Effect of impurity on Cu electromigration

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This work was performed by the Research Alliance Teams at various IBM Research and Development Facilities

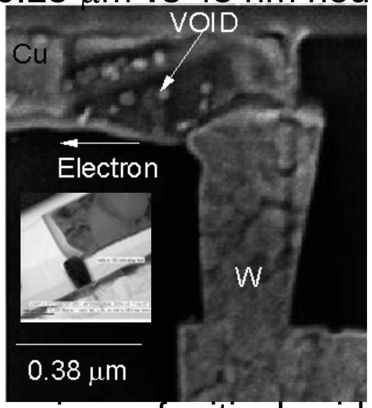
Outline

- **Electromigration Roadmap**
  - EM scaling rule
- **Improve EM techniques:**
  - e-plating chemistry, alloy, alternative liner, metal cap
  - Modify Cu surface
- **Solute effect on Cu EM**
  - Electroplating chemicals (S, Cl, C, O)
  - Alloy seed: Cu(Ti), Cu(Al), Cu(Sn), Cu(Zr), Cu(In)
  - Liner: PVD Ti(Ta), CVD Co, CVD Ru, PVD Ru
  - Metal cap: CoWP, CVD Ru
- **Conclusions**

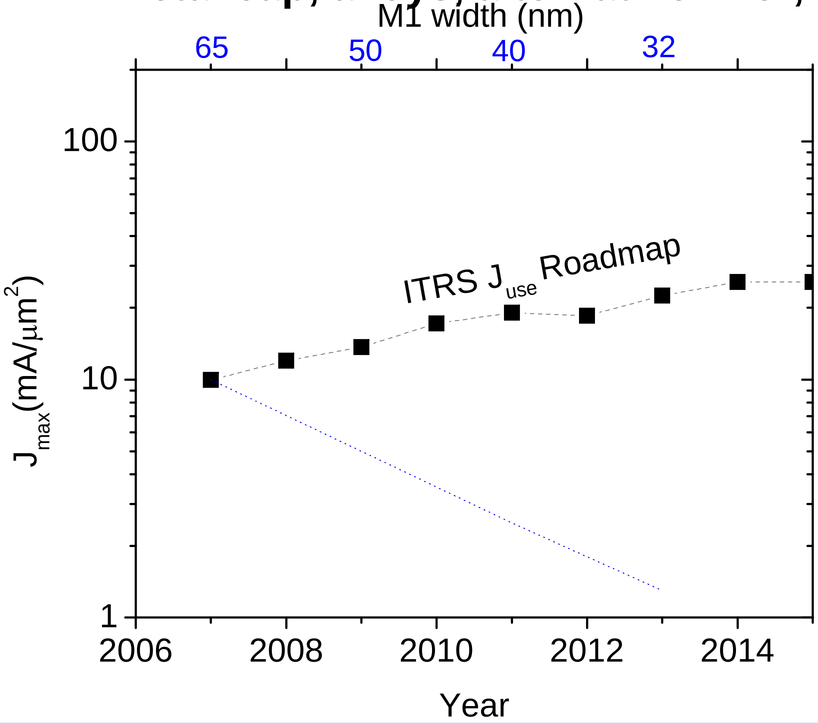
EM Roadmap

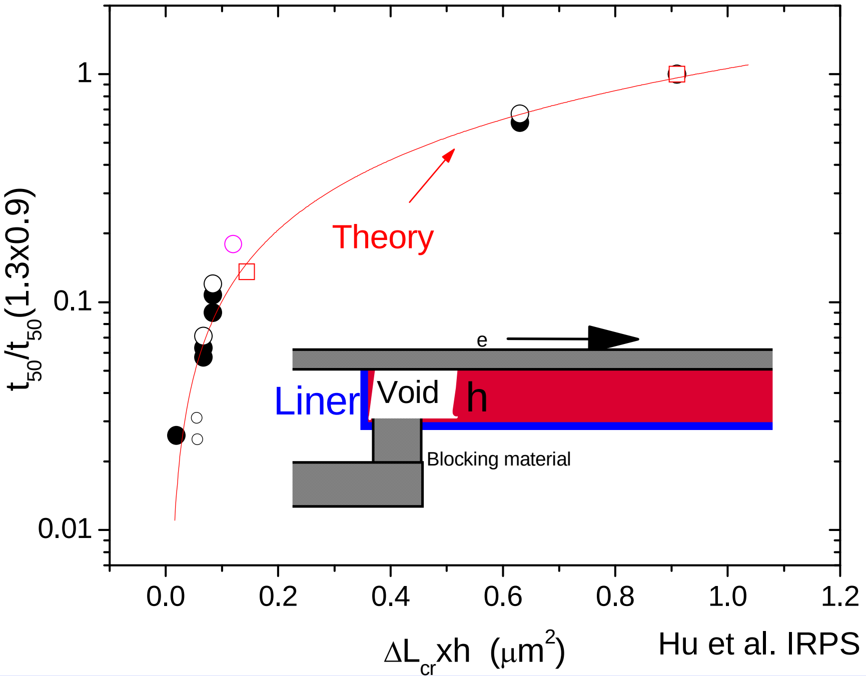
- **Scaling challenges:**
  - –Increasing difficulty to fabricate reliable wafers
  - –Lifetime degradation with technology scaling limits design scaling
    - Fraction of atoms on fast diffusion path increases
    - Fatal void volume decreases – shorter time to failure
    - Increasing polycrystalline sections in Cu lines: more fast paths
    - Juse drops by half in every new generation
  - –Need to pursue techniques for EM enhancement
    - **Metal cap, alloys, alternative liner, Cu surface modification**

0.25 µm vs 45 nm node



Comparison of critical void volume





Hu et al. IRPS '04

Diffusion Path in Cu Damascene Interconnections

EM drift velocity (mass flow) = $(\mathbf{D_{eff}}/KT)F_e$

1. Interface Diffusion:
   - D_i: Cu/Ta (0.7 or 1.4, or >1.8 eV)
   - **D_s: Cu/SiCNH (0.8-1 eV)**
2. Grain boundary Diffusion
   - **D_{gb} (0.75-0.87 eV)** *(Surholt & Herzig, Acta mater. '97)*

❑ Cu mass flow:

❖Polycrystalline line structure

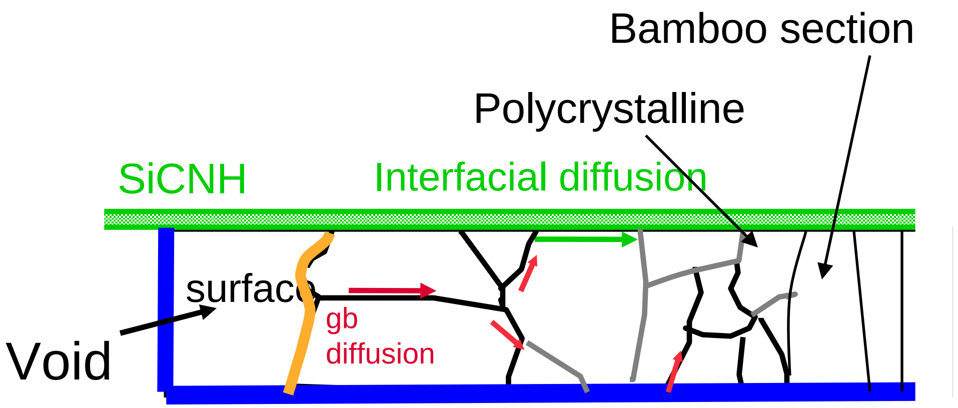
$$v_d = [(\delta_{gb}/d)D_{gb}Z_{gb}^*]e\rho j/kT$$

❖Bamboo-like line structure

$$v_d = [\,\delta_S(1/h)D_S Z_S^*\,]e\rho j/kT$$

❖Bamboo/polycrystalline line structure

$$v_d = A\,[D_{eff}Z_{eff}^*\,]e\rho j/kT$$



~Drift velocity of bamboo-like line, if length of polycrystalline section < Blech Short Length

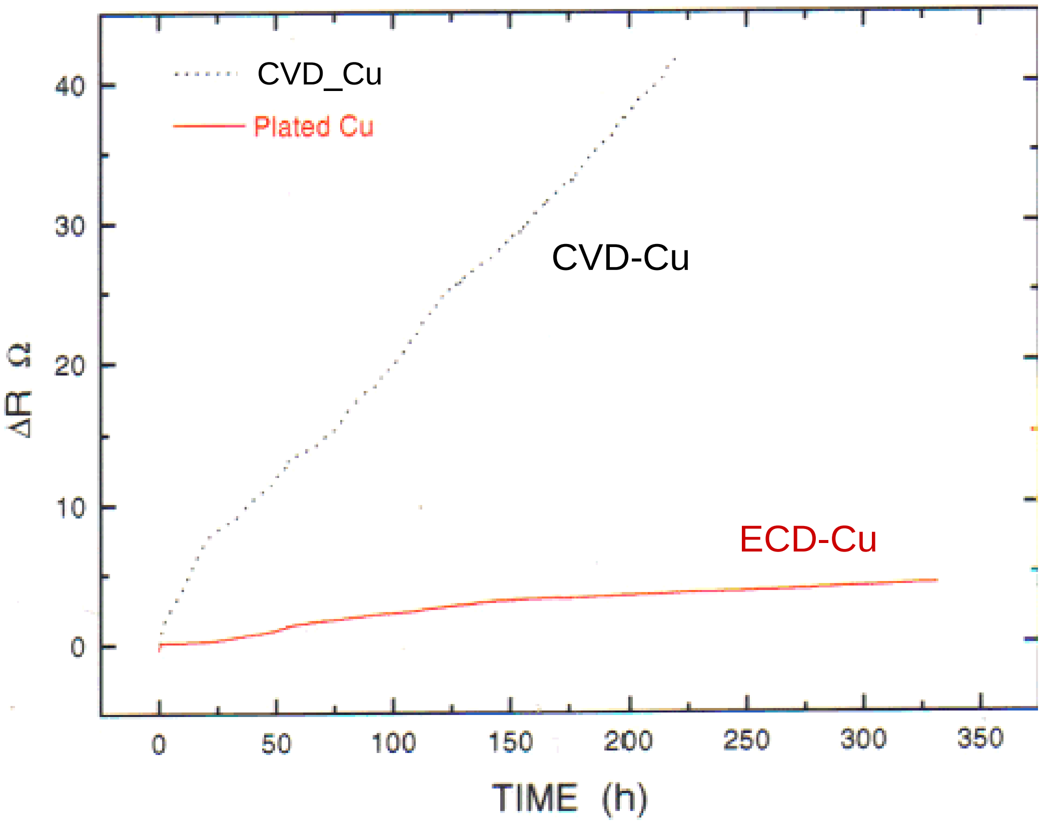
~ function of bamboo and polycrystalline sections

Solute Effect: Non-metallic impurities

Discovery of Superior EM Reliability of ECD-Cu in 1992

- ECD-Cu has a better activation energy and lifetimes than PVD- and CVD-Cu
  - Attribute this superior EM to microstructure and/or impurity

  - ← ECD-Cu has a larger Cu grain size
  - ← ECD-Cu has more impurities, such as Cl, C, O, S



Electromigration activation energy

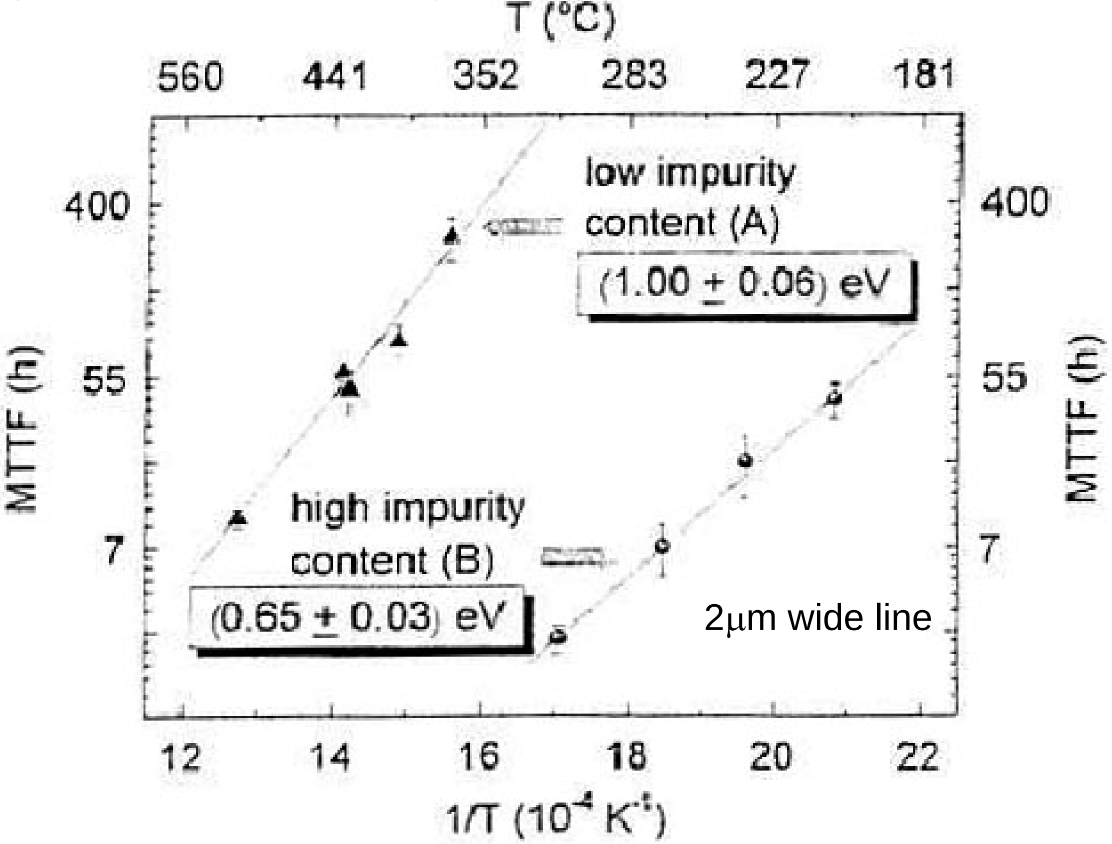
CVD Cu 0.7-0.8 eV

Plated Cu 1.1-1.3 eV

Non-metallic impurities

M. Stangl et al. Thin Sold Films, 517, 2687 (2009)

- ❑Two electroplated solutions (A & B): Solute concentration in B is 10x of A
- ➢Indicates **higher impurity** degrades EM lifetime and activation energy



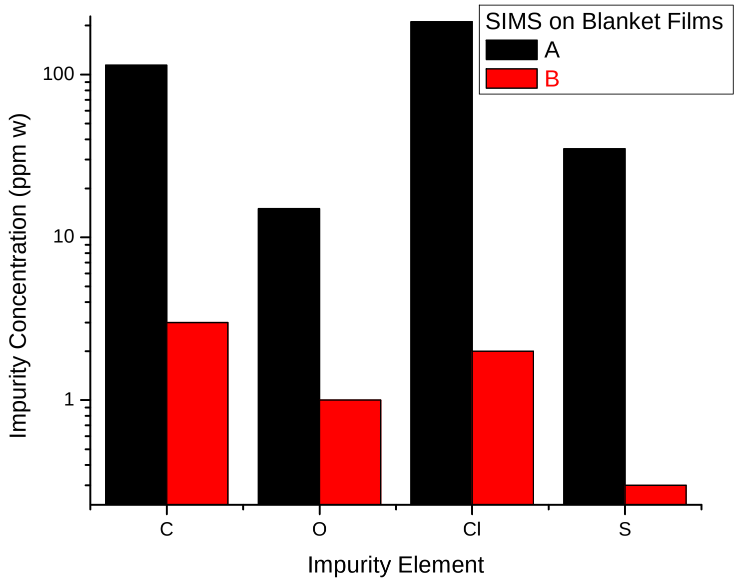
2μm wide line

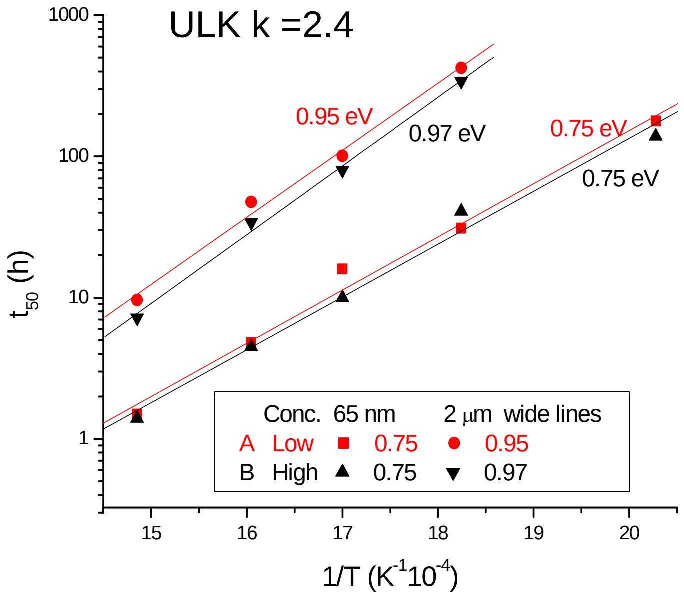
Fig. 5. Lifetime vs. (1/*T*) with extracted values for EM activation energy for Cu interconnect lines with low (A) and high (B) content of non-metal impurities.

Non-metallic Impurities

- Observed **no** significant EM difference between two chemistries with different impurity concentrations (confirmed by SIMS on blanket wafer or line)
- ECD Cu **1.1** eV vs. CVD Cu **0.8** eV on 2 μm wide lines (Hu&Luther, Mat. Chem. and Phys. 1995).
  - **CVD Cu**: **Polycrystalline** line - **GB** diffusion dominated; Q=0.8 eV
    - Consistent with Cu **GB diffusion activation energy**(*Surholt & Herzig, Acta mater. '97)*
    - **Same Q** obtained from ECD Cu **fine grain size** line (Hu et al. IITC 2007)
  - **Plated Cu**: Abnormal Cu grain growth resulted in a **near bamboo** line structure
    - Mass flow controlled by the slow interface diffusivity not GB

➢**Microstructure ~ bamboo grain** is the **key for superior ECD_Cu** thin film lines





Metallic Impurities - EM Cu Alloy

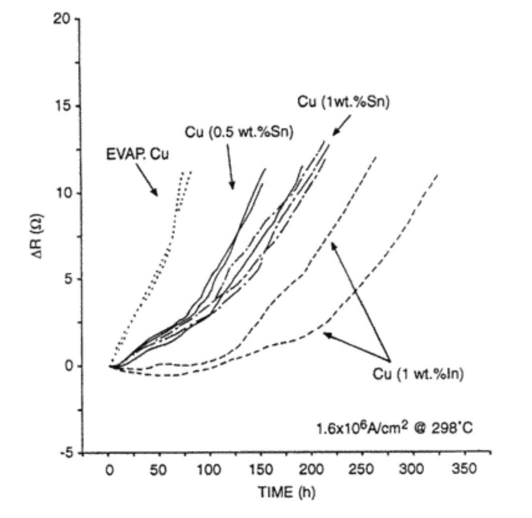
- Cu–**GB** and/or Cu-$SiC_xN_yH_z$ **interface** diffusivities determined mass flow
- Literature reported: Ti, Al, Co, Zr, Sn, In, Pd, Mg, Ag, etc. enhance EM lifetimes
  - ✓Michael & Kim, 2001 reported Al increases Cu grain boundary diffusion
  - ✓Hu et al., 1995 reported Mg degrades Cu lifetimes

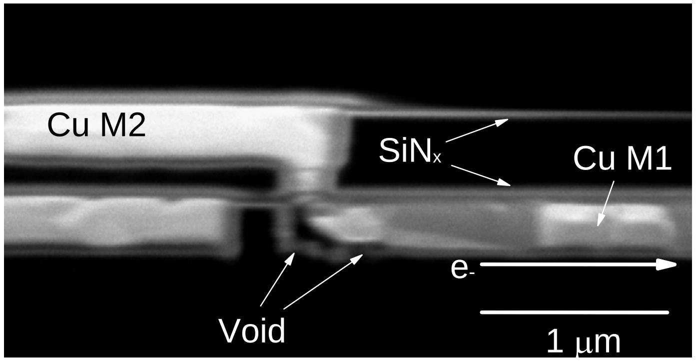
➢Impurity increases Cu resistivity

Solubility limit @ 400ºC	**Resistivity at%**	**Pin Cu GB Diffusion**
–Pd > 20 at.%	0.9 μΩ-cm	Yes
–Al ~ 20 at.%	0.95 μΩ-cm	No
–Sn ~ 7 at%	3.1 μΩ-cm	Yes
–Mg ~ 3 at.%	0.8 μΩ-cm	No
–Ti < 0.3 at.%	16 μΩ-cm	Yes
–Co ~ 0.04-.1 at.%	6.9 μΩ-cm	No
–Zr ~ 0		Yes
–Ru ~ 0		No
–Ta ~ 0		No

Solute Effect

- Early work on metallic impurities**:**
  - Ion milled Metal lines: Ta/Cu, Cu(Mg), Cu(Sn), Cu(In), or Cu(Zr)/Ta (Hu et al. TSF('95), US 7090710)
    - Lifetimes degraded by Mg
    - Lifetime and EM activation energy increased by Sn, In, Zr
  - Damascene Cu(Ti), Cu(Zr), Cu(In)
    - Zr, Ti enhanced Cu lifetimes and activation energies (Hu et al, Micro. Eng. (2006))
    - In **degraded** lifetime if Ta liner was contaminated
  - Lift-off Ti(Ta) liner/Cu line on W (US 6503641)
    - Alloy liner increase lifetime and activation energy



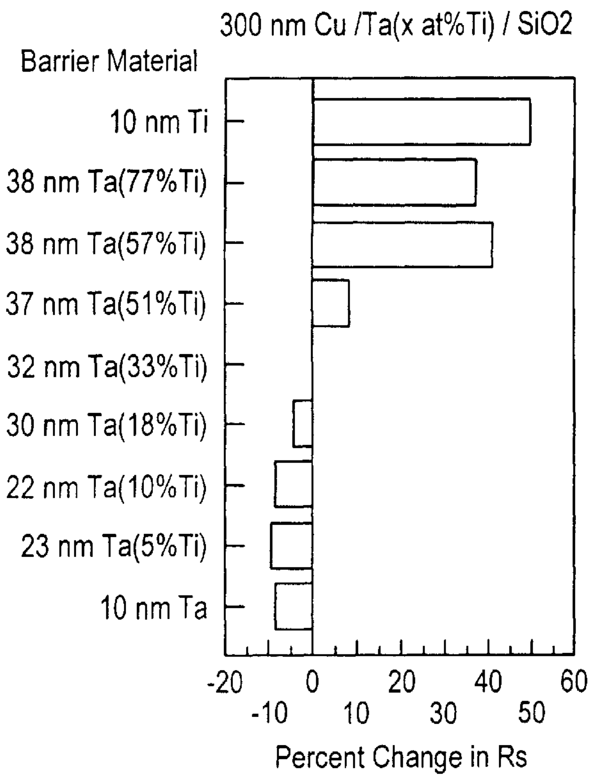


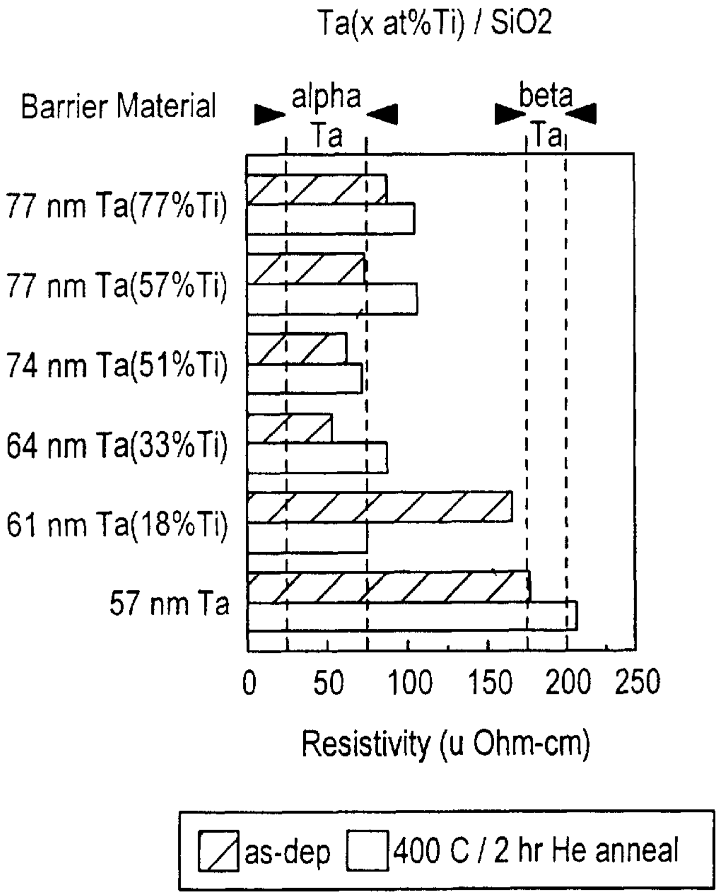
Fast diffusion along Ta/Cu interface
Heavily contaminated Ta

Ti(Ta) alloy liner

Effect of Ta(Ti) Liner on Cu Resistivity

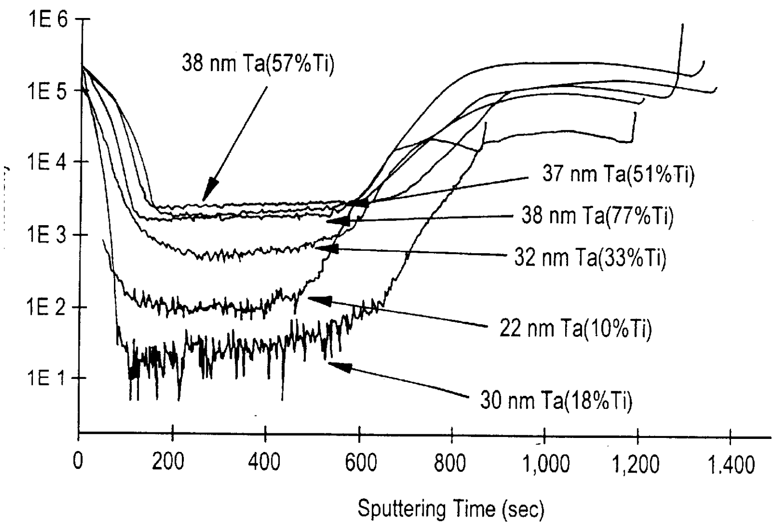
- Annealed at 400^{o}C for 2h
    - Reactions of Ti/Cu: TiCu and TiCu$_3$ (Hu, et al. MRS. 1986)
    - Sharply increased Cu ρ for Ti > 33%
    - Liner ρ dropped as Ti > 33%, more fractions of α-Ta



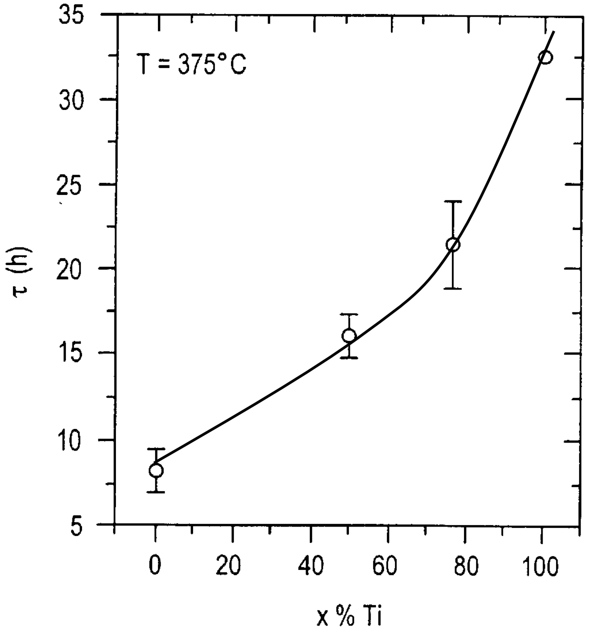


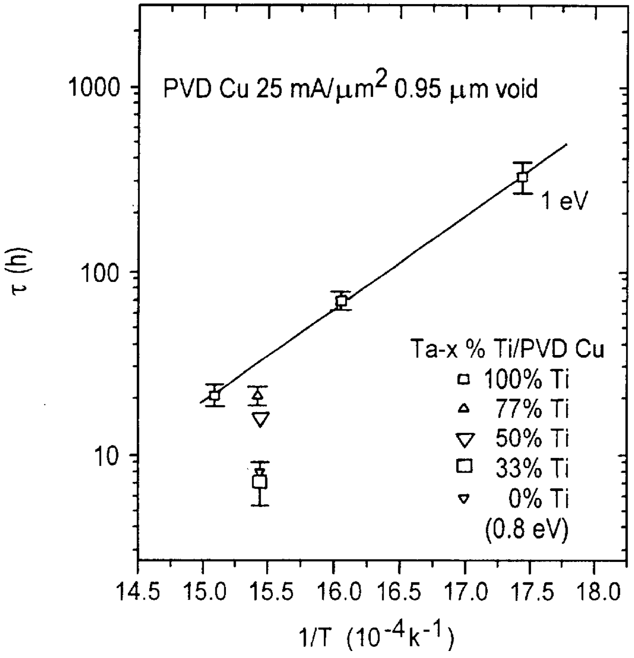
Effect of Ti(Ta) Alloy Liner on Cu EM

- Increase Ti conc. in Ta(Ti) liner on PVD polycrystalline Cu lines
  - Amount Ti in Cu increased
  - Enhanced factor increased
  - GB_Q increased from **0.8 to 1 eV**
- Ta(Ti): Lower manufacture **cost** and **liner** ρ
- With reduced BEOL thermal budget
  - Can cut down Cu resistivity increase and improve lifetime



300 nm Cu/Ta(Ti) samples annealed in He at 400C for 2 hr

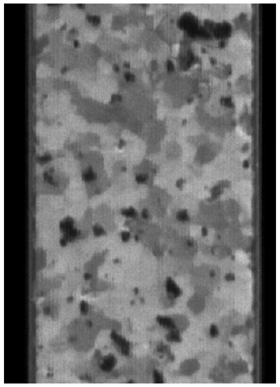




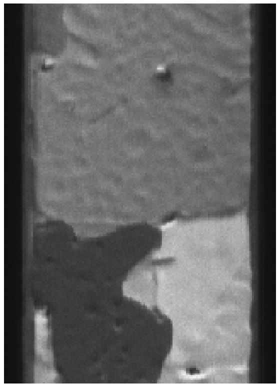
Cu microstructure Variation Obtained by Adjusting Fabrication Steps

- ☐ Wafer A: Cu CMP performed right after Cu electroplating with post Cu deposition anneal omitted → Fine grain
- ☐ Wafers B: Cu CMP processing after a 100ºC anneal, similar microstructure → Large grain

Wafer A



Wafer B

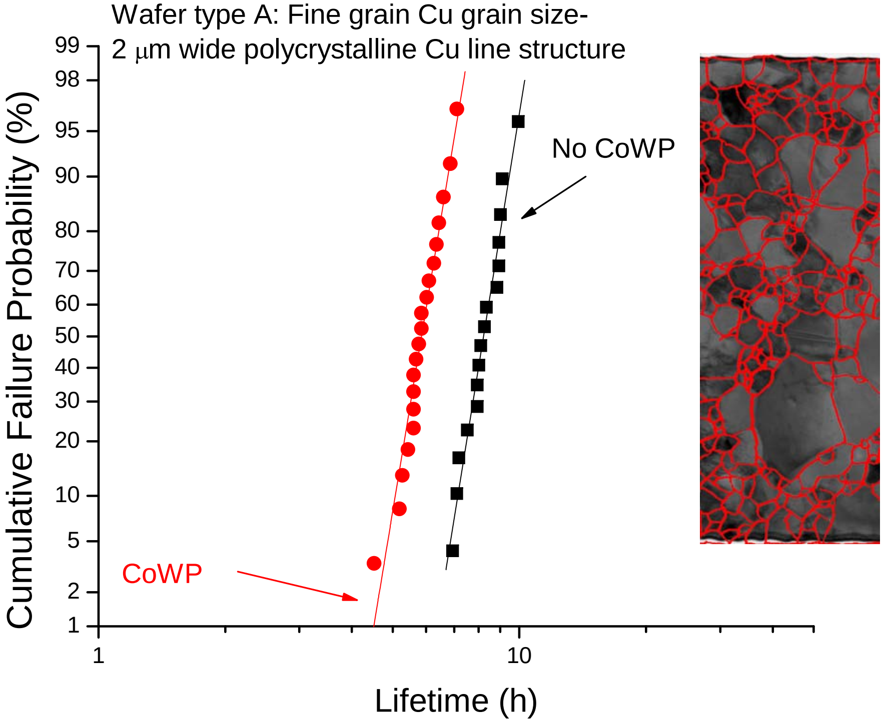


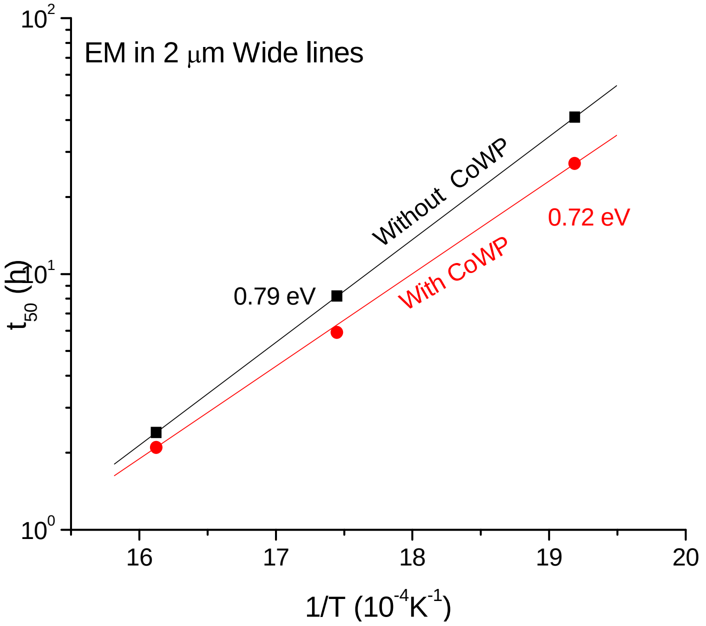
- ☐ **Varied Cu grain size**
  - ❖ Polycrystalline: GB study
  - ❖ Bamboo-like: Interface study

Hu et al. IITC '07

Effect of Co on Cu GB Diffusion

- ❑CoWP cap greatly improved EM lifetime in near bamboo-like line
- ❑Skip pre-CMP anneal wafer had GB continuous network path
- ❑Samples annealed at 400ºC for 2h allowed Co diffused into Cu GB
  - ➢**No EM** lifetime enhancement



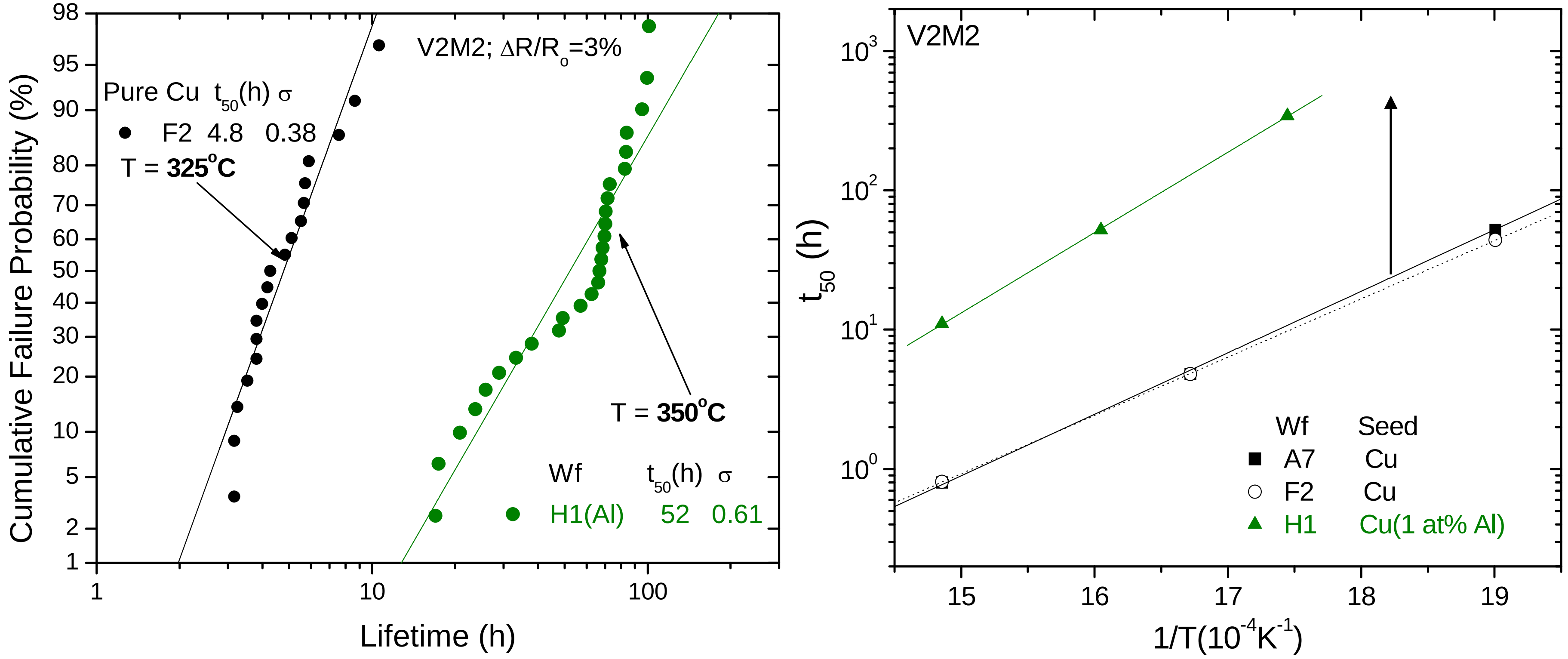


- ❑CoWP shuts down Cu interfacial, **not GB diffusions**
  - ❖GB diffusion activation energy can be **directly** measured: ~ **0.72eV to 0.79eV**
  - ❖Co has **no effect, or reduced** GB diffusion activation energy

Solute Effect: Al

1) Standard EM test structure on 65 nm wide lines
   - 1% Al alloy seed
2) Cu(Al) Drift velocity
   - With or without post plated Cu 100°C anneal
     - 1.5 μm wide lines: **Polycrystalline** and **near bamboo** structures
   - 1% and 2 at. % Al
   - SEM images: Void, hillock, grain size

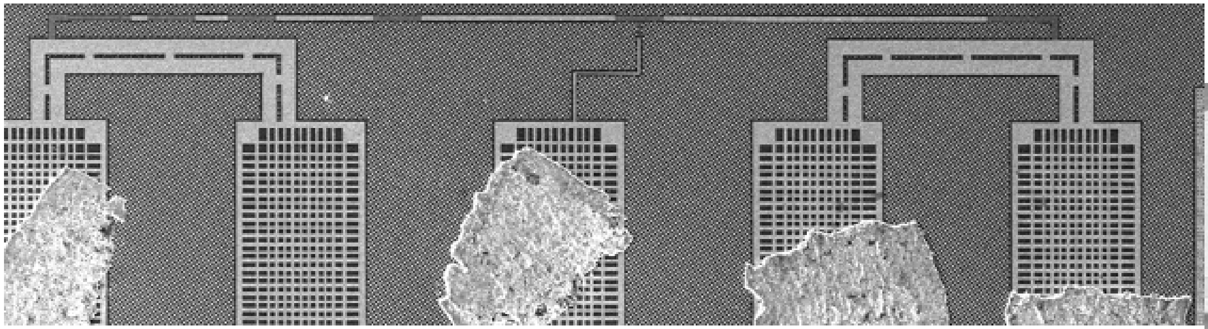
EM in 65 nm Wide Cu Alloy Line

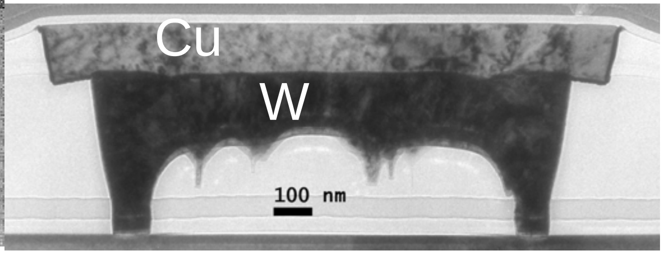


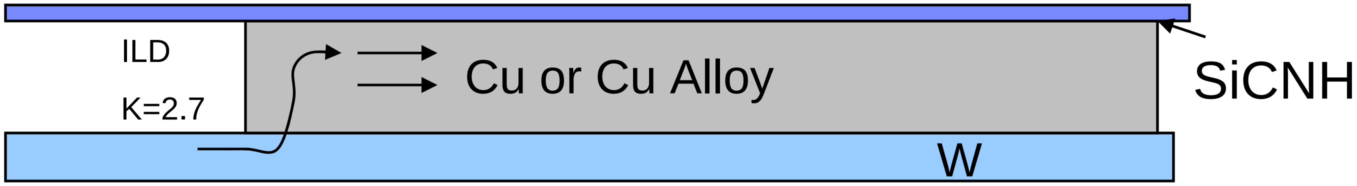
- **1% Al** alloy seed in 65 nm wide line
  - Significantly **enhanced** EM lifetimes
    - Increased EM activation energy from **0.85 to ~ 1.1 eV**
    - **Similar results obtained by** Yokogawa, Tsuchiya: JAP('07)

EM Drift Velocity Experiment

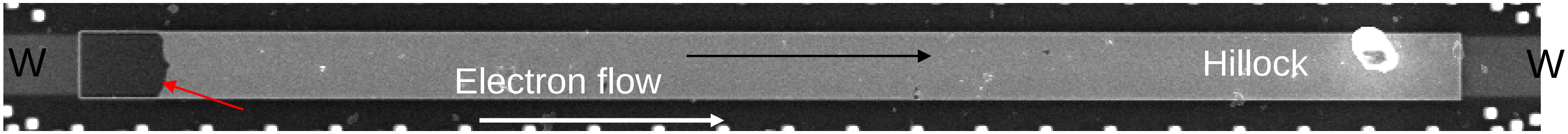
- **Cu line segments of 5, 10, 30, 60, 100 μm long on a continue W line**
- **Fundamental understanding of EM mass flow on 1.5μm wide line**



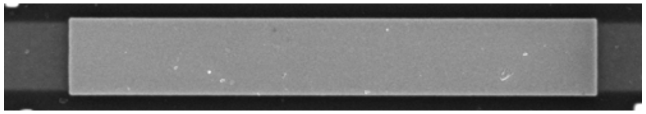




- Voids near at the cathode end and hillocks around at anode end of the line

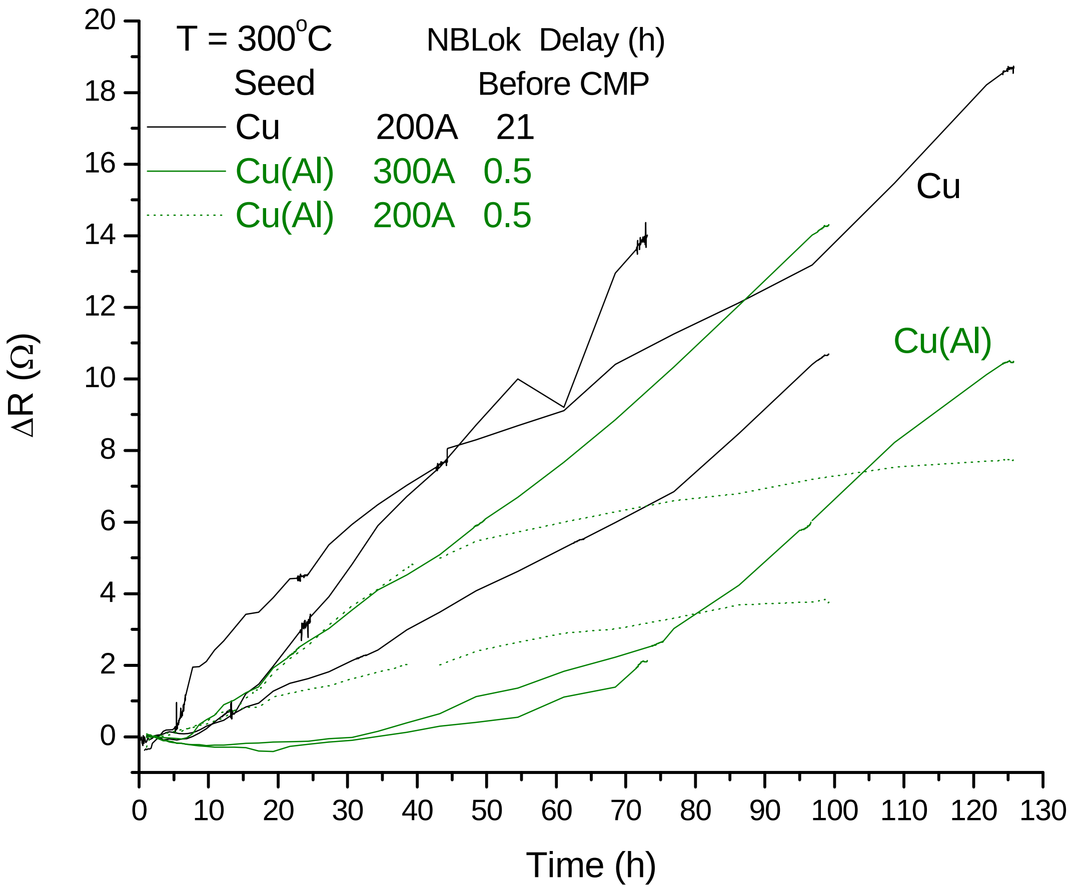


- No EM damage observed in 5 and 10 μm wide line (Blech length)



EM Cu(1% Al) Drift Velocity

Resistance Technique: 1% Al alloy seed

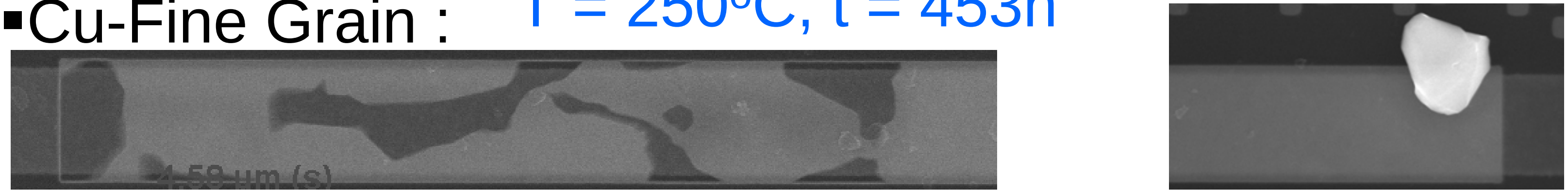


Wf A: Samples were skipped post plated Cu 100°C annealing

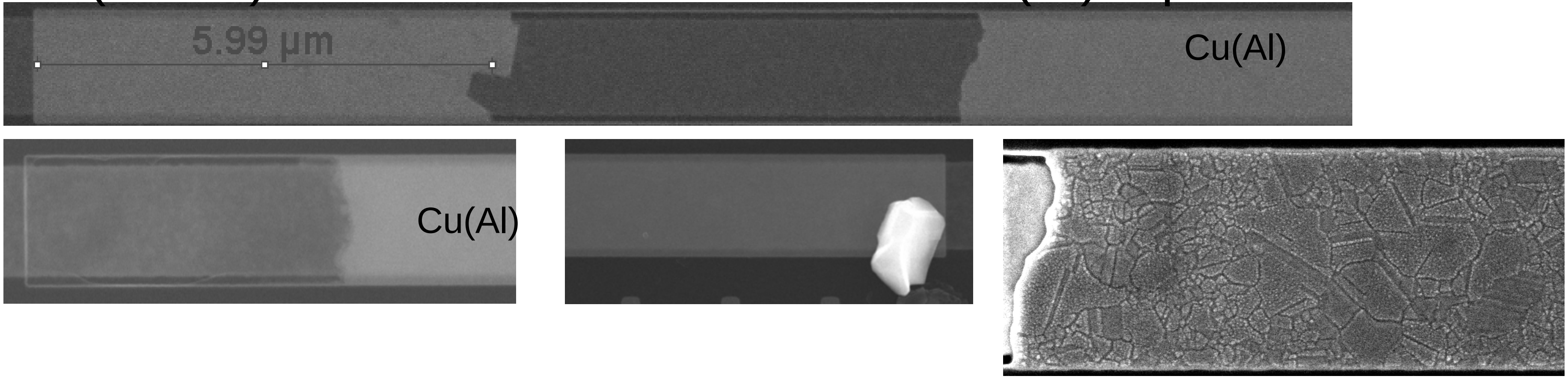
- ❑1% Al alloy seed in the polycrystalline (**fine grain size)** lines
  - ❖Mass flows alone grain boundaries
  - ❖Similar EM resistance degradation and void length
    - ➢ Impurity, Al, had little or no effect on Cu GB

Void Growth: Effect of Impurity and Microstructure

- Cu-Fine Grain : T = 250^{o}C, t = 453h



- Cu(1% Al) Fine Grain: Void volume in Cu(Al) > pure Cu

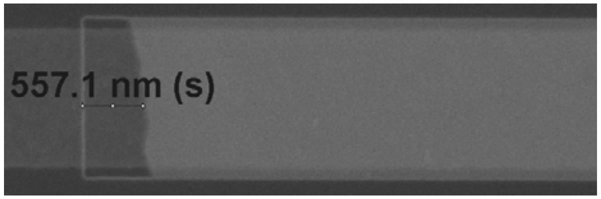


❑ Skip POR post plated Cu anneal
  - Fine grains mixed with some large grains

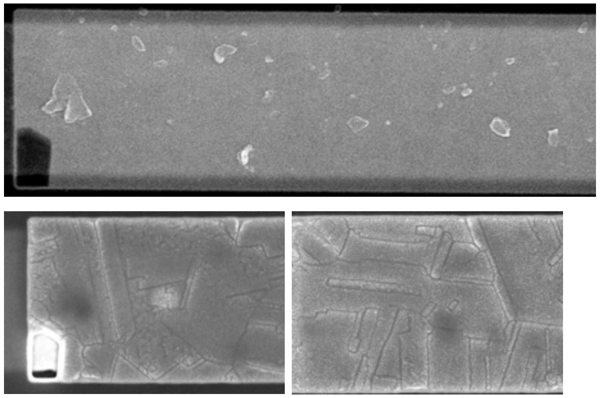
Void Growth: Impurity and Bamboo Grain

T = 250°C, t = 453h

- Cu-100°C Anneal (Wafer B type)
  - Large Cu grain



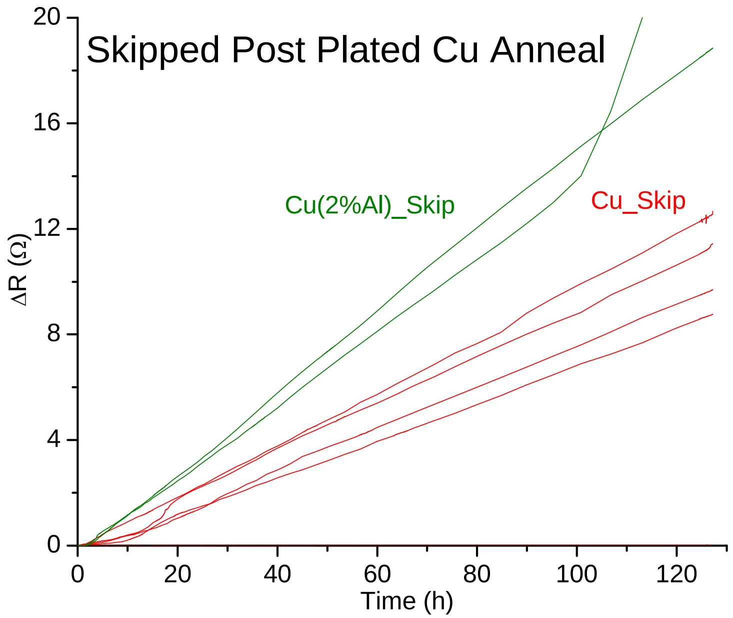
- Cu(1% Al)-100°C Anneal (B type)
  - ➢ Large Cu grain
  - ➢ Smaller void growth rate



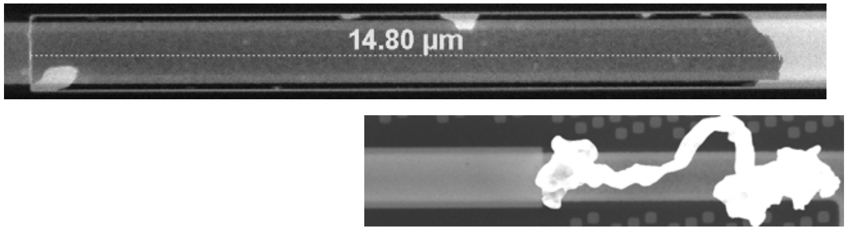
- ❑ 100°C anneal after Cu plating
  - ➢ Large **bamboo-like** grains
- ❑ Compared void growth from large and fine Cu grain samples

➔ Al mitigated interface and not GB diffusion

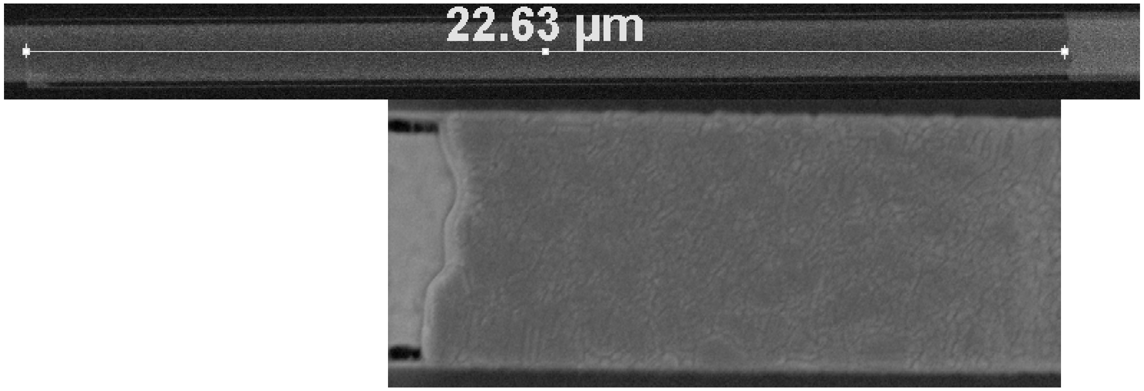
Fine Grain Cu: Solute effect on Cu GB diffusion, Cu(2%Al) seed



❑Cu fine grain

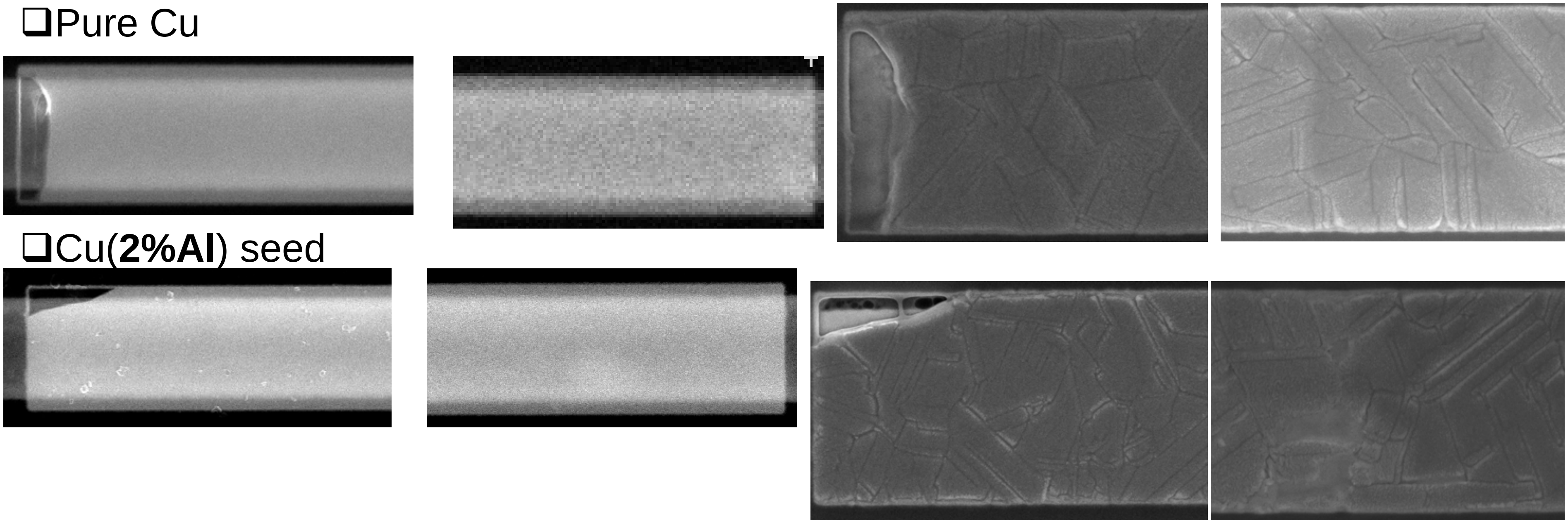


❑Cu(2%Al) fine grain



- ❑Fine Cu grain size obtained by **skipping post plated Cu anneal**
- ❑2%Al alloy seed on 1.5 µm wide polycrystalline Cu lines
  - ❖GB diffusion dominated: Void growth rate Cu(Al) > Cu
  - ❖Al enhanced Cu void growth rate in polycrystalline line
    - ❖Agrees with N.L .Michael, C.U. Kim. J. Appl. Phys. 2001
  - ❖Al increases Cu grain boundary diffusivity

Void Growth: **100ºC annealed** samples before CMP



- Pure Cu
- Cu(**2%Al**) seed

- 2%Al alloy seed: POR Anneal before CMP
  - **Near bamboo-like** lines: Interface diffusion dominated
    - Void growth rate Cu >> Cu(2%Al)
    - Impurity, Al, **decreased** Cu interface diffusion

Effect of non-metallic and metallic impurities on Cu EM

- ❑Observed no difference between high and low non-metallic impurities **Cl, C, S, O**
  - **Microstructure** plays the key role in the superiority of **ECD-Cu** to CVD or PVD
- ❑Ti(Ta) liner
  - Improved PVD polycrystalline Cu line lifetimes
  - Increased EM Cu GB Q_{EM} 0.8 to 1 eV
- ❑In, Zr, Sn increased Cu lifetime and Q
  - ❖However, **In** increased void growth rate if Ta was heavily contaminated
- ❑1%Al seed for 65 nm wide lines
  - Enhanced EM lifetimes/increased EM Q_{EM} from 0.85 to **1.1 eV**
- ❑1.5 to 2 μm wide polycrystalline lines
  - Ti, Sn, Zr, In **reduced** Cu GB diffusivity
  - Co has no effect in Cu GB diffusion
  - **Al, Mg** enhanced Cu **GB** diffusivity
    - ➢ Al could reduced lifetime enhancement for 22 nm and beyond
  - Impurities, Al, Ti, Zr, Sn, Co **mitigated** Cu interface diffusion
    - ➢ **Enhanced** Cu lifetimes for near bamboo-like or bamboo-polycrystalline
  - ➢Oxidized alloy wafers dramatically degraded Cu lifetimes