Materials Science and Engineering
National Tsing Hua University

熱電能源管理實驗室
Thermo-Electric Energy Management (TEEM) Laboratory

Electromigration

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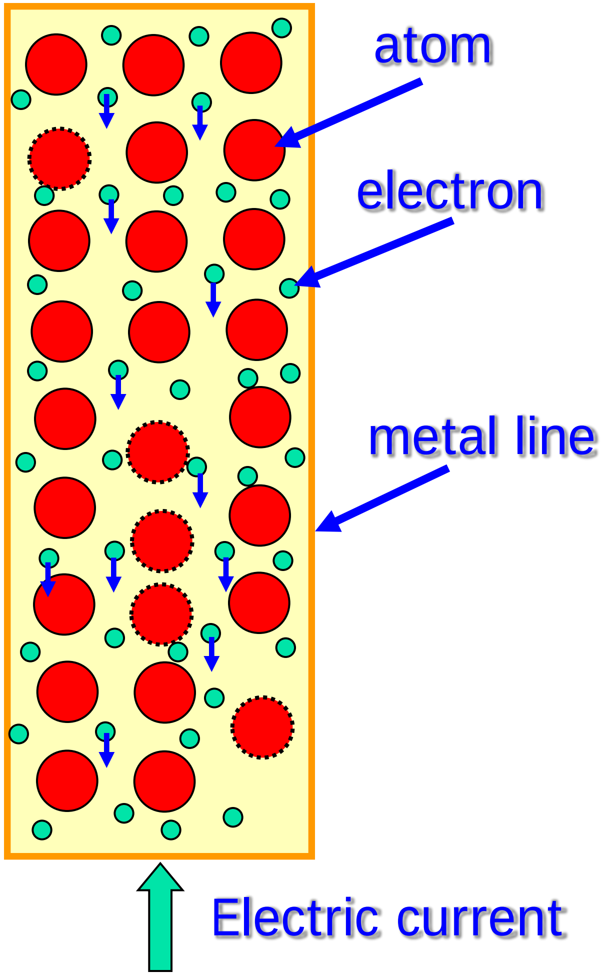
August 5, 2010

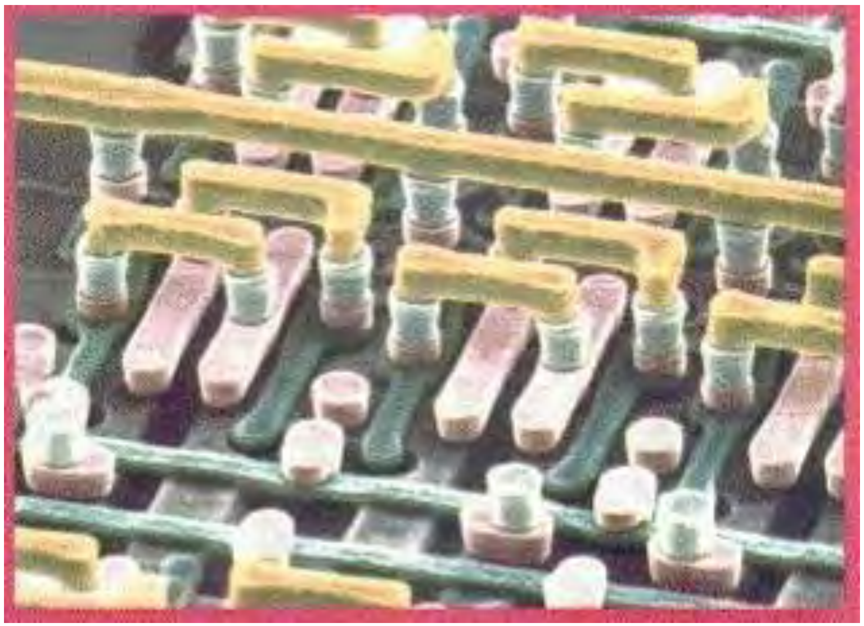
Outline

- Interconnect reliability
- Researches on Electromigration
- Example: Nanotwinned Cu
- Fundamental knowledge/training

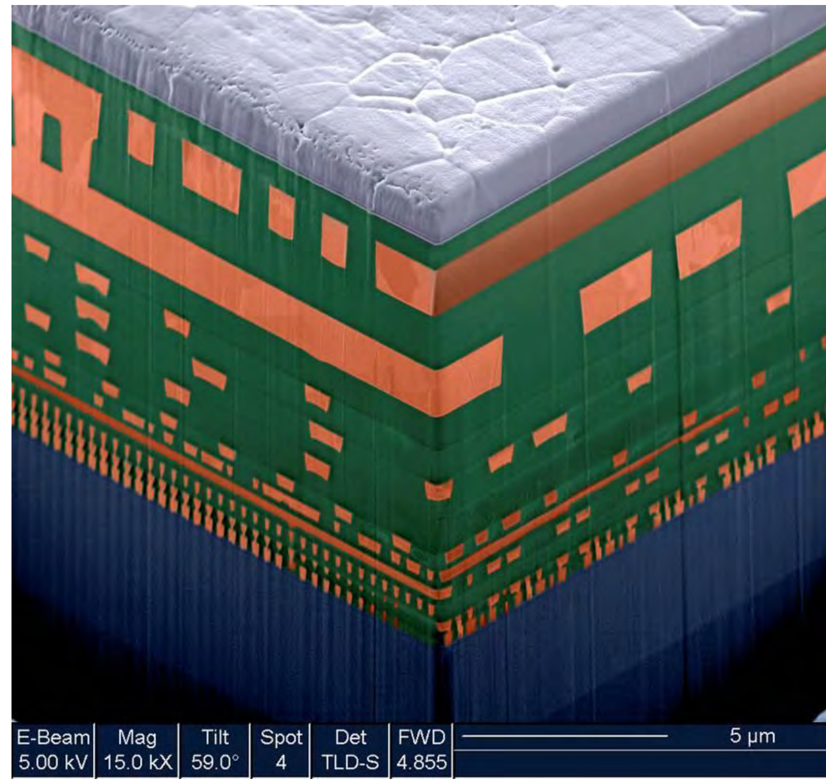
What is electromigration (EM)?



Interconnects in IC chips

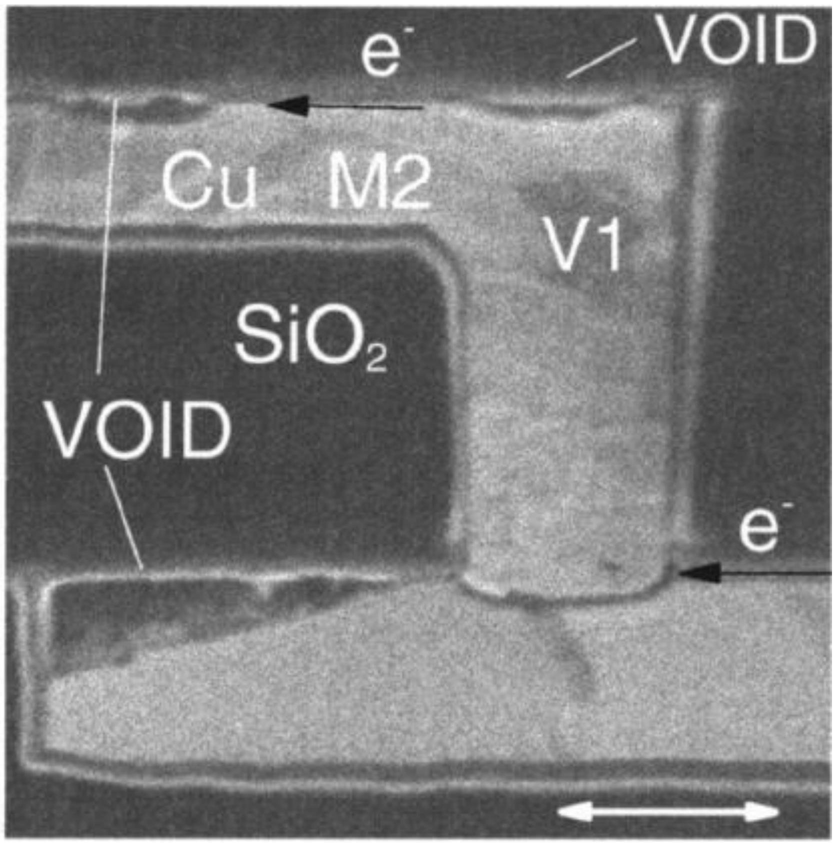


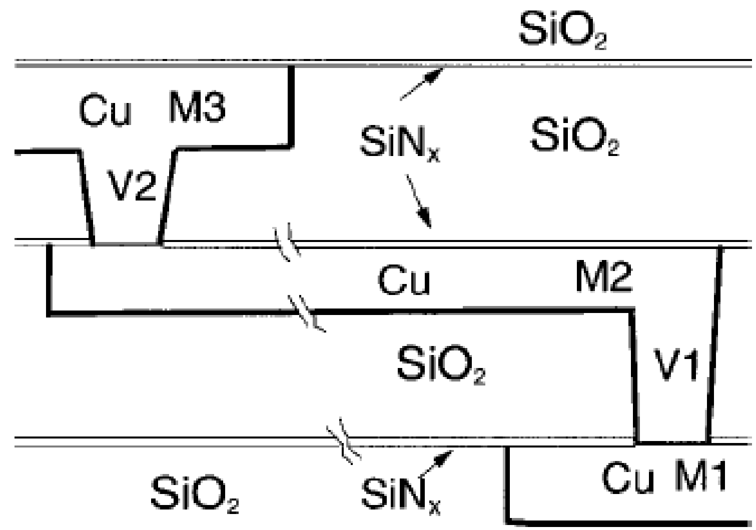
Al(Cu) Interconnects
0.5 μm line width/space
→**100 m/cm^2 in a single layer**
→**1 km of interconnect per chip**
IBM J. of Res. & Develop., July 1995



Cu interconnects
IBM's 90 nm technology with Cu/low-k
0.12 μm line width/space

EM-induced failures – Cu interconnects

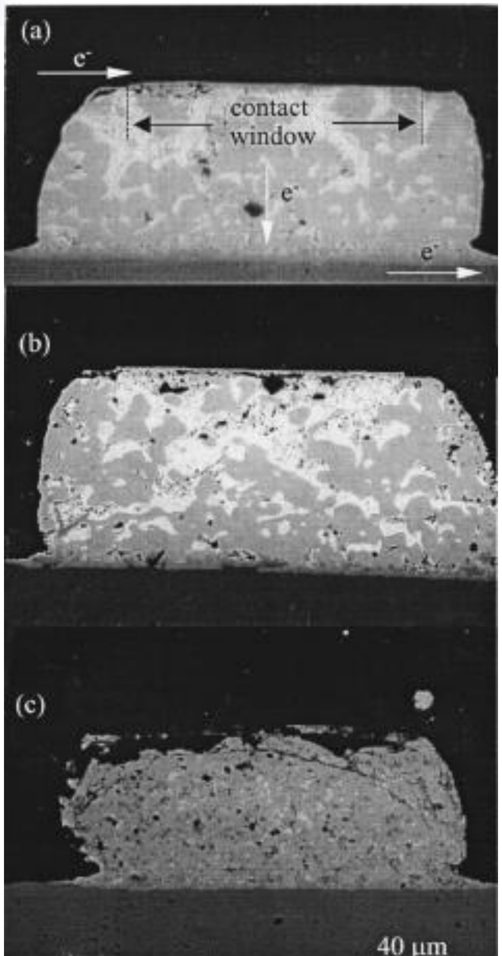


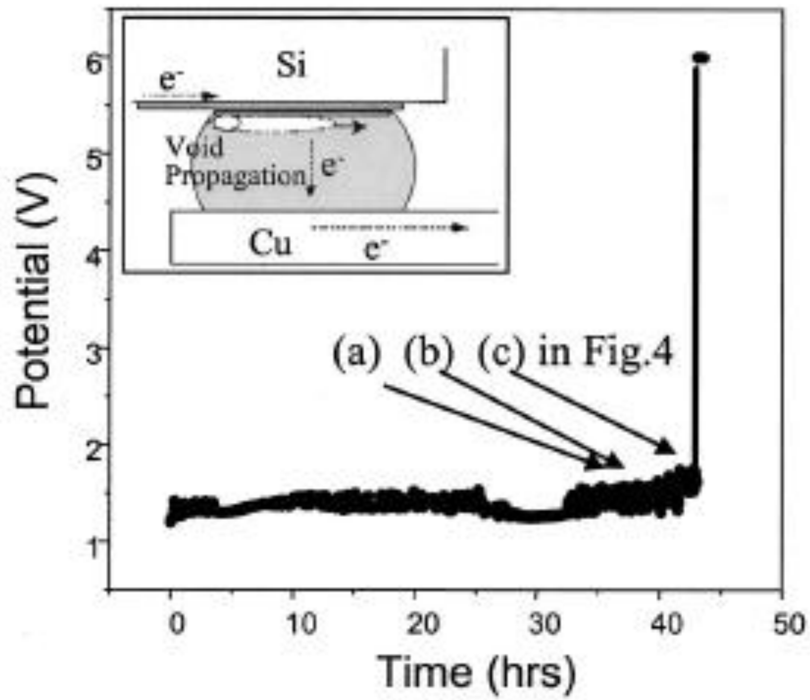


Three-level dual damascene Cu interconnects stressed at 295 °C at 2.5×10^6 A/cm^2 for 1000 h

C. K. Hu et al, *APL*, 78, 904 (2001).

EM-induced failures – flip chip solder bump

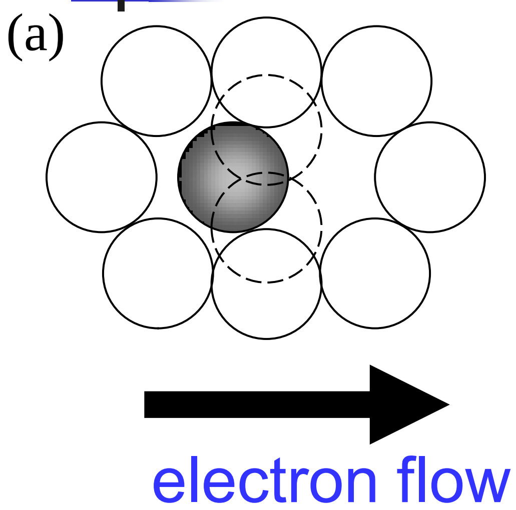


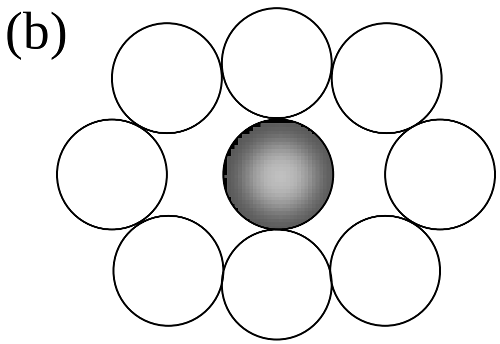


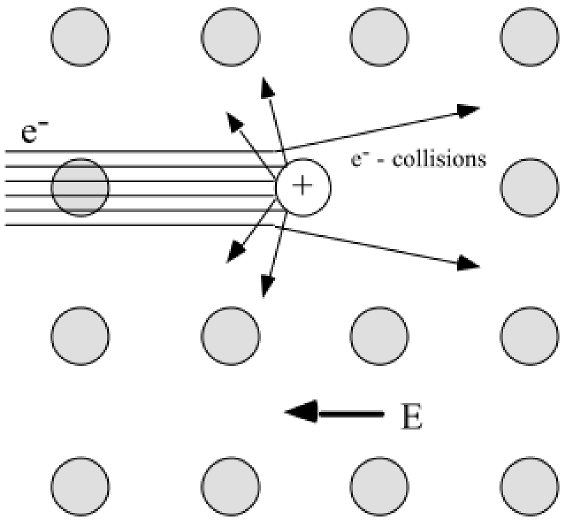
Void formation and propagation in a SnPb flip chip solder bump stressed at 125 °C at 2.25x10^4 A/cm^2 for (a) 38 h, (b) 40 h, and (c) 43 h.

E. C. C. Yeh et al, *APL*, **80**, 580 (2002).

Atomic model of EM







A sketch of the diffusion of the shaded Al atom to a neighboring vacancy. The pair has four nearest neighbors in common, including the two drawn in broken curves. (a) before diffusion and (b) halfway during diffusion

Electromigration = Thermal diffusion + Electrical force

EM driving force

- Electromigration: a combination of thermal and electrical effects on mass transport.

$$J = -D\frac{\partial C}{\partial x} + C\frac{D}{kT}F_{em} \qquad D = D_0 e^{-\frac{\Delta H_m}{kT}}$$

pure metal → $\frac{\partial C}{\partial x}$ = 0

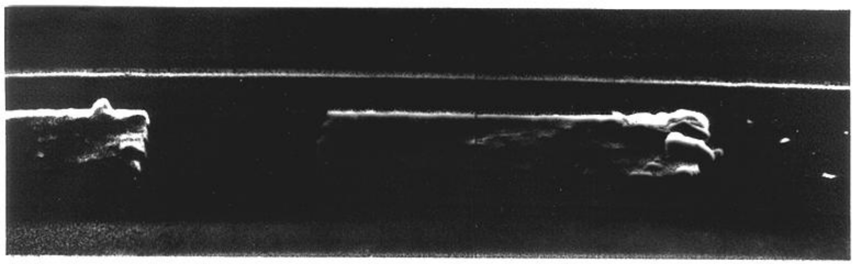
- The EM driving force of the net atomic flux :

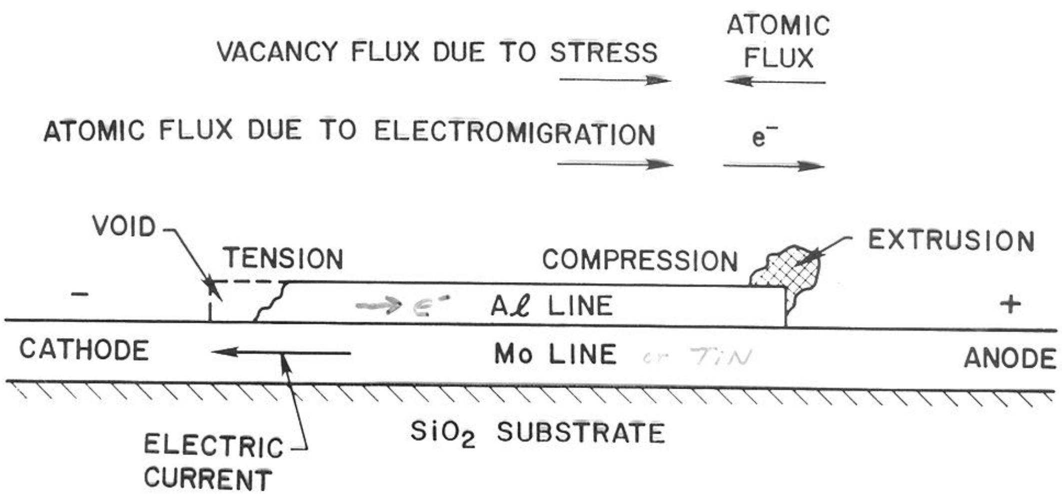
$$F_{em} = Z^* e\varepsilon = (Z^*_{el} + Z^*_{wd})e\varepsilon$$

Z^*_{el}: Electrostatic force due to the electric field acting on diffusing ions

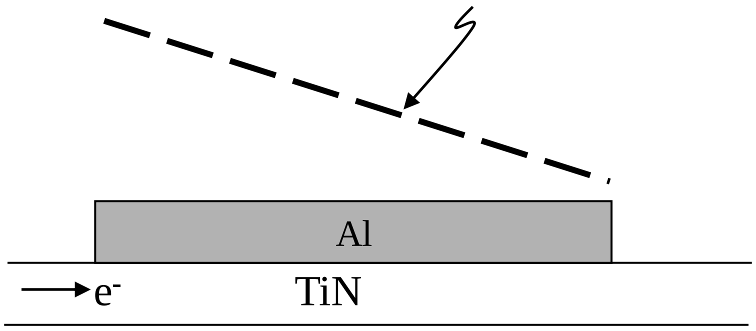
Z^*_{wd}: Electron wind force due to the electron-atom momentum exchange effect

EM-induced back stress



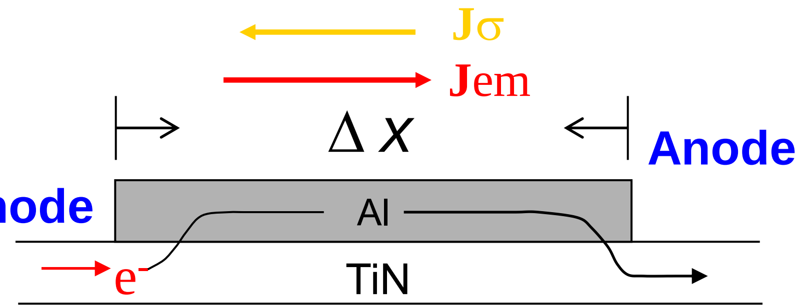


vacancy gradient due to stress



Critical product in short strip

$$J = -C\frac{D}{kT}\frac{d\sigma\Omega}{dx} + C\frac{D}{kT}Z^{*}eE$$



If J = 0, there is no net electromigration flux.

$$\Rightarrow \frac{\Delta\sigma\Omega}{\Delta x} = Z^{*}e\rho j$$

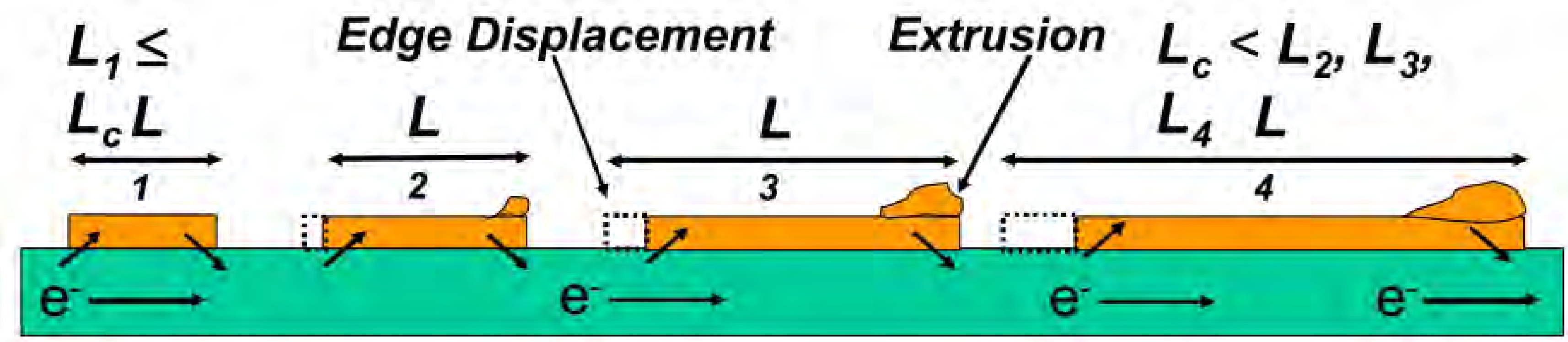
E= Electric Field (E = ρj)

⇒ **Critical product**

$$(j\Delta x)_{critical} = \frac{\Delta\sigma\Omega}{Z^{*}e\rho}$$

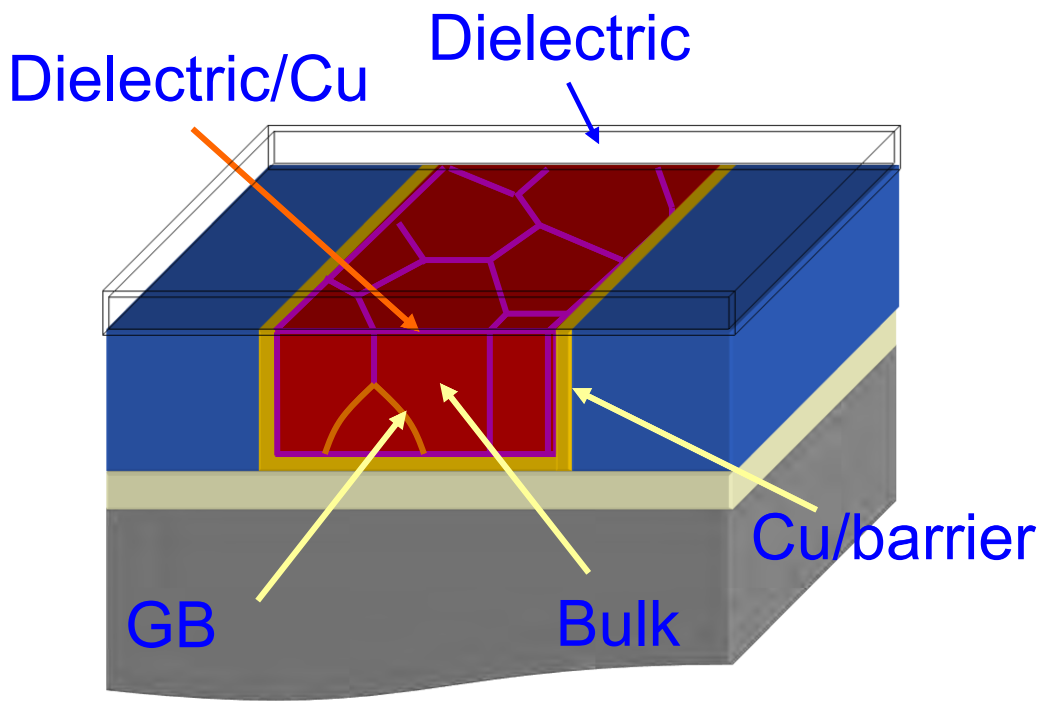
If $j\Delta x < (j\Delta x)_c$ → No EM damage

Blech effect



- The Blech effect says that below a certain critical length, L_c, no EM damage formation will arise.
- Similarly, for a given interconnect of length L, the resistance change due to EM damage will cease below a certain current density, j_c.

Electromigration paths



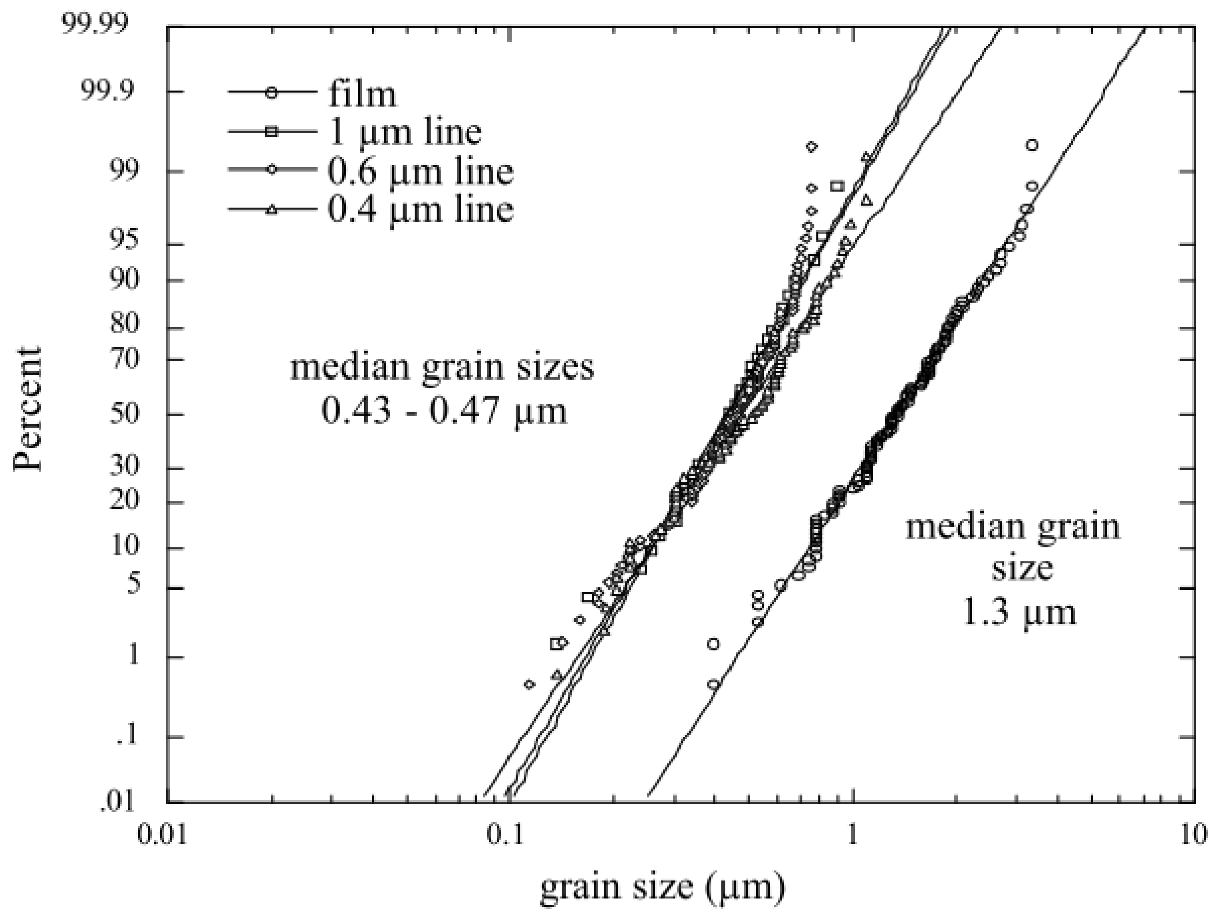
Temperature-dependent EM mechanisms

TABLE I. Melting point and diffusivities of Cu, Al, and eutectic SnPb.

	Melting point (K)	Temperature ratio 373 K/T m	Diffusivities at 100 °C (cm^2/s)	Diffusivities at 350 °C (cm^2/s)
Cu	1356	0.275	Lattice $D_l = 7\times10^{-28}$	$D_l = 5\times10^{-17}$
			Grain boundary $D_{gb} = 3\times10^{-15}$ Surface $D_s = 10^{-12}$	$D_{gb} = 1.2\times10^{-9}$ $D_s = 10^{-8}$
Al	933	0.4	Lattice $D_l = 1.5\times10^{-19}$	$D_l = 10^{-11}$
			Grain boundary $D_{gb} = 6\times10^{-11}$	$D_{gb} = 5\times10^{-7}$
Eutectic SnPb	456	0.82	Lattice $D_l = 2\times10^{-9} - 2\times10^{-10}$	Molten state $D_l > 10^{-5}$

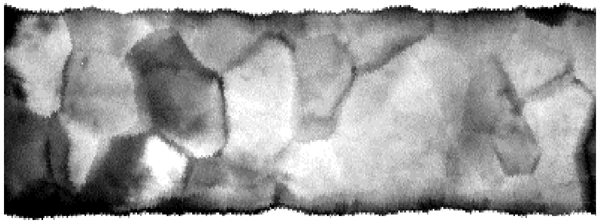
K. N. Tu, *JAP*, **94**, 5451 (2003)

Grain-size dependent EM for Al(Cu) interconnects



Bamboo

Polycrystalline

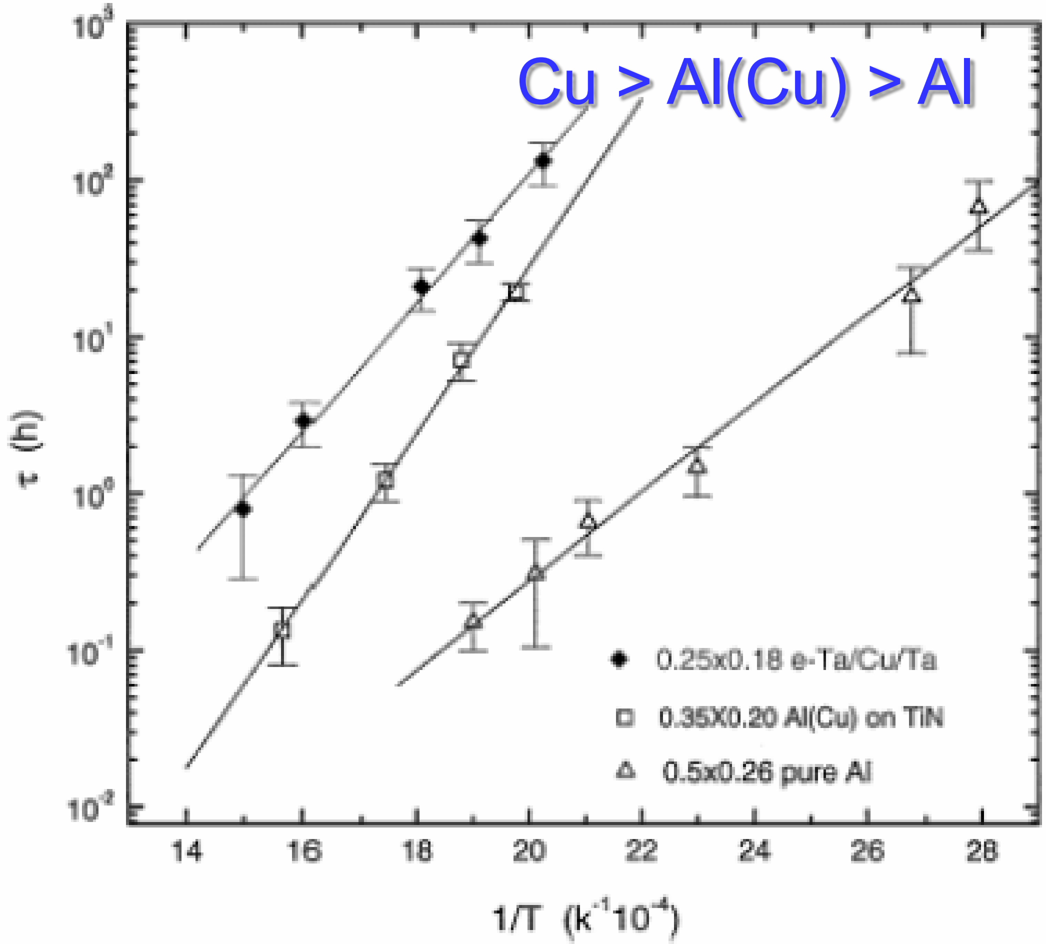


E_A(B.B.) ~ 0.9eV

E_A(Poly) ~ 0.6eV

M. Gall, Ph.D. Thesis, UT Austin, 1999

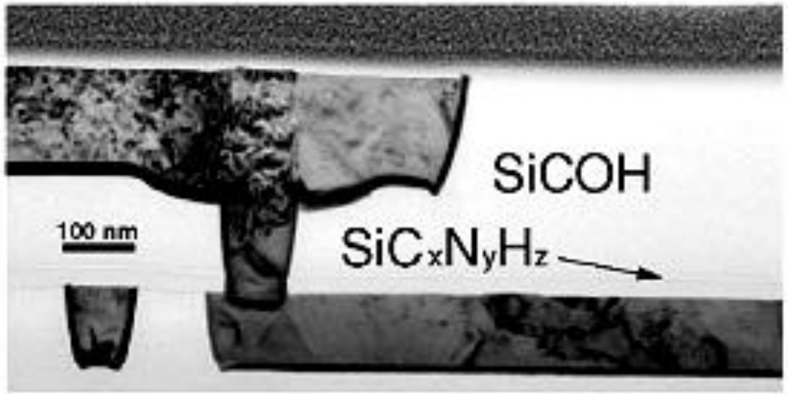
EM life time for Al, Al(Cu) and Cu



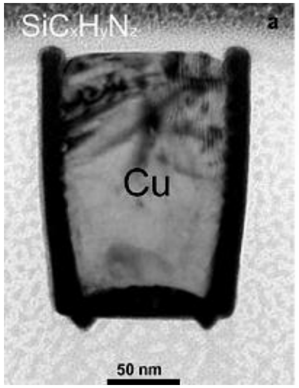
C. K. Hu et al., Mat. Chem. Phys. 52, 5, 1998; R. Rosenberg et al. “Copper Metallization for High Performance Silicon Technology”, Ann. Rev. Mat. Science V.30, pp.229-262, 2000.

EM paths for Cu interconnects

- Major EM path: Cu/dielectric interfaces
- Solutions:
  - Surface treatment prior to dielectric dep.
  - Metal capping
  - Alloying

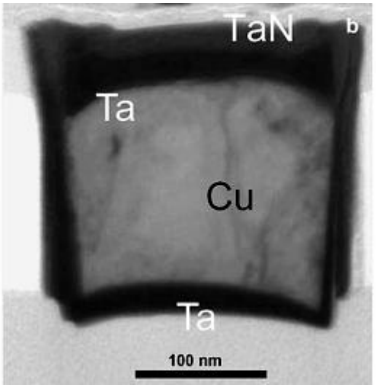


$SiC_xN_yH_z$



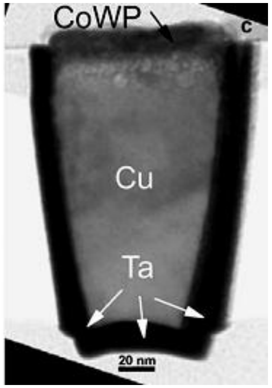
E_a=0.9~1 eV

TaN



E_a=1.4 eV

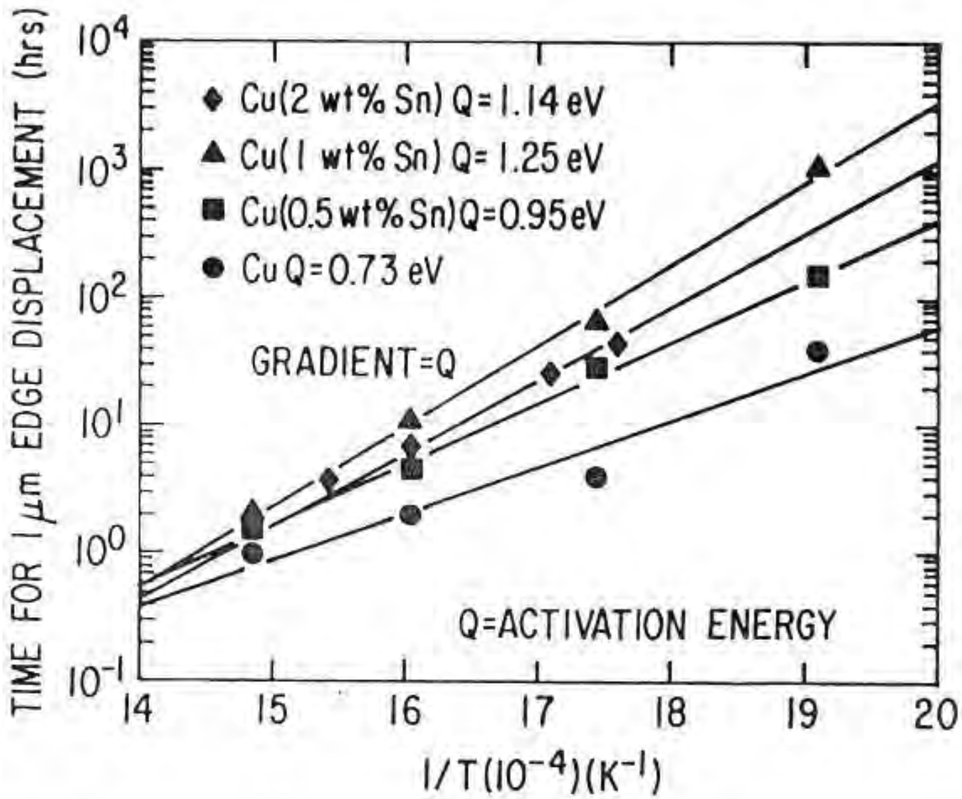
CoWP



E_a=2 eV

C. K. Hu et al, *Thin Solid Films*, 504, 274 (2006).

EM of Cu(Sn) interconnects



Film	Resistivity (μΩ-cm) at 20°C
Sputtered Cu	2.1
Al (2 wt% Cu)	3.2
Cu (0.5 wt% Sn)	2.4
Cu (1 wt% Sn)	2.9
W	5.3

Activation energy for EM

Cu < Cu-0.5Sn < Cu-1Sn < Cu-2Sn

Resistivity

Cu < Cu-0.5Sn < Cu-1Sn < Al(Cu)

Research for what?

- Understanding the structure-processing-property relationship
  - Directions of new material development
  - Model and mechanism?
- Enhanced properties for better performance of existing applications or new applications
  - Experimental and theoretical verification
  - Prototyping applications and feasibility testing
- Confirming known facts is a training procedure not a research goal!

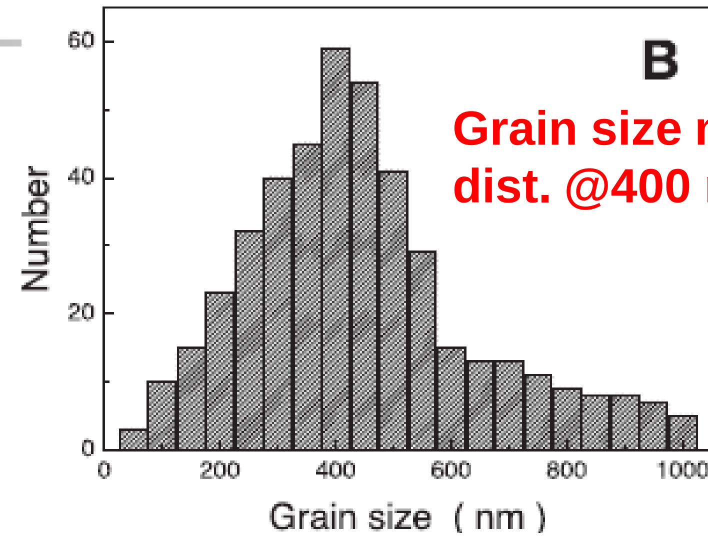
EM resistance improvement

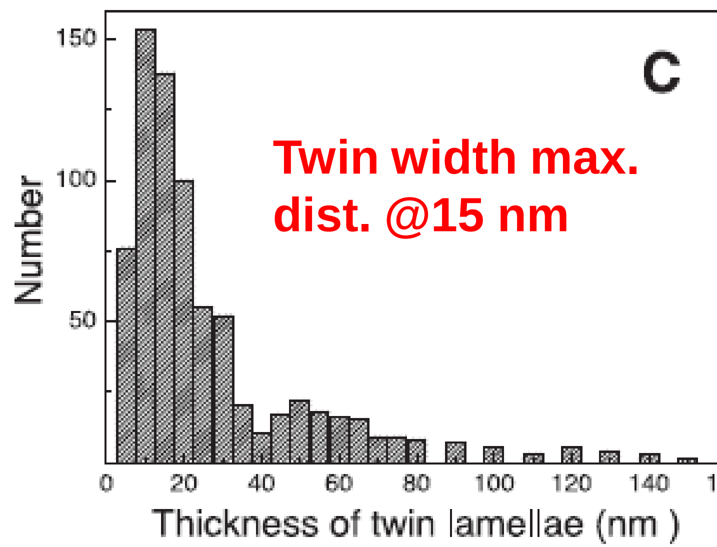
- For Al interconnects, we add tiny amount of Cu and Si into the Al metallization.
- For Cu interconnects, what can we add?

Nanotwinns

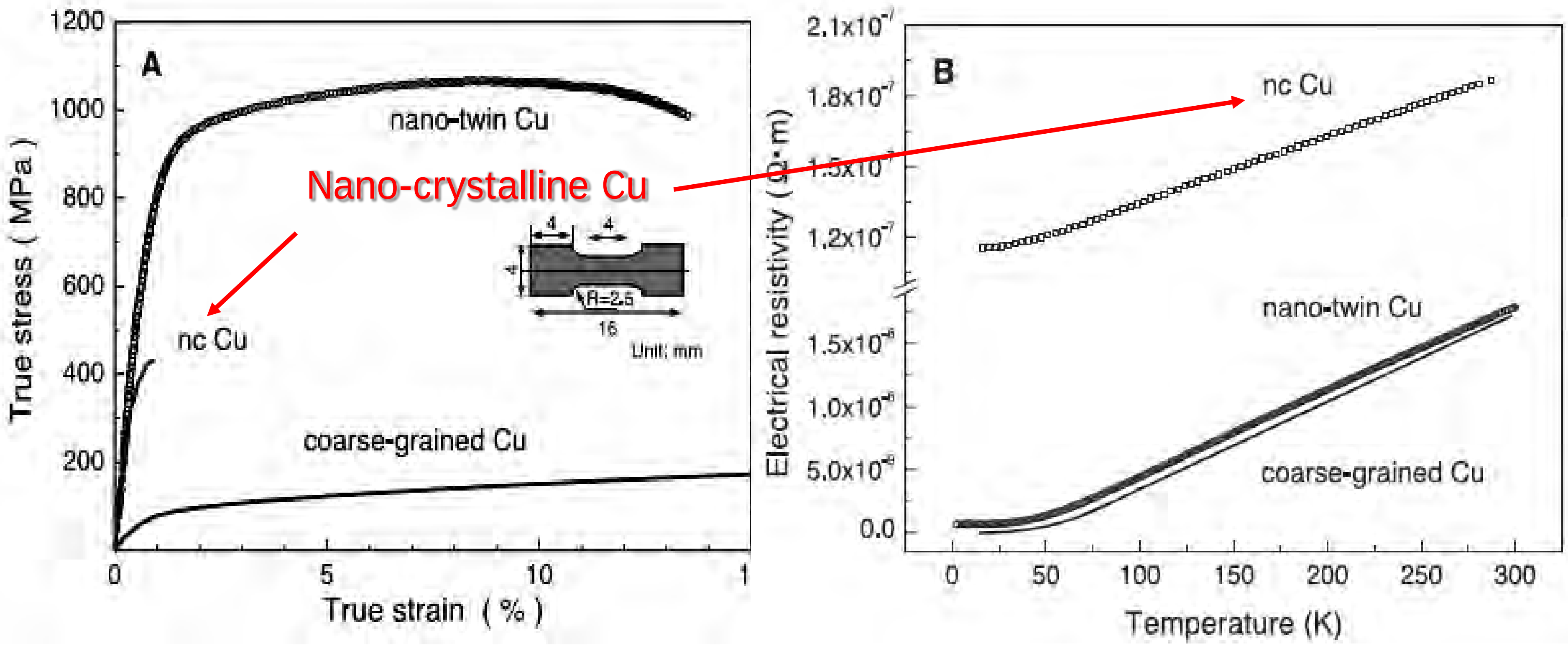
Twin-structured Cu metallization

L. Lu, *Science*, **304**, 422 (2004).





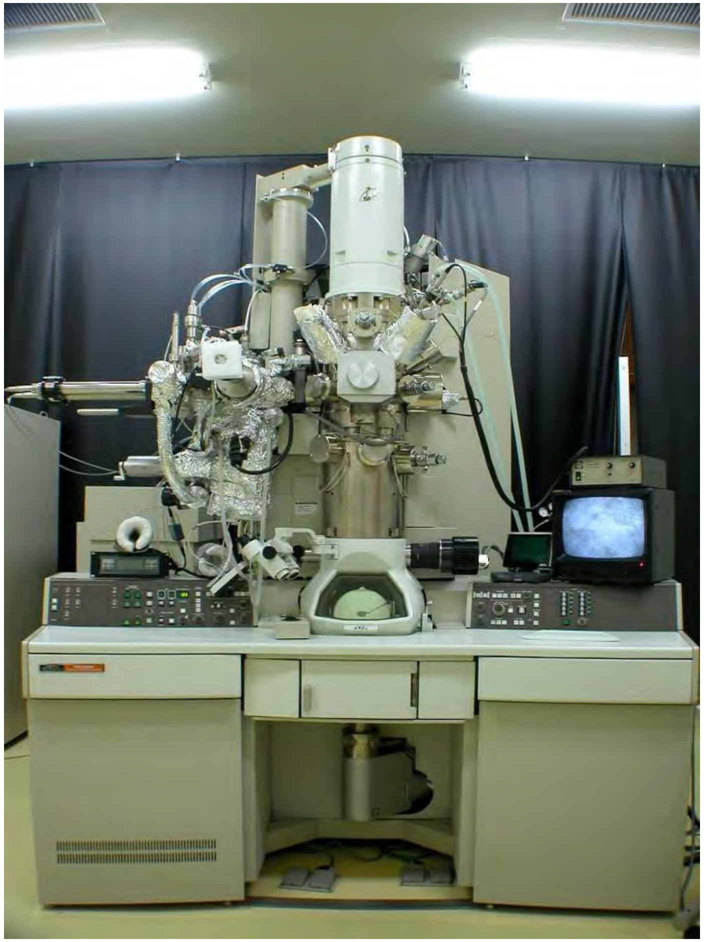
Twin-structured Cu metallization

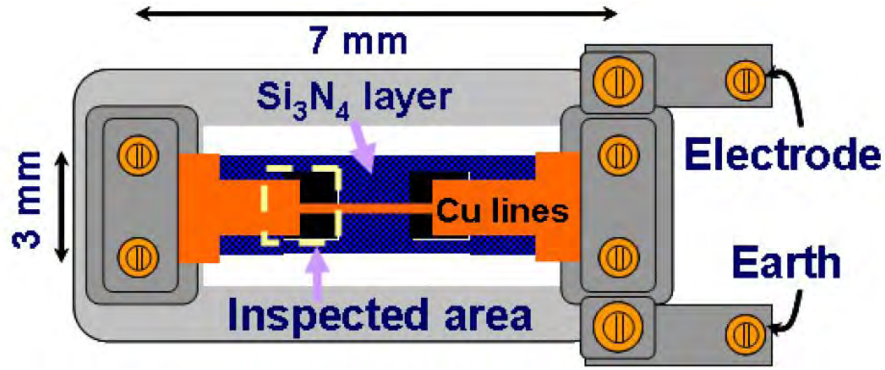


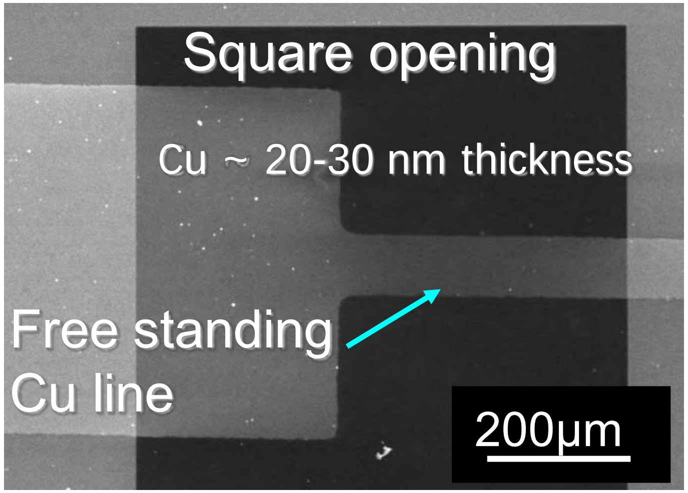
L. Lu, *Science*, **304**, 422 (2004).

Experimental setup

UHV-TEM (JEM 2000V)

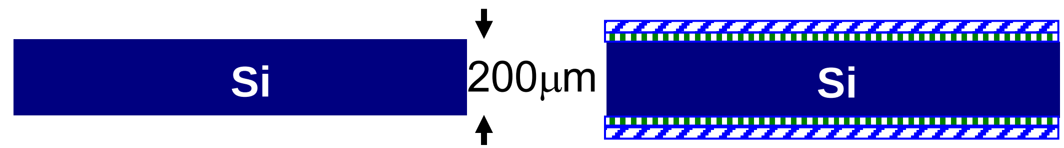




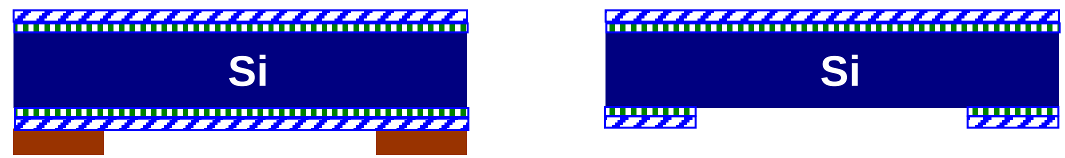


Specimen preparation

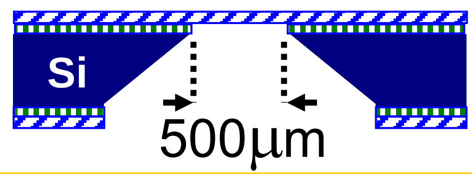
SiO_2/Si_3N_4 deposition



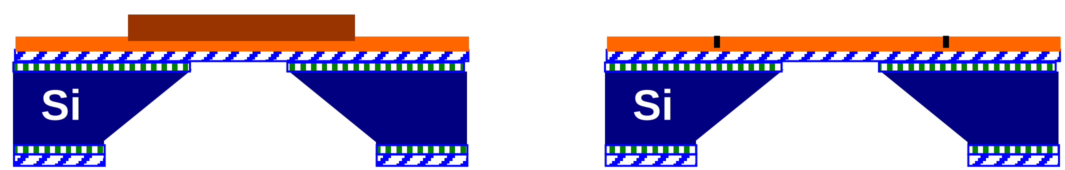
SiO_2/Si_3N_4 Patterning



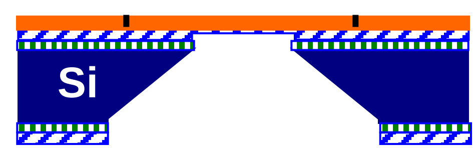
KOH wet etching



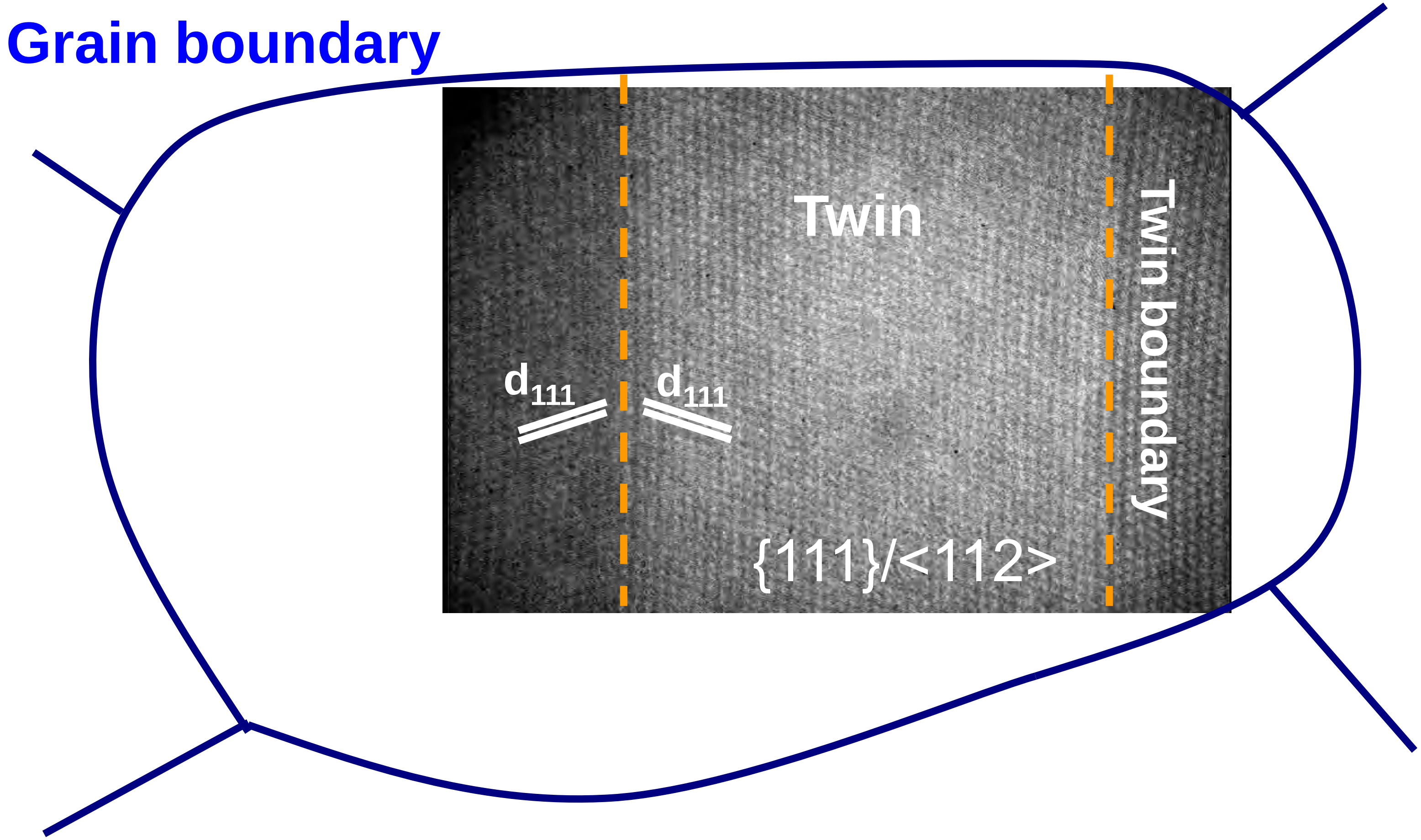
Cu deposition/patterning



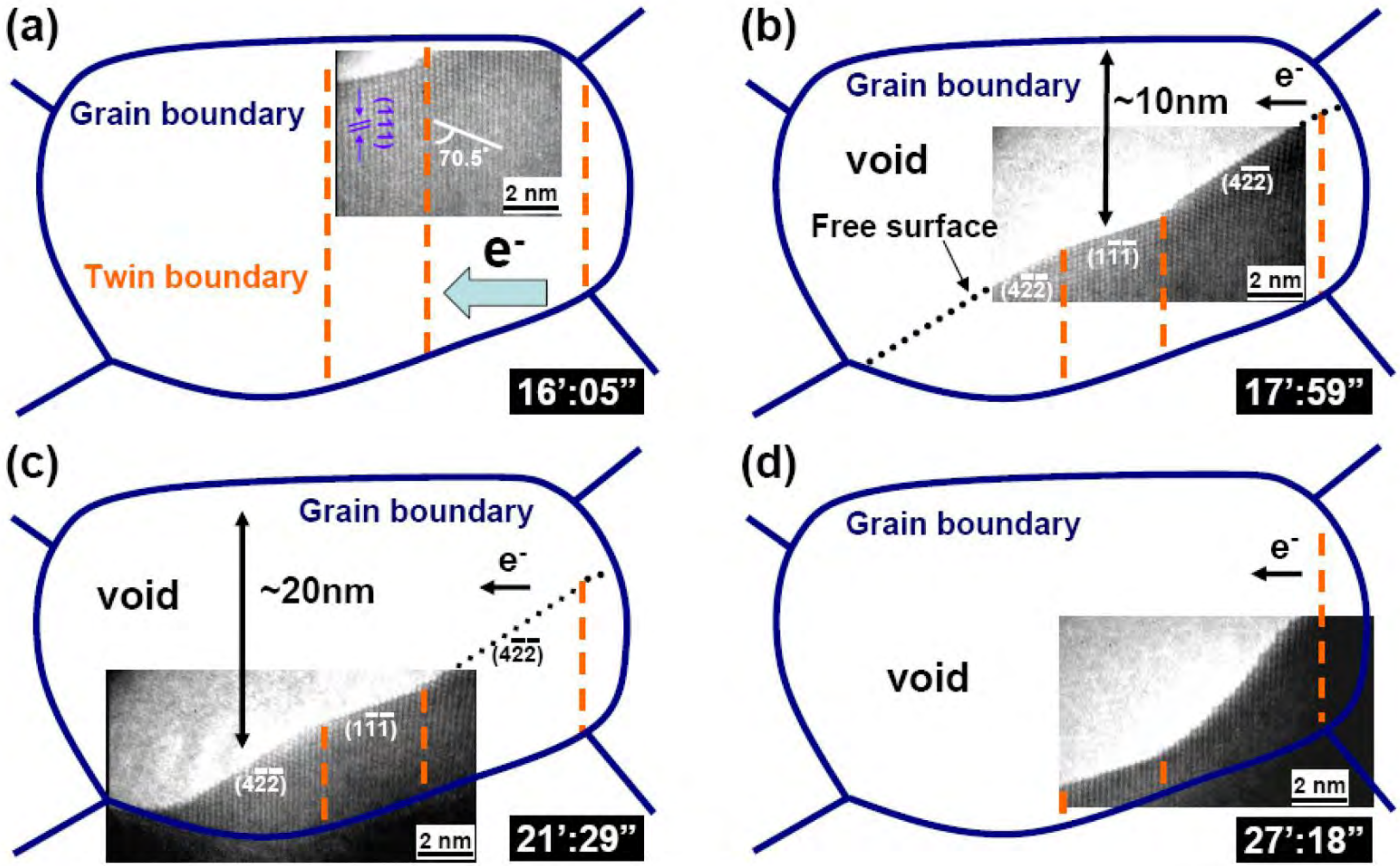
Heat treatment & RIE etching



Twin-structured (110)-oriented Cu grain

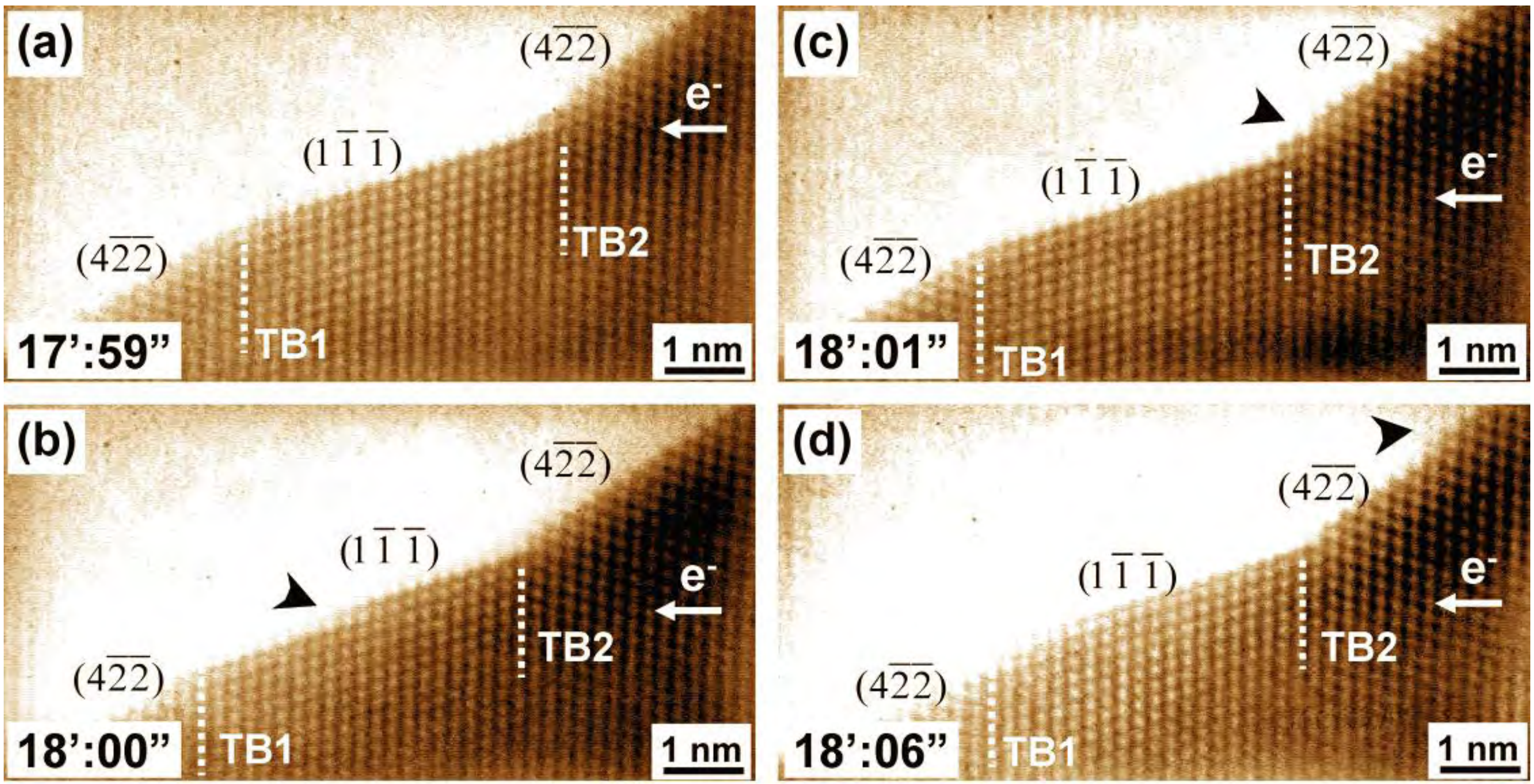


EM-induced atomic migration at twin-modified grain boundary



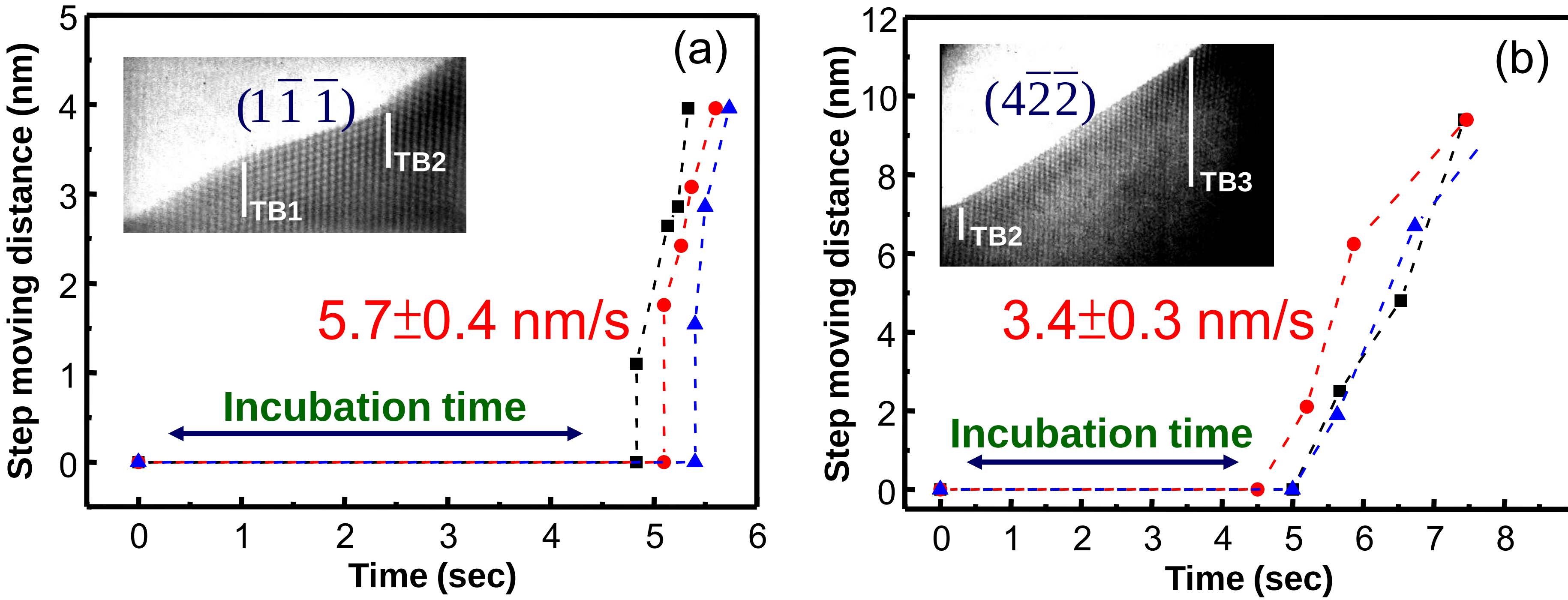
K. C. Chen et al, *Science*, **321**, 1066 (2008)

Effect of twin boundary on EM



K. C. Chen et al, *Science*, **321**, 1066 (2008)

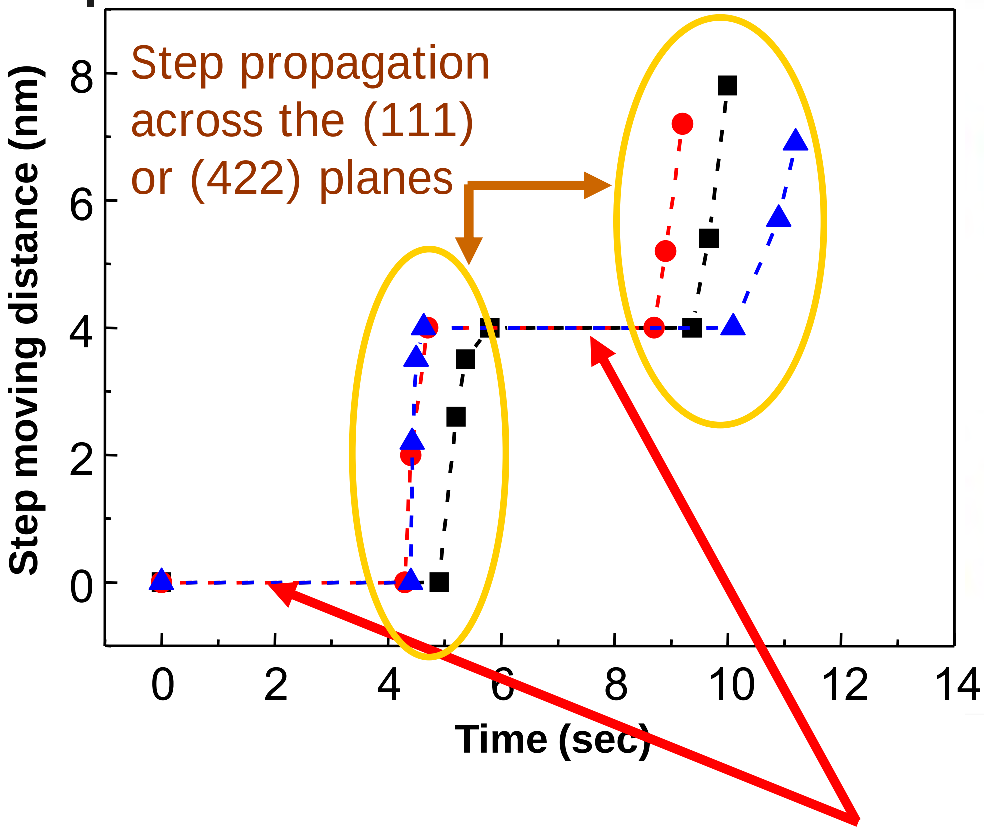
Moving speed of the atomic steps at twin-modified boundary

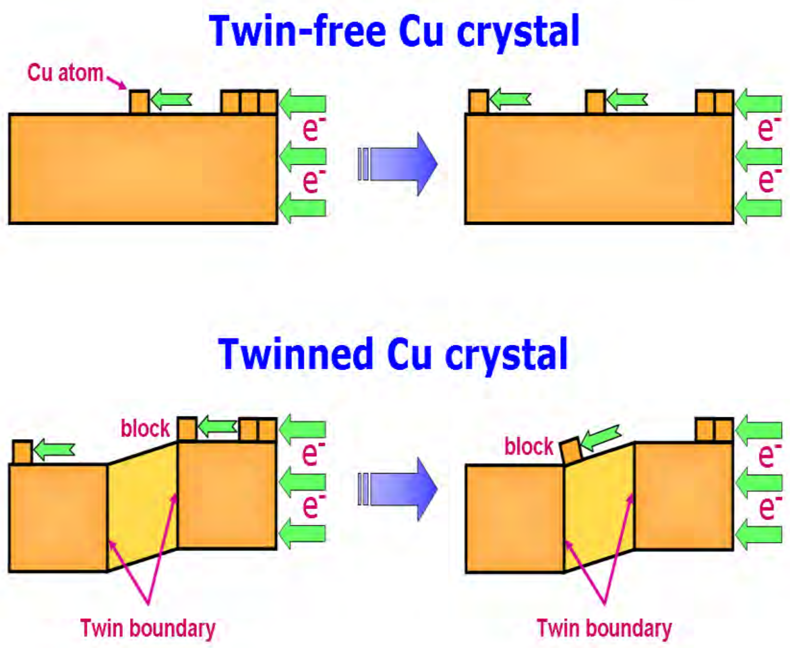


Twin boundaries ➡ **time lag of ~ 5 seconds**

K. C. Chen et al, *Science*, **321**, 1066 (2008)

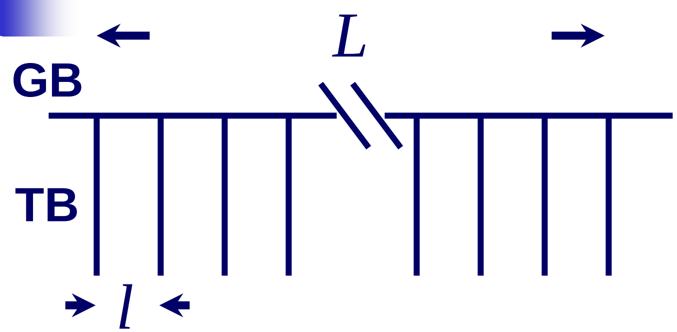
EM-induced atomic step movement



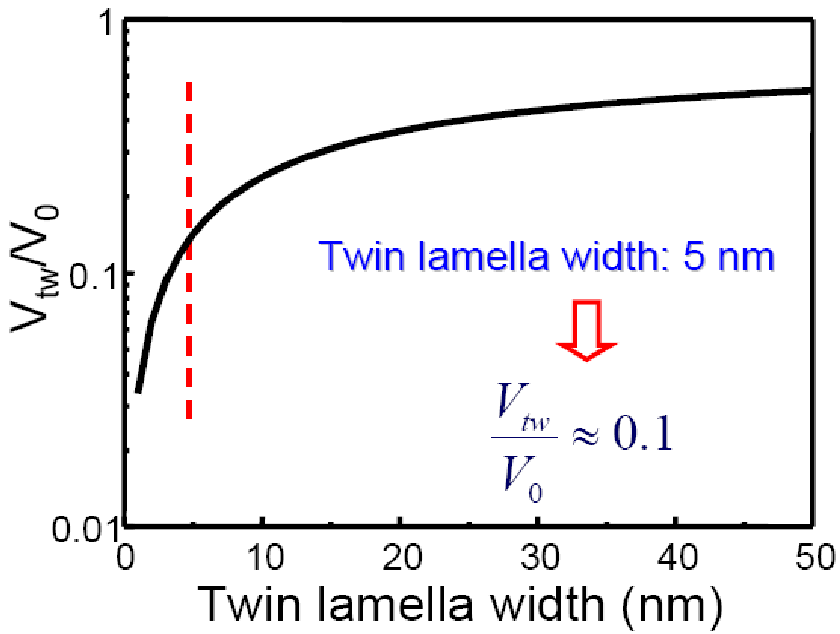


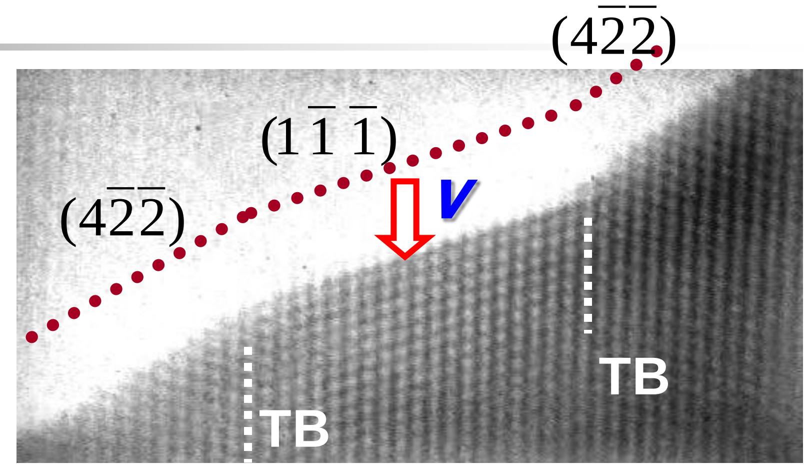
Incubation time for nucleating a new step on the (111) or (422) plane

Analysis of EM-induced voiding rate



Twin width





V_0: twin-free Cu

V_{tw}: twinned Cu

K. C. Chen et al, *Science*, **321**, 1066 (2008)

Fundamental knowledge/training

- Fundamental knowledge:
  - Semiconductor processing technology, Micro Electro-Mechanical Systems, Kinetics of Materials, Diffusion in Solids, Phase transformation, …
- Equipment training:
  - Sputter, E-beam, Electrochemical deposition, Reactive ionic etching, Photo lithography patterning , Sputter, Rapid thermal annealing, 4-point probe, Electrical stressing/measurement, Photomask design, …
- Lab skills:
  - TEM, SEM, XRD, Origin, LabView, Image processing, …
  - **Design what you need!!!**

Potential research topics

- EM-induced grain growth (GB migration)
- EM-induced TB migration
- EM characteristics of nanotwinned Cu lines
- Cu/CNT composite
- Cu nanowire
- Oxidation behavior of nanotwinned Cu
- Existence of EM-induced back stress