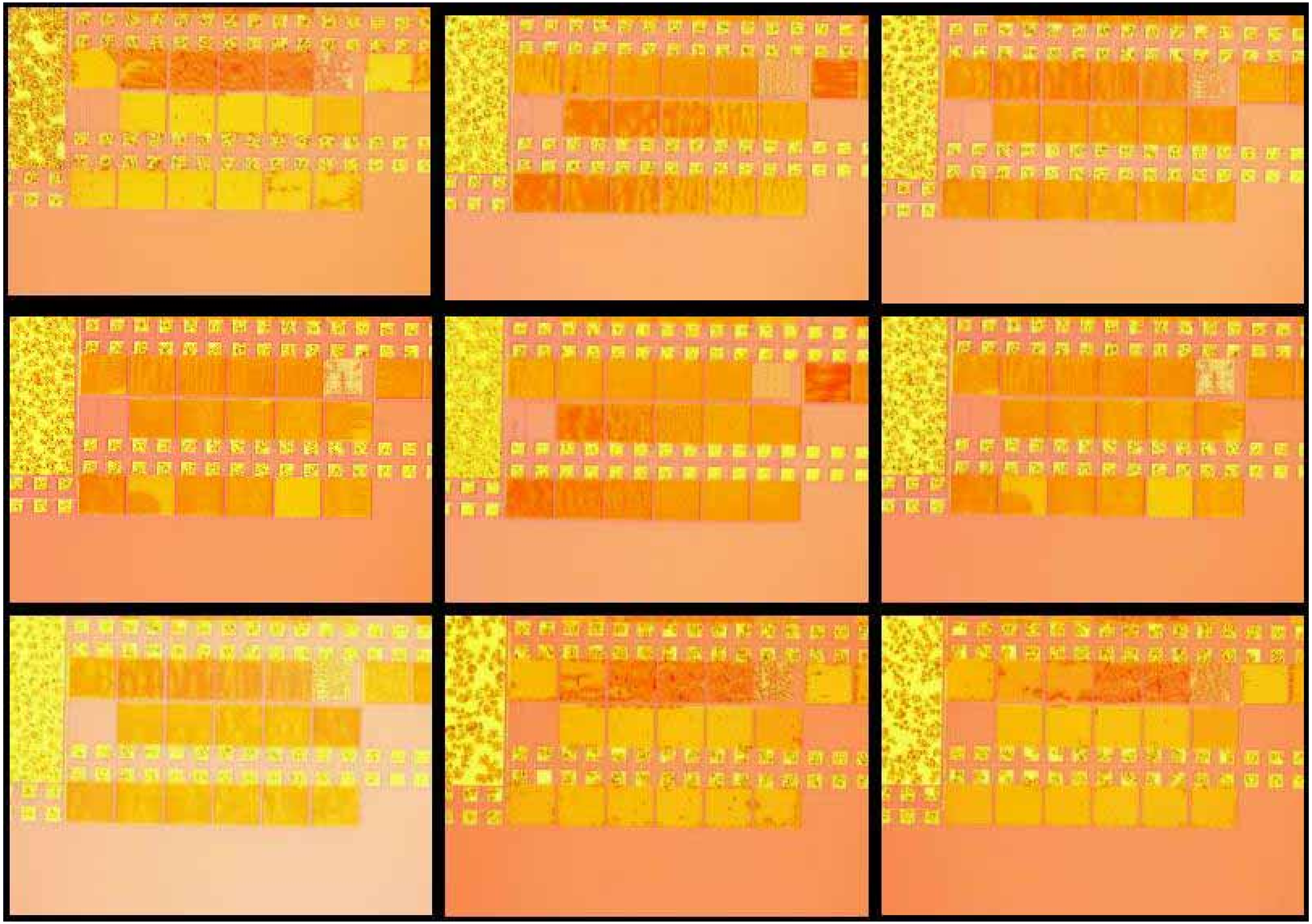


Optical Inspection of Cu-Ti



No Corrosion

Optical Inspection of Cu-Mg



Profuse Corrosion

Summary of Optical Inspection

- Significant corrosion was seen after water box test in case of seed layer formed by 69Cu, Cu-Ag, Cu-Sn, and Cu-Mg alloys

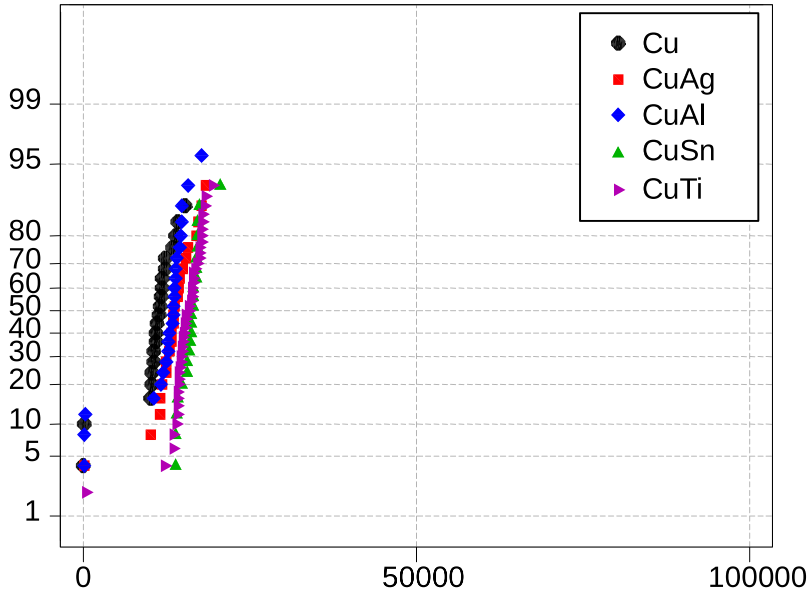
- Very little corrosion was observed in case of Cu-Al, whereas Cu-Ti seed layer showed no corrosion.

- Preferred corrosion sites are edges and corners of Cu features, especially those adjacent to large field regions.

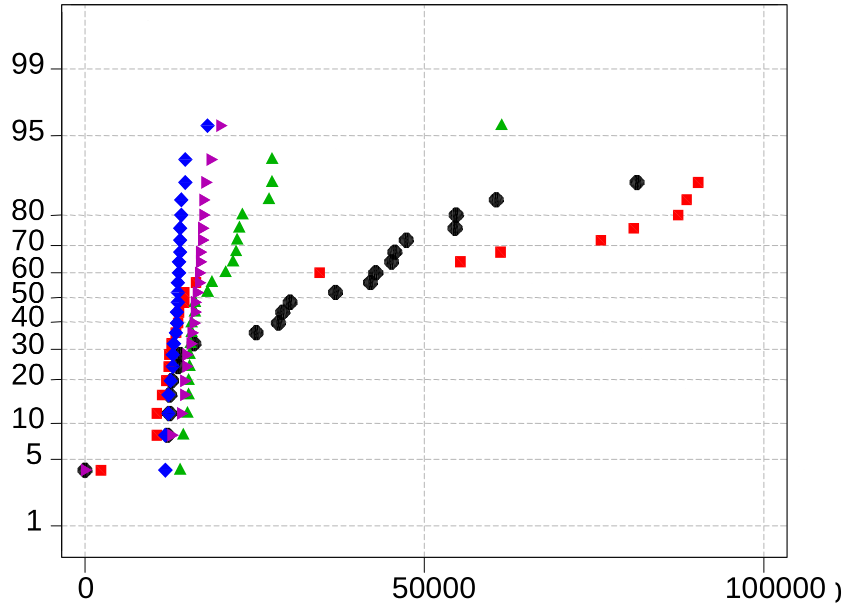
Serpentine Resistance before and after exposure to water vapor

L/S = 0.32/0.32 μm

Before water-box exposure



After water-box exposure



Water box exposure caused the highest increase in serpentine resistance for <u>69Cu</u> and <u>Cu-Ag</u>, followed by <u>Cu-Sn</u>.

No change in serpentine resistance was noticed in case of <u>Cu-Al</u> and <u>Cu-Ti</u> seed layers.

Summary of E-Test

• ECD Cu with 69Cu seed rendered the lowest line resistance and the highest with CuTi seed.

• Alloying elements imparted no significant impact on line leakage current.

• Excellent corrosion resistance was seen in single level metal structures formed using Cu-Al and Cu-Ti alloys as seed layer. This is likely due to a possible formation of a protective oxide film on Cu surface (e.g., Al_2O_3, TiO_2).

•While Ag and Sn diffuse easily throughout Cu during annealing, it doesn't seem to form a protective layer

•Cu-Sn alloy needs to be studied further. While the optical images showed significant corrosion, the serpentine resistance was affected less than in case of 69Cu and Cu-Ag.

Final Remarks

•Ag is considered to be the best candidate for improving electromigration resistance in consideration of its fast homogenization, low electrical resistivity, and high atomic mass. However, actual EM data is still needed.

•Ti shows the best corrosion resistance but increases electrical resistivity in both seed and ECD Cu.

•Al shows excellent corrosion resistance and produces negligible increase in electrical resistivity for ECD Cu.

•Sn is the highest atomic mass element tested and considered to be good for electromigration resistance.