Electrochemical Plating of Metastable Fine Grain Cu for Cu-Cu Hybrid Bonding Applications

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on behalf of Pingping Ye

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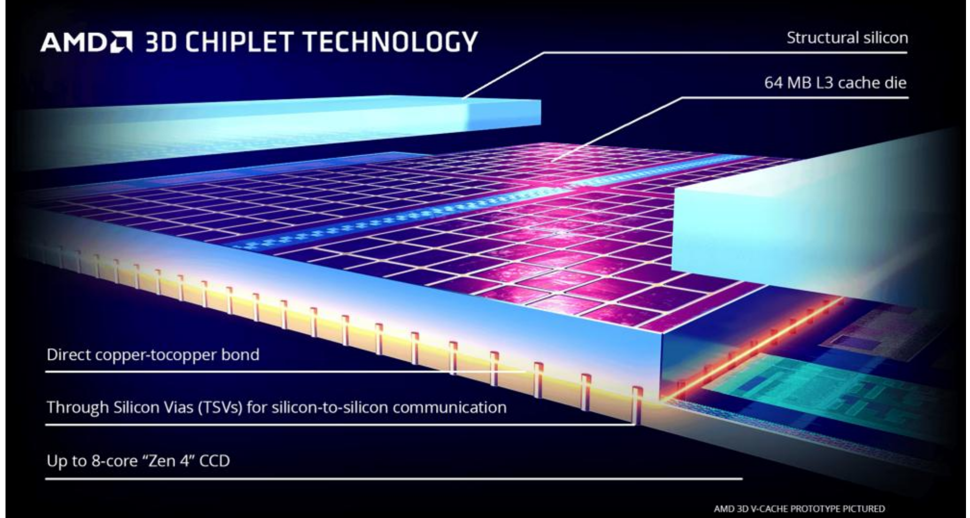
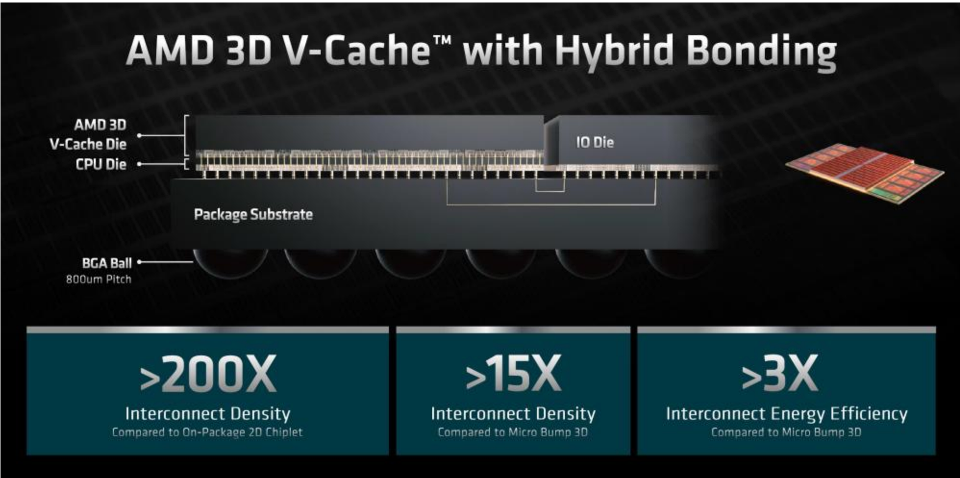
Outline

- Introduction
- Screening of metastable fine grain on blanket wafer
  - XRD
  - Sheet resistance
- Cu grain evolution of self-annealing
  - Disparity of Cu grain evolution on blanket vs. patterned wafer
  - Disparity of Cu grain evolution on different patterned wafers
- Fabrication of metastable fine grain on patterned wafer
  - Mechanism
  - Examples
- Conclusion

Introduction

- The need for hybrid bonding
  - Increasing the density of interconnections to enable more functionality in each devices
  - Traditional solder technology is not suitable for pitch size below 10µm
    - ➢ Brittle intermetallic compounds (IMCs)
    - ➢ Circuit shortage (bridging solder), thermal stress, electromigration
- Some of the benefits of hybrid bonding
  - Reducing the resistance due to the Cu-Cu direct bonding without foreign material
  - Reducing the latency due to shorter interconnect





https://www.amd.com/content/dam/amd/en/documents/epyc-business-docs/product-briefs/3d-vcache.pdf

1.5 µm pitch

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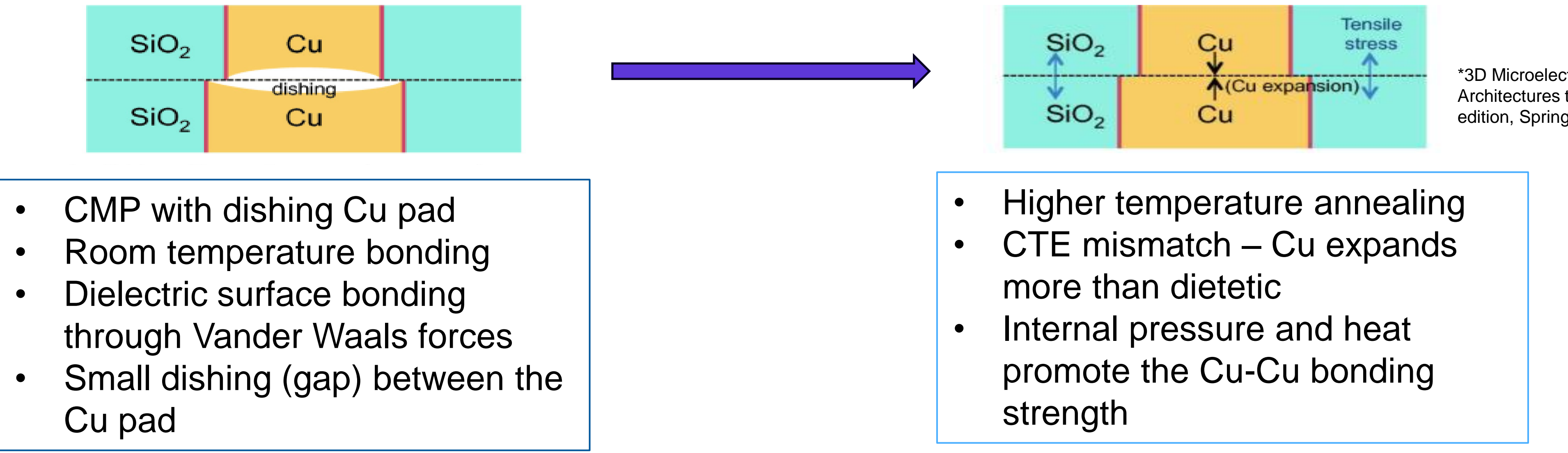
Introduction

- Hybrid bonding process



*3D Microelectron IC Packaging: From Architectures to Applications, second edition, Springer

- Sensitive memory applications (HBM) require a reduction in thermal budget
- Grain engineering - thermal budget reduction paths
  - Modify the microstructure of Cu, particularly the grain orientation, grain size, grain boundary and their distribution
  - Enhance material properties such as mechanical strength, electrical conductivity, and electromigration

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Grain Engineering - Thermal Budget Reduction Paths

▪ Nanotwinned Cu:

- Nanotwinned Cu with (111) plane parallel to the bonding interface
- Higher atomic diffusivity of (111)

Dsurface (m^2/s) / Temp(°C)	Cu(111)	Cu(100)	Cu(110)
150	6.85×10^{-10}	2.15×10^{-14}	6.61×10^{-16}
200	9.42×10^{-10}	1.19×10^{-13}	5.98×10^{-15}
250	1.22×10^{-9}	4.74×10^{-13}	3.56×10^{-14}
300	1.51×10^{-9}	1.48×10^{-12}	1.55×10^{-13}

Calculated Cu surface diffusivity on (111), (100), and (110) planes at various temperatures, ranging from 150 °C to 300 °C *

* C.-M. Liu et al, Low-temperature direct copper-to-copper bonding enabled by creep on (111) surfaces of nanotwinned Cu. Sci. Rep. 5, 9734 (2015).

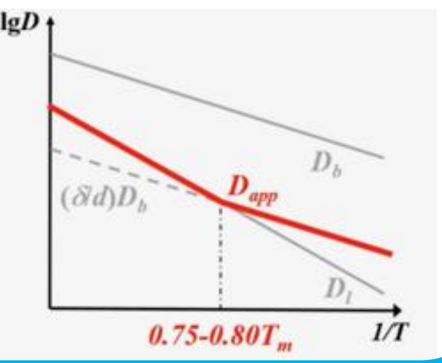
▪ Metastable Fine-Grained Cu:

- Grains are stable during queue time before bonding process and grain grows during bonding process
- Energy released during grain growth promote Cu interdiffusion:

$$\Delta E \propto (1/d_i - 1/d_f)$$

Temperature effect on diffusion coefficient D – lattice vs. grain boundary

- ➢ Grain boundary diffusion : **low T**
- ➢ Grain bulk / lattice diffusion: **high T**



Reference: J. Appl. Phys., Vol. 86, No. 5, 1 September 1999

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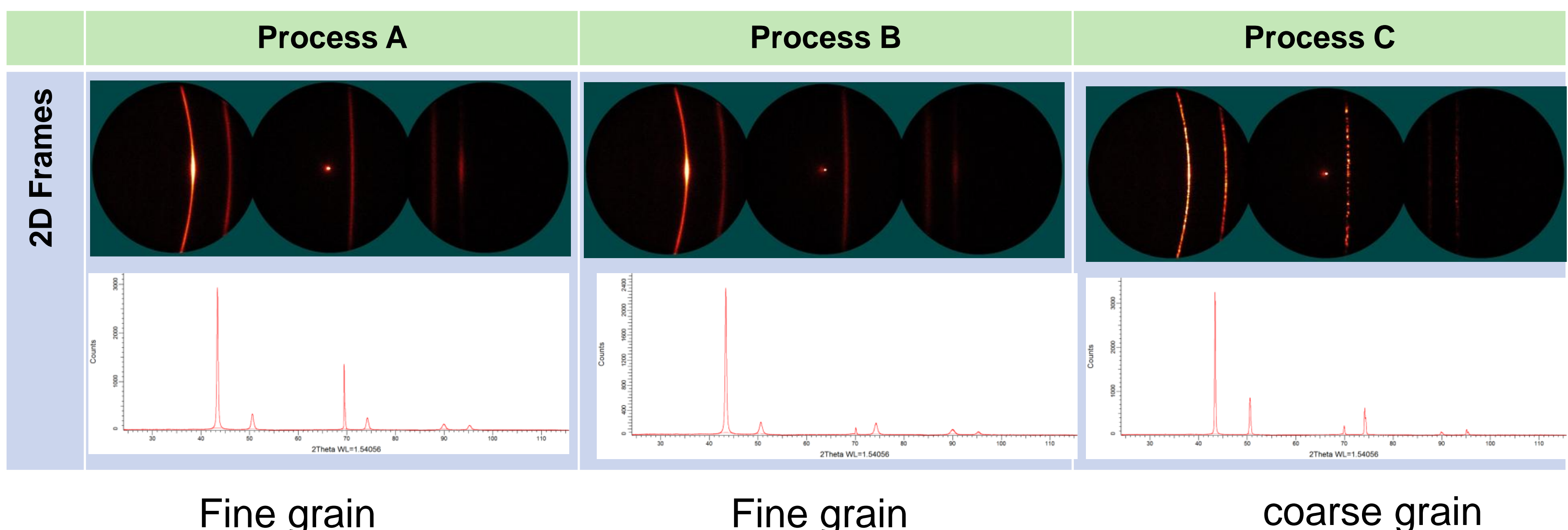
Screening of metastable fine grain on blanket wafer - XRD

- Chemistry and waveform screening
  - Debye rings
  - Peak width



Fine grain | Fine grain | coarse grain

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Mechanism of Cu grain evolution

- Velocity of a grain boundary $v = M * \Delta G$
  - M: grain boundary mobility ; ΔG: driving force / chemical potential difference / stored energy

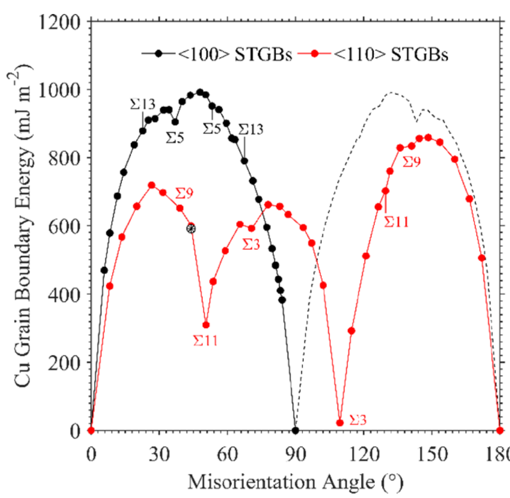
ΔG: Driving Force – thermodynamics based	
Positive force	**Negative force**
grain boundaries	Zener pinning -3γFv /2r • γ: surface energy • Fv: Volume fraction of pinning particles • r: particle radius
stacking faults	
Dislocation	
surface energy	
elastic strain/stress	
plastic strain/stress	

M: Mobility – kinetics based - Arrhenius equation

$$M(T) = M(T0) * \frac{T0}{T} e^{-\frac{Ea}{K}\left(\frac{1}{T}-\frac{1}{T0}\right)}$$

Ea: activation energy

- Grain boundary energy vs. misoriention angle



- Special high angle boundary (coincident site lattice)

- high stacking fault energy resulting in effectives of intragrain recovery / recrystallization – none-metastable status

Reference: ACTA METALLURGICA, VOL. 17, JULY 1969
JOURNAL OF APPLIED PHYSICS VOLUME 94, NUMBER 5

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Tschopp et al. Integrating Materials and Manufacturing Innovation (2015) 4:11 DOI 10.1186/s40192-015-0040-1

Mechanism of Cu grain evolution

- Velocity of a grain boundary $v = M * \Delta G$
  - M: grain boundary mobility ; ΔG: driving force / chemical potential difference / stored energy

ΔG: Driving Force	Thermodynamics based
Positive force	**Negative force**
grain boundaries	Zener pinning -3γFv /2r • γ: surface energy • Fv: Volume fraction of pinning particles • r: particle radius
stacking faults	
Dislocation	
surface energy	
elastic strain/stress	
plastic strain/stress	

- Chemistry design:
  - lower the positive driving force
  - Rely less on Zener pinning to extend the self-annealing duration.

M: Mobility – kinetics based - Arrhenius equation

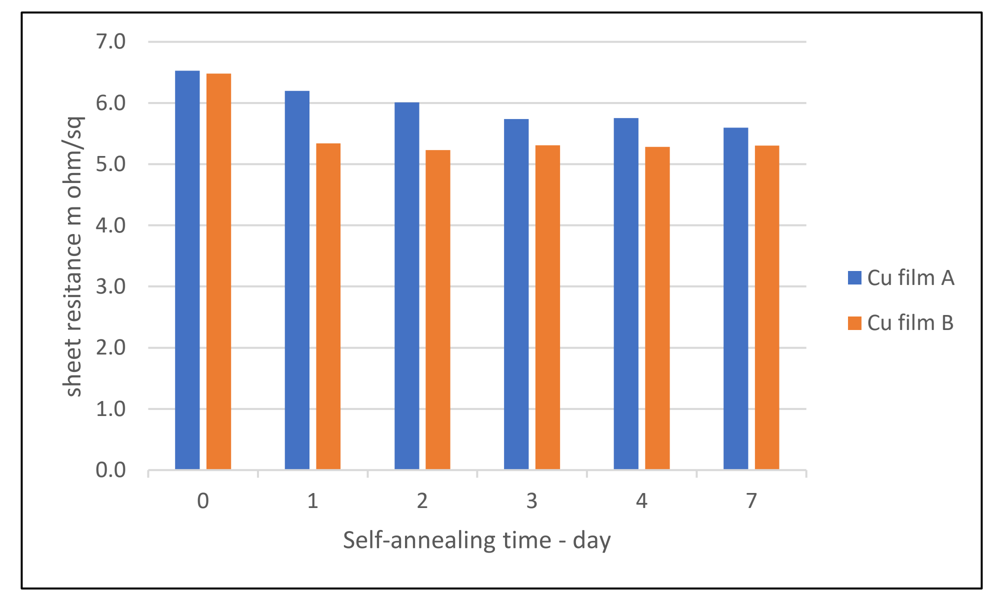
$$M(T) = M(T0) * \frac{T0}{T} e^{-\frac{Ea}{K}\left(\frac{1}{T} - \frac{1}{T0}\right)}$$

Ea: activation energy

Reference: ACTA METALLURGICA, VOL. 17, JULY 1969
JOURNAL OF APPLIED PHYSICS VOLUME 94, NUMBER 5

Screening of metastable FG on blanket wafer – Sheet resistance

- Waveform screening

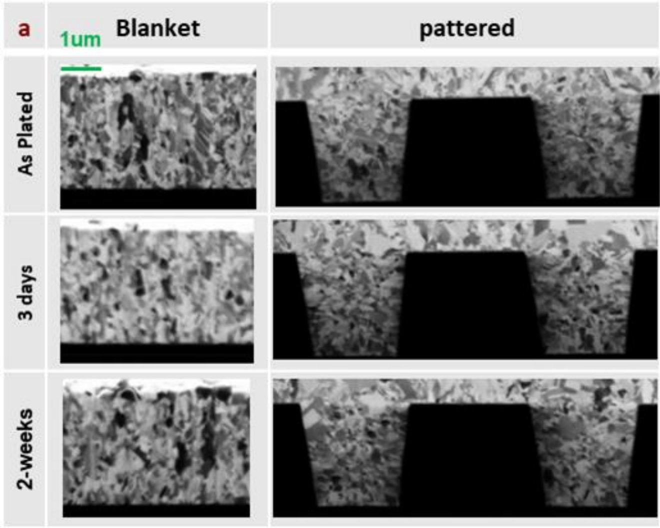


- In the case of Cu film A, the sheet resistance gradually decreases throughout the 7- day period – metastable fine grain Cu
- Conversely, for Cu film B, there is a significant decrease in sheet resistance by the second day, followed by a stable level thereafter – rapid thermodynamic stability

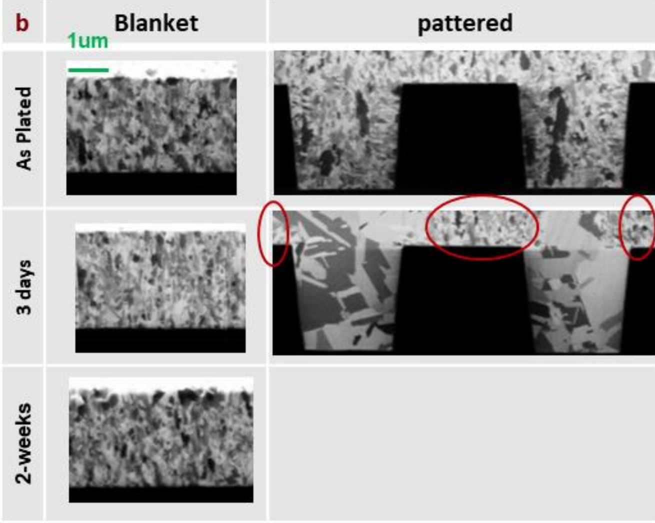
Disparity of Cu grain evolution on blanket and patterned wafer

FIB / ion image for grain size characterization

- Process A



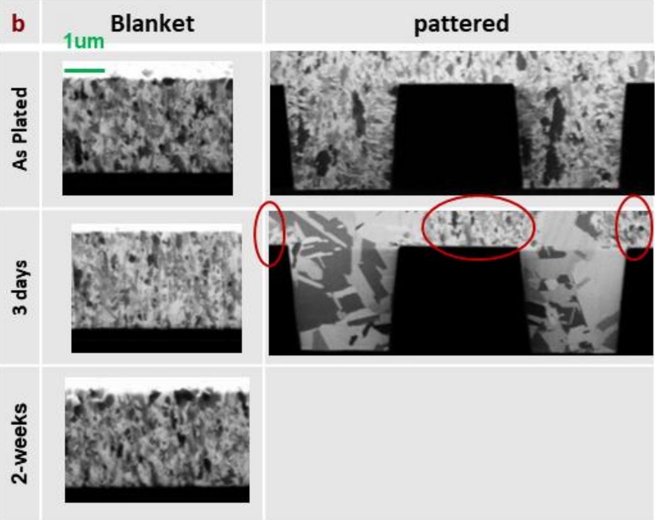
- Process B



- In the case of Process, A, the fine grain exhibits stability for 2 weeks of room temperature self-annealing on both types of wafers.
- Conversely, Process B demonstrates stable fine grain on the blanket wafer, but on the patterned wafer, grain growth occurs inside the vias after 3 days of self-annealing.
- Not all the Cu structure evolution on the blanket wafer can transfer to the patterned wafer

Disparity of Cu grain evolution on blanket and patterned wafer

- Velocity of a grain boundary $v = M*\Delta G$
  - M: grain boundary mobility; ΔG: driving force



- Mobility is similar on both blanket wafer and patterned wafer (inside the via) at room temperature
- Difference in driving force: stress relieved constrained inside the via served as additional force

Reference: ACTA METALLURGICA, VOL. 17, JULY 1969
JOURNAL OF APPLIED PHYSICS VOLUME 94, NUMBER 5

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Disparity of Cu grain evolution on different patterned wafers

- Factors that affect grain stability : via density, via CD, and aspect ratio
  - For wafer A, grain grows with both formulation #1 and #2
  - For Wafer B, grain is stable with both formulation #1 and #2

	Self – annealing for 3 weeks	
	Formulation 1	**Formulation 2**
Wafer A		
Wafer B		

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Fabrication of metastable FG on patterned wafer

- Key grain stability criterions from different customers / processes
  - Metastable fine-grain Cu capable of maintaining its fine-grain structure at room temperature for at least 3 to 4 weeks
  - Grain growth at bonding temperatures, typically around 200 to 250°C
- Requirement of grain stability at medium temperature
  - Grain stability at medium temperature with different time frame according to integration process
- Impurity requirement
  - The lower the amount of inclusions, the better

Example #1 of metastable fine grain

Annealing condition	Ion images	Grain size
As plated **stable**	1 µm	~`100 nm
4 weeks self - annealing **stable**	1 µm	~ 100 nm
150 °C - 2 h **stable**	1 µm	~100 nm
250 °C - 2 h **growth**	1 µm	> 200 nm

- Fine grain on as plated and self-annealing
  - Minimization of the positive driving force
- Fine grain - 150°C annealing
  - Limited grain boundary mobility
- Grain grows at 250°C
  - higher mobility at 250 °C promote the grain growth
- Expect to enhance bonding strength at 250°C

Example #2 of metastable fine grain

Annealing condition	Ion images	Grain size
As plated **stable**	1 µm	~`100 nm
170 °C - 40 min **stable**		~ 100 nm
170 °C - 40 min + 210 °C - 5min **stable**		~100 nm
280 °C - 2 h **growth**		> 200 nm

- Fine grain : as plated
- Fine grain : 170°C - 40 min
- Fine grain :170°C - 40 min and followed by 210°C - 5 min
- Grain grows at 280°C
- Expect to enhance bonding strength at 280°C

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Conclusion

- Screening of metastable fine grain on blanket wafer through the XRD and sheet resistance
- Disparity of Cu grain evolution on blanket and patterned wafer could be due to the stress building up inside the patterned wafer
- Factors that affect grain stability on patterned wafer: via density, via CD, and aspect ratio
- Mechanism of fabrication of metastable FG on patterned wafer
- Showcase our metastable fine grain examples

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