STANFORD
MATERIALS SCIENCE
AND ENGINEERING

PROBING PLASTICITY AT SMALL SCALES:

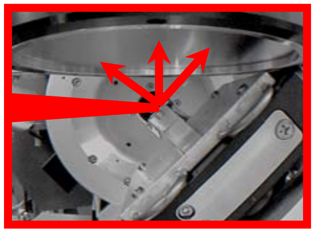
FROM ELECTROMIGRATION IN ADVANCED CU INTERCONNECTS TO DISLOCATION STARVATION IN AU NANOPILLARS

Arief S. Budiman
Materials Science and Engineering, Stanford University
Advisor: Professor William D. Nix

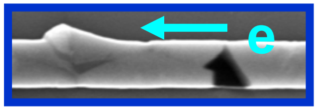
OUTLINE

THE TECHNIQUE:

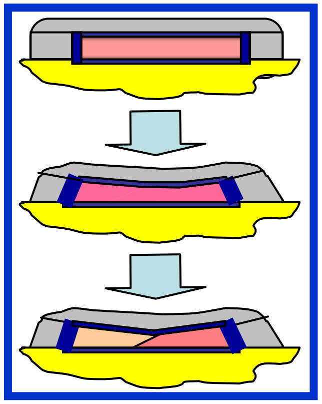
→ Synchrotron White Beam X-Ray Submicron Diffraction as Plasticity Probe for Study of Small Scale Mechanics



PLASTICITY IN ADVANCED INTERCONNECTS:

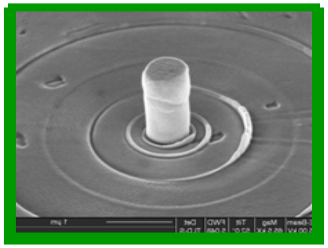


- The Basic Observation
  (Samples made by Intel Corp.)
- The Texture Observation
  (Samples made by AMD)
- The Practical Implications for EM Reliability Community in Industry



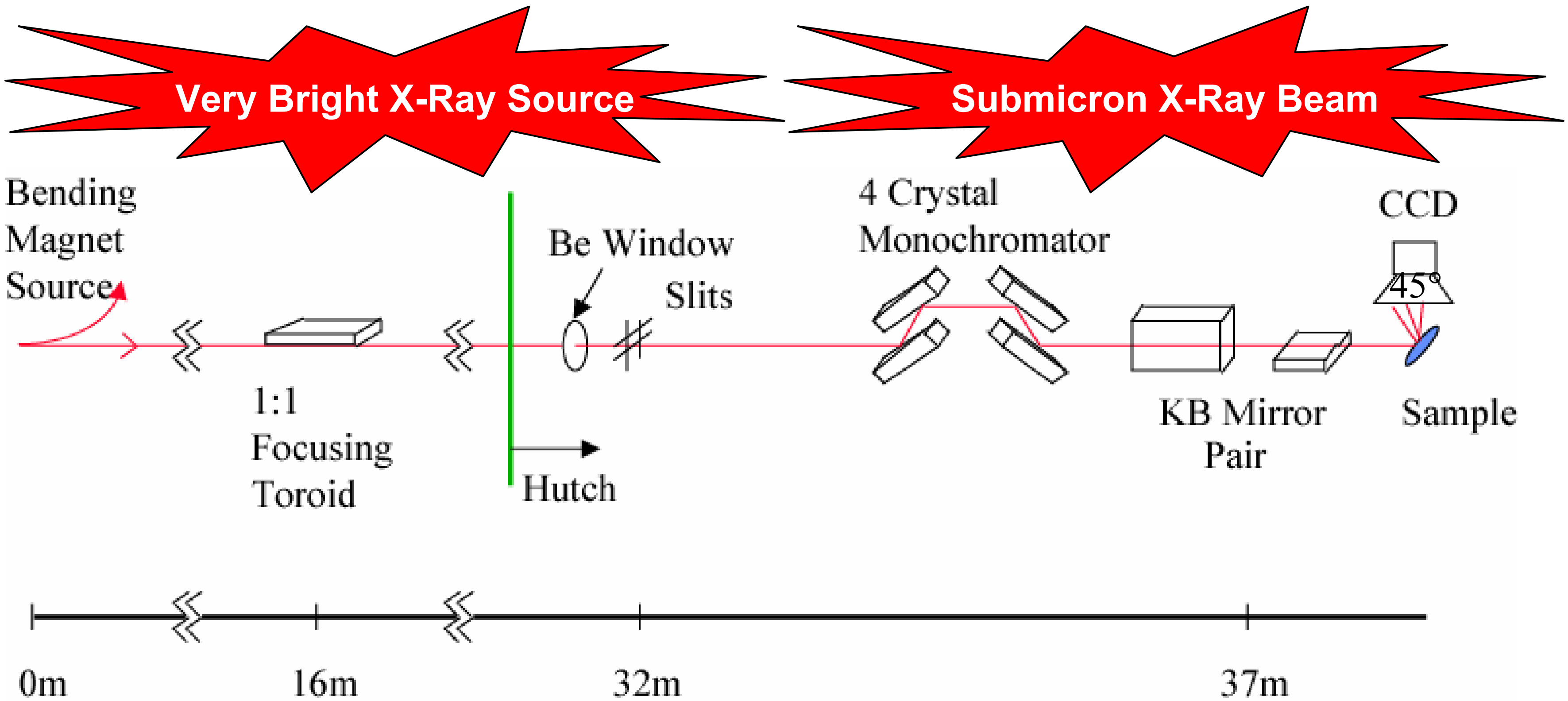
SMALL SCALE PLASTICITY IN CRYSTALS

- Size Effects in Au Nanopillars:
  → Smaller Pillar, Stronger Pillar!



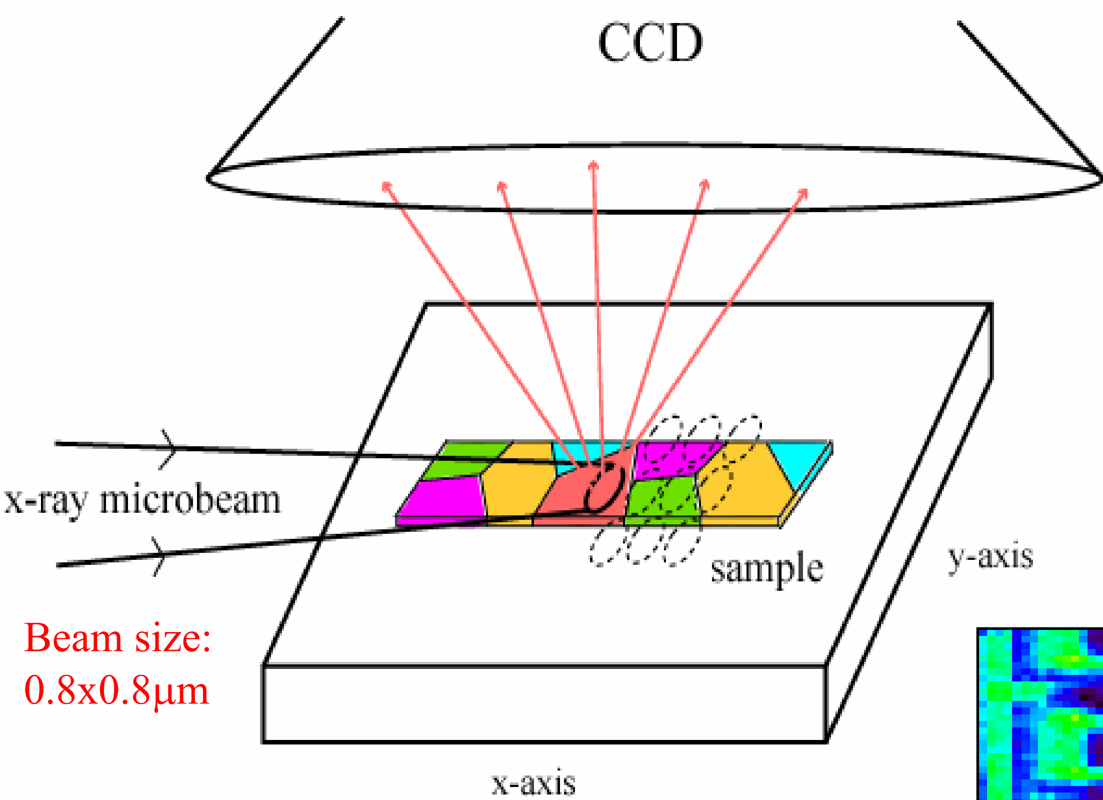
CONCLUSIONS

Synchrotron X-ray Submicron diffraction

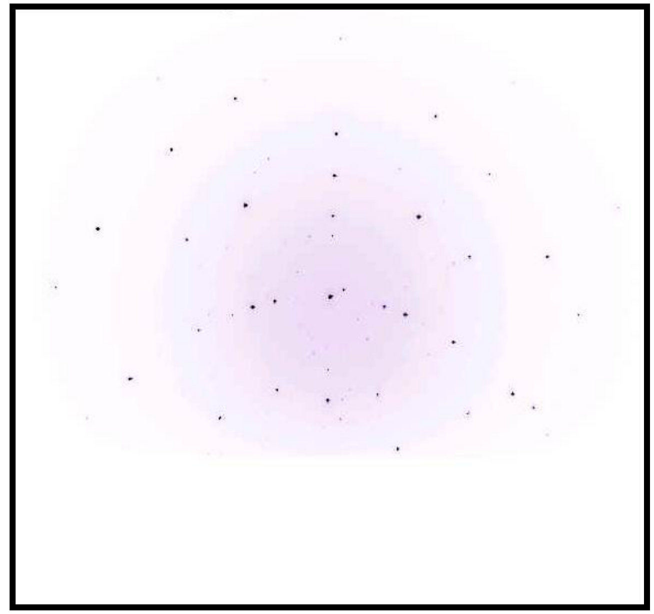


X-RAY DIFFRACTION PROBE FOR SMALL SCALE DEVICES

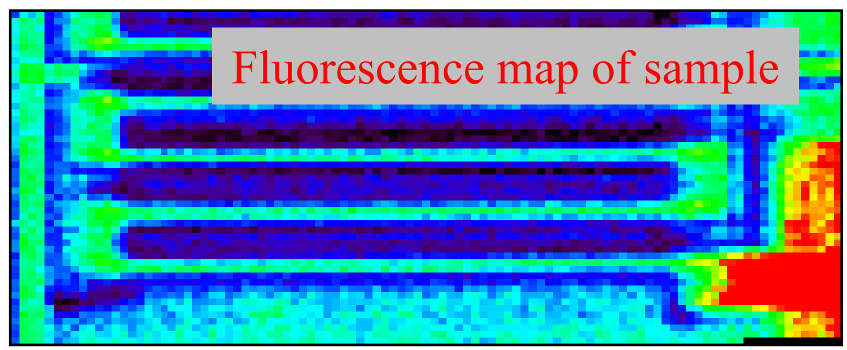
Scanning X-Ray Microbeam Technique



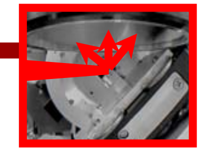
Beam size:
0.8x0.8μm



CCD frame w/ Laue patterns

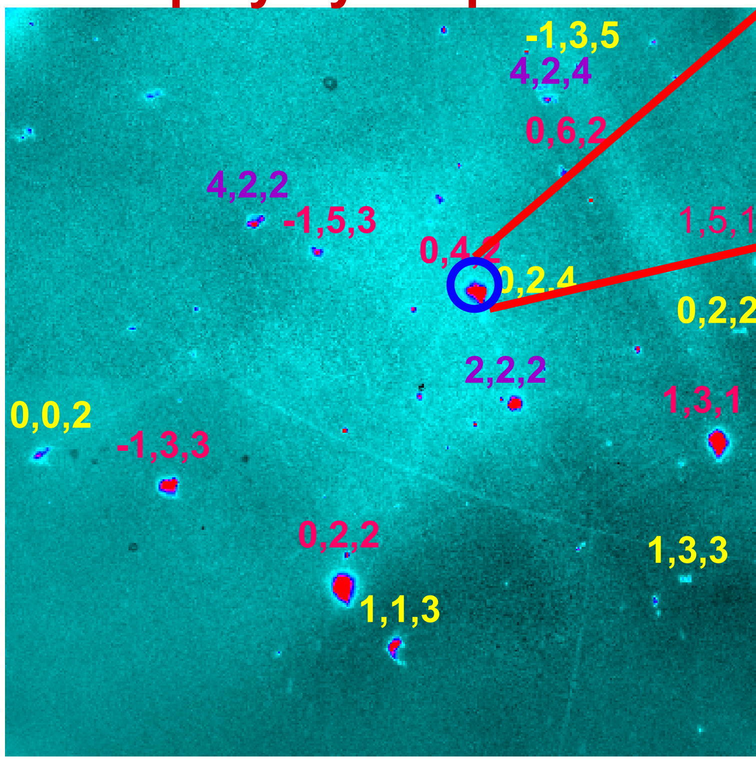


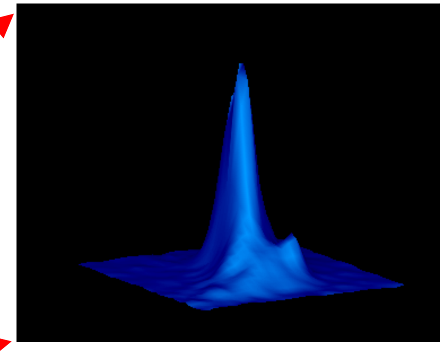
X-ray source: ALS Synchrotron, Berkeley Lab



What can we learn from a single white beam (Laue) pattern ?

Cu polycrystal pattern

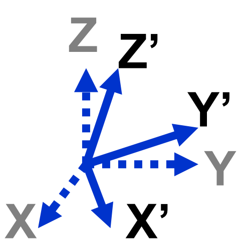




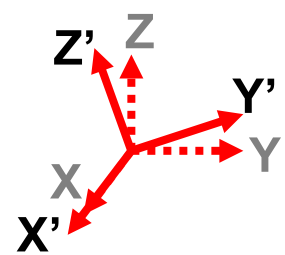
Phase identification/ Crystal orientation: pattern indexation (~0.01° accuracy)

Plastic deformation: Spot shapes

Crystal rotation: Small shifts in spot <u>absolute</u> positions (~0.01° accuracy)



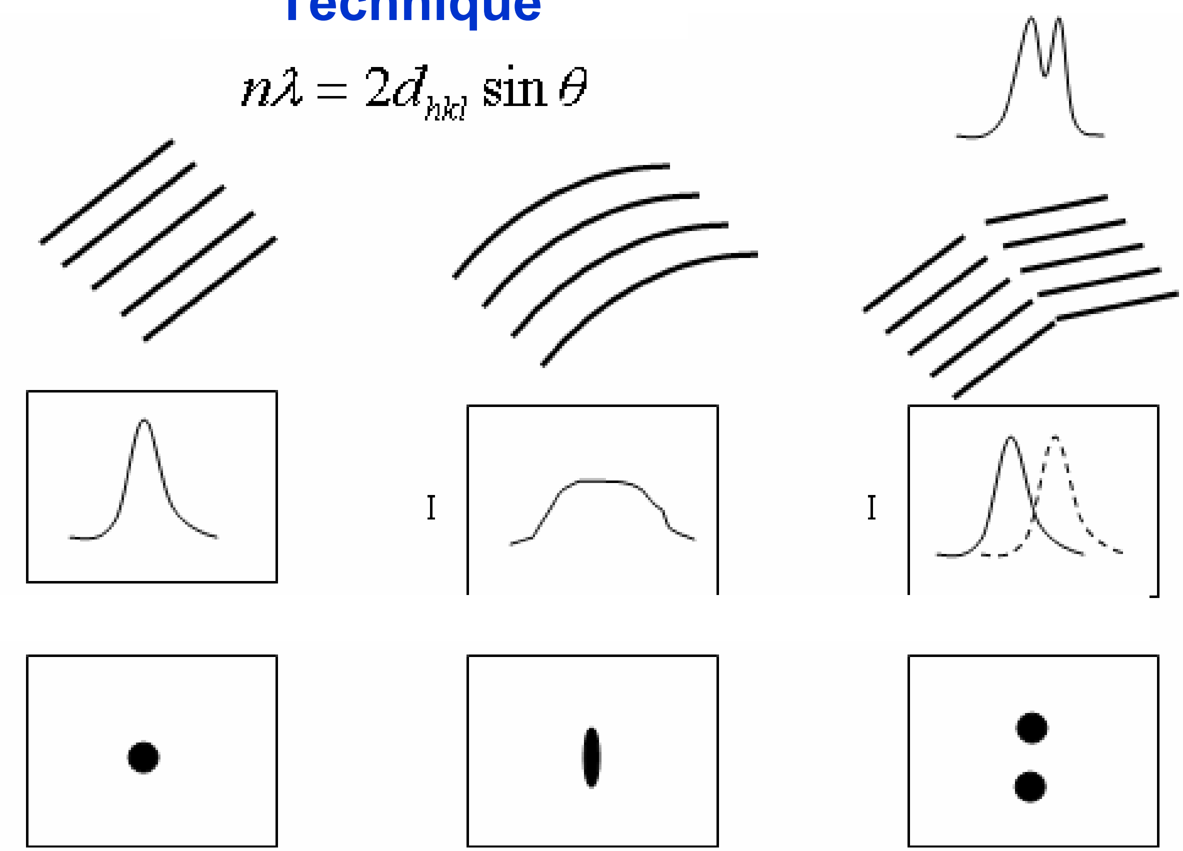
Deviatoric strain tensor: Small shifts in spot <u>relative</u> positions Crystal deformation at constant volume (~ 10^{-4} accuracy)



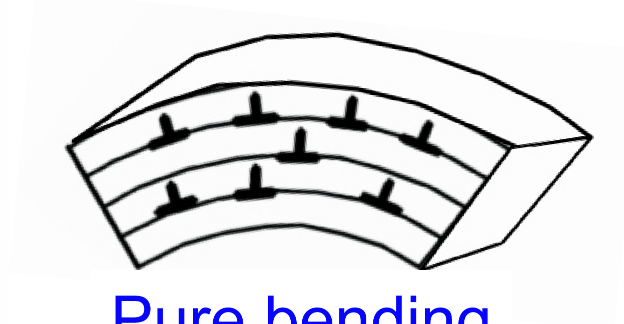
X-Ray Microdiffraction – Peak Broadening, Peak Splitting

White Beam (Laue) Technique

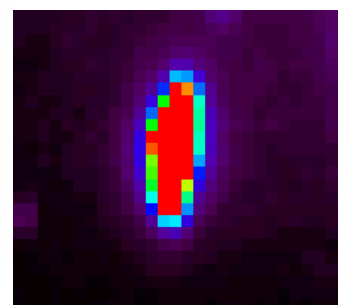
$$n\lambda = 2d_{hkl}\sin\theta$$



Peak shapes provides information on plastic deformation and dislocation distribution in the diffracted volume



Pure bending



$$\rho = \frac{1}{Rb}$$

… a practical way to do <u>direct quantitative measurement</u> of <u>plasticity</u> in crystals upon deformation

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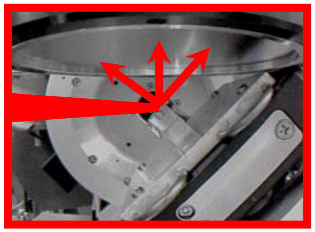

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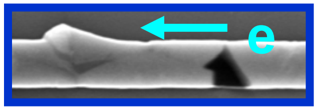

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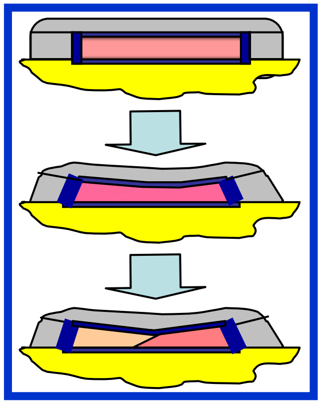

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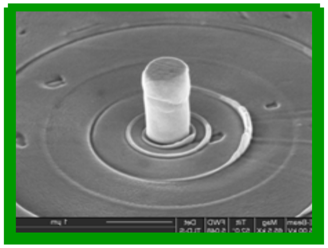

CONCLUSIONS

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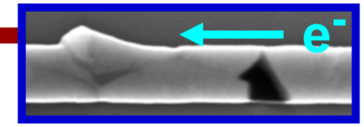
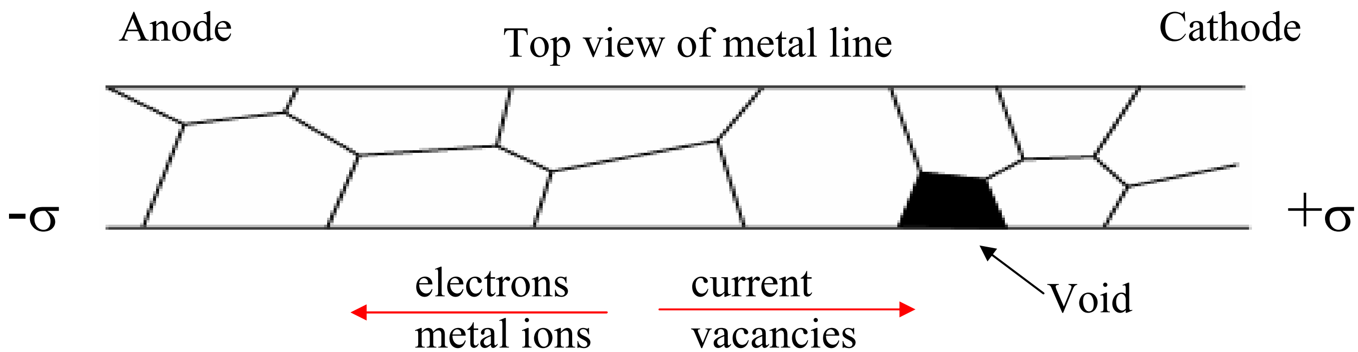
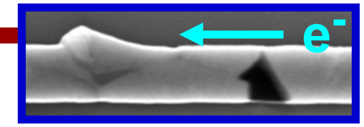


Electromigration in Interconnects



Electromigration flux: $$J_{EM} = \frac{Dc}{kT}\left(eZ^{*}\rho j - \Omega \frac{d\sigma}{dx}\right)$$

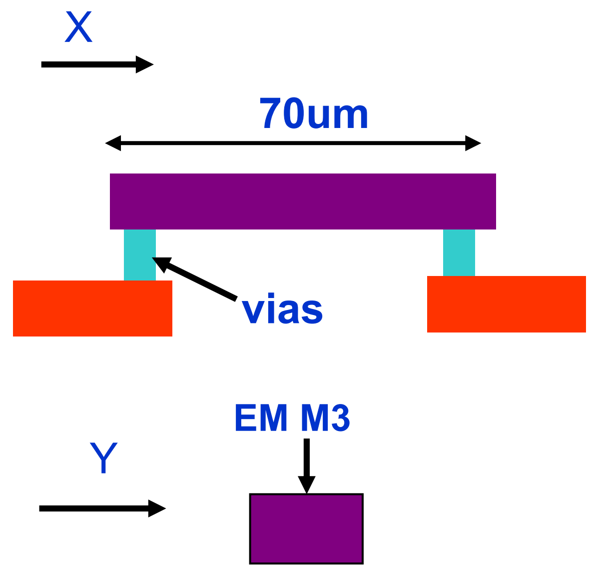
Unexpected mode of plastic deformation during EM in Al interconnects
- Valek et al., *Appl. Phys. Lett.* 81 (2002) 4168-4170



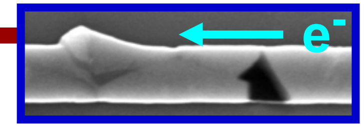
In situ EM Experiment with X-ray Microdiffraction

THE SAMPLE: Cu, 70 μm long, 1.64/0.56 μm wide, 0.97 μm thick
passivation: ~4 μm of polymer & nitride

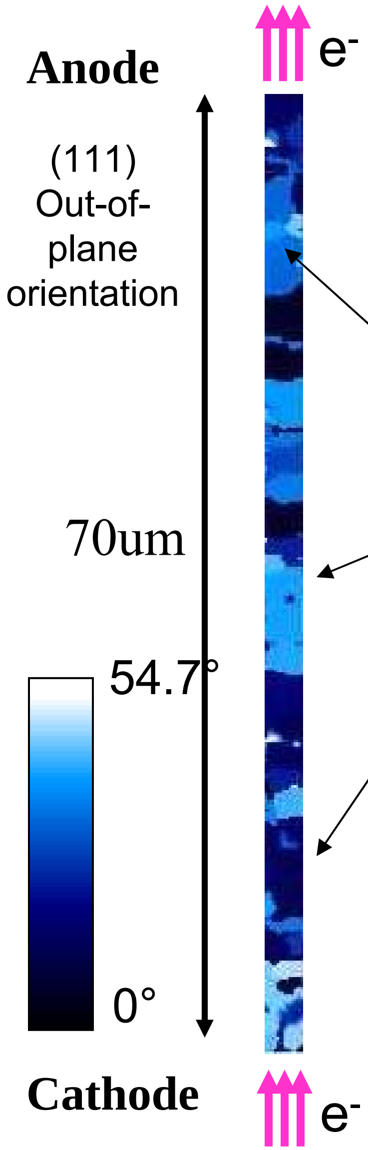
In-situ x-ray microdiffraction scans:
- at room temperature
- at **Temp (360°C)**
- at **Temp** with current ramping up to **3.1 MA/cm2**



Red: M2
Purple: M3 (EM Line)

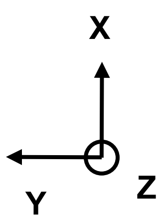


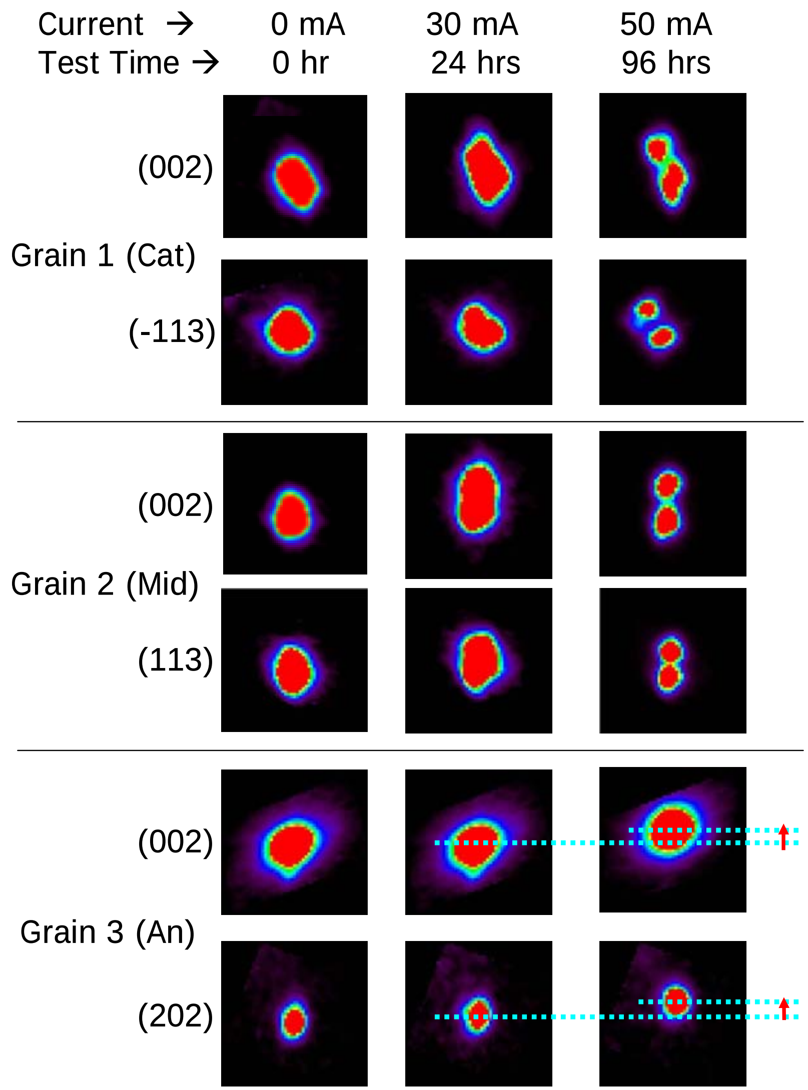
EM-Induced Plasticity in Cu Interconnects



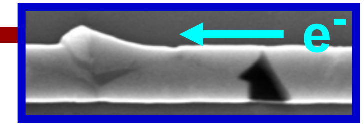
Wide line (1.6 μm)

Large single grains spanning across the width of the line





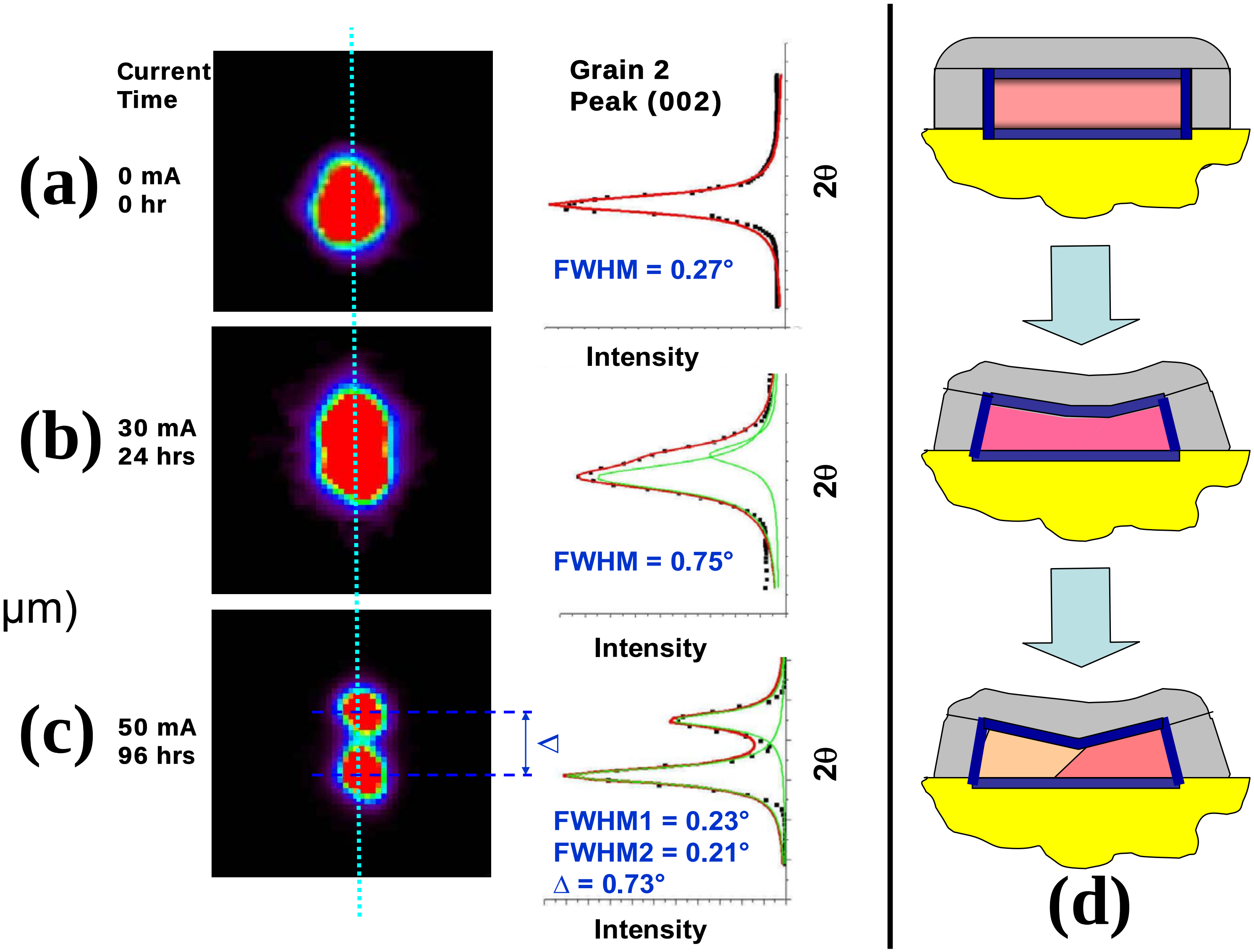
Budiman et al., *Appl. Phys. Lett.* 88, 233515 (2006)

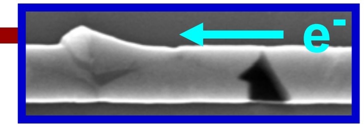


Peak Splitting – Quantitative Study

Grain 2
Peak (002)

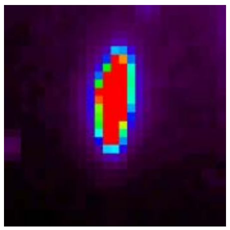
Wide line (1.6 μm)





Geometrically Necessary Dislocations

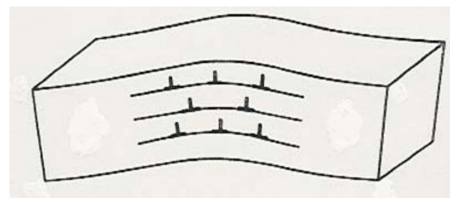
Peak shapes provides information on plastic deformation and dislocation distribution in the diffracted volume



$$\boxed{\rho = \frac{1}{Rb}}$$

Cahn-Nye Relation

Pure bending



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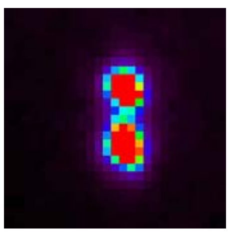
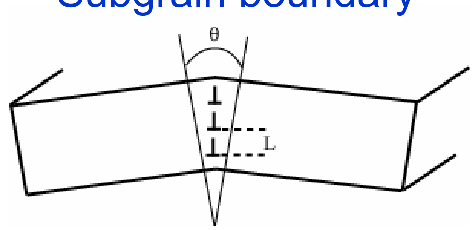


$$\boxed{\tan\theta = \frac{b}{L}}$$

Subgrain boundary



For Cu, Burgers Vector b = 2.546 Å

x_{c1} = 69.44°
x_{c2} = 70.24°
$\theta = x_{c2} - x_{c1} = 0.73°$

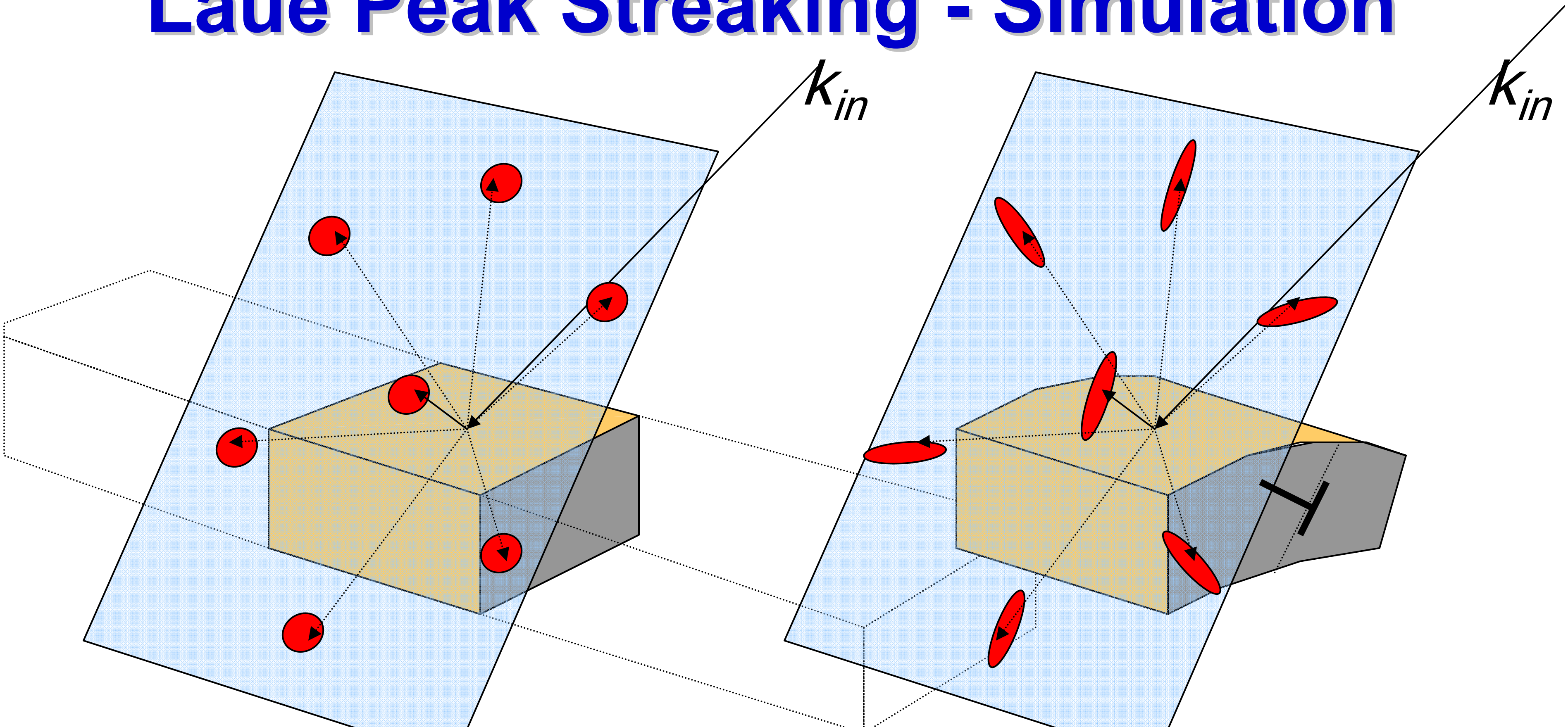
Using the above formula, **L = 182 Å = 0.0182 μm**

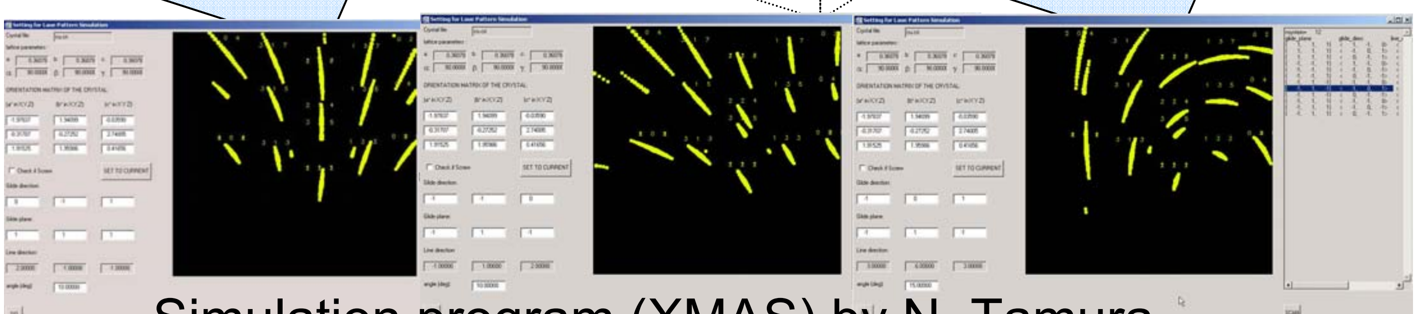
Thickness of Cu line = 0.97 μm

Total number of GND's = **53**

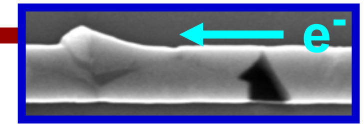
ρ_{GND} = 3.3 x $10^{13}/m^2$

Laue Peak Streaking - Simulation

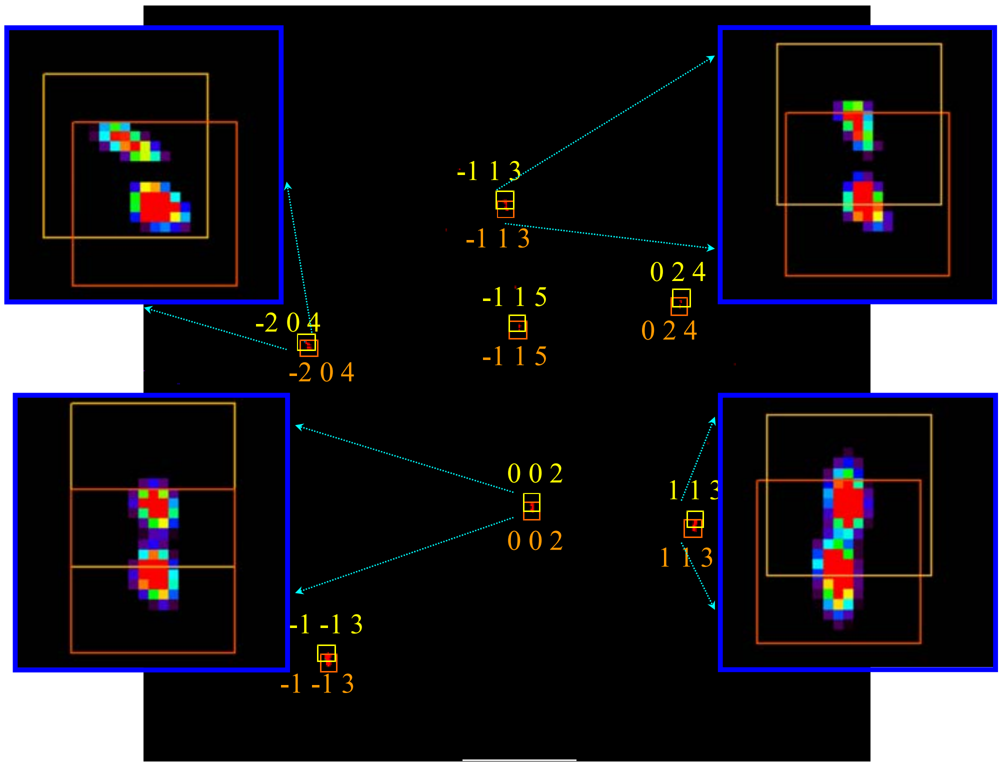




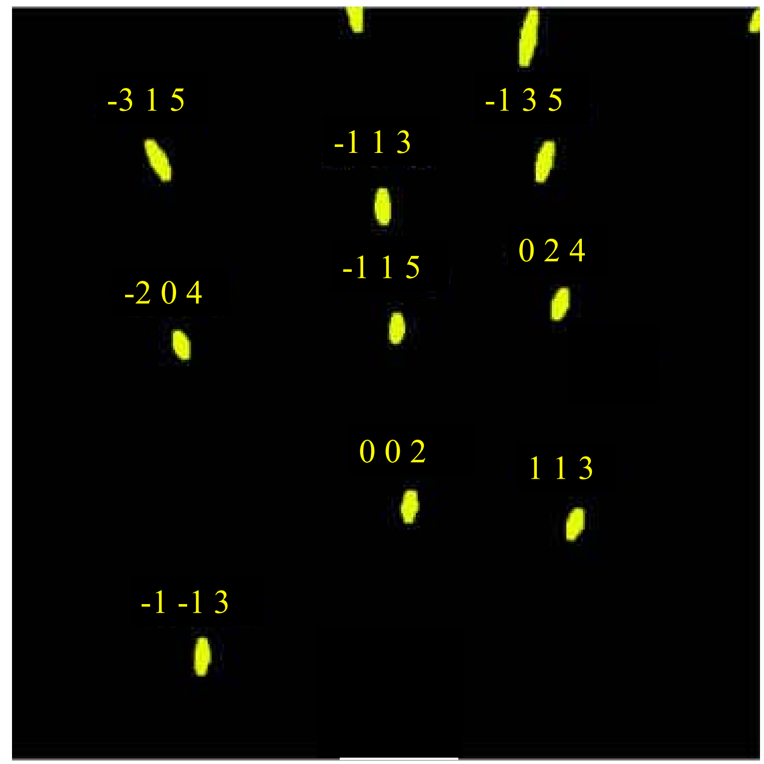
Simulation program (XMAS) by N. Tamura



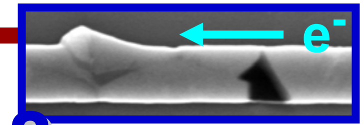
Consistent with a particular slip system of FCC crystal



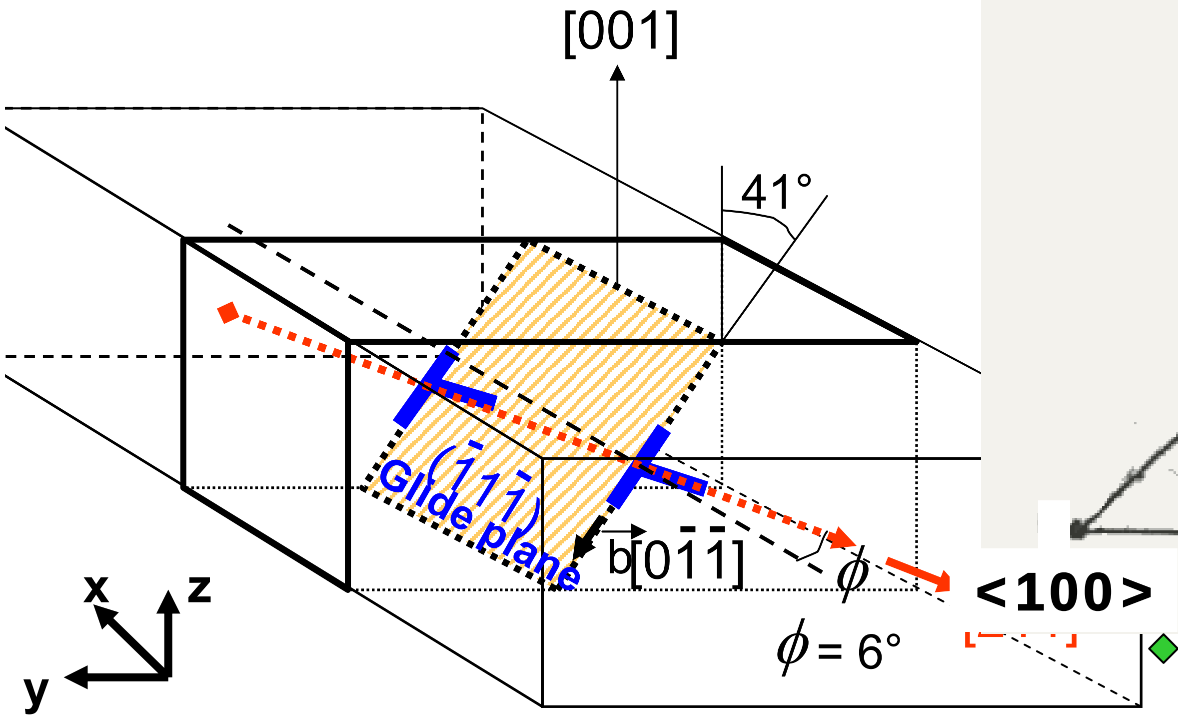
Experimental

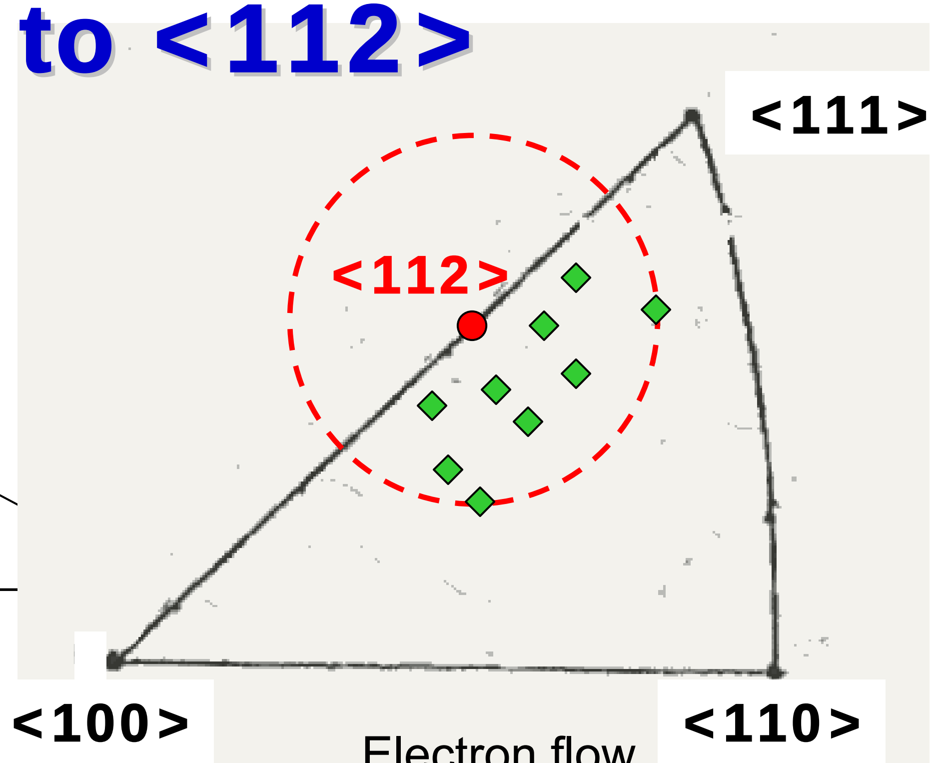


Simulation
$(\bar{1}1\bar{1})$ / $[0\bar{1}\bar{1}]$



Single Active Slip System & Proximity to <112>

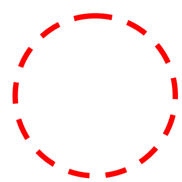




Electron flow direction (in unit crystal coordinate)

Statistics:

- 3 wide Cu lines were examined
- Between 5 to 9 each line were found with this observed behavior after similar EM test time, current density and temp.



Within 10º of a particular <112> (which is the axis of plastic deformation)

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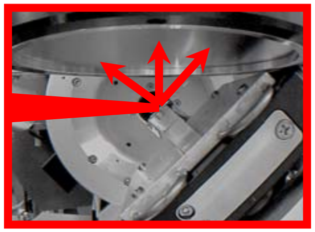

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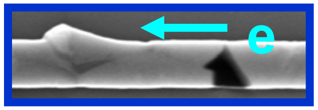

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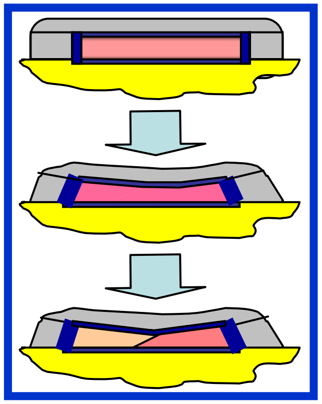

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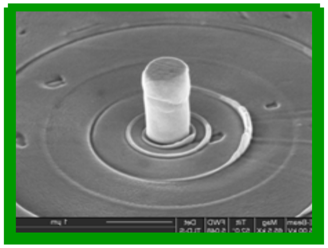
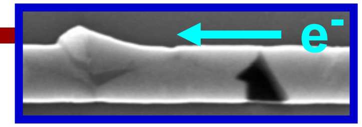
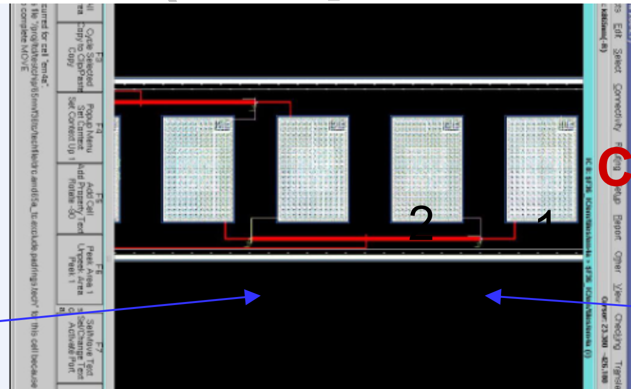


CONCLUSIONS

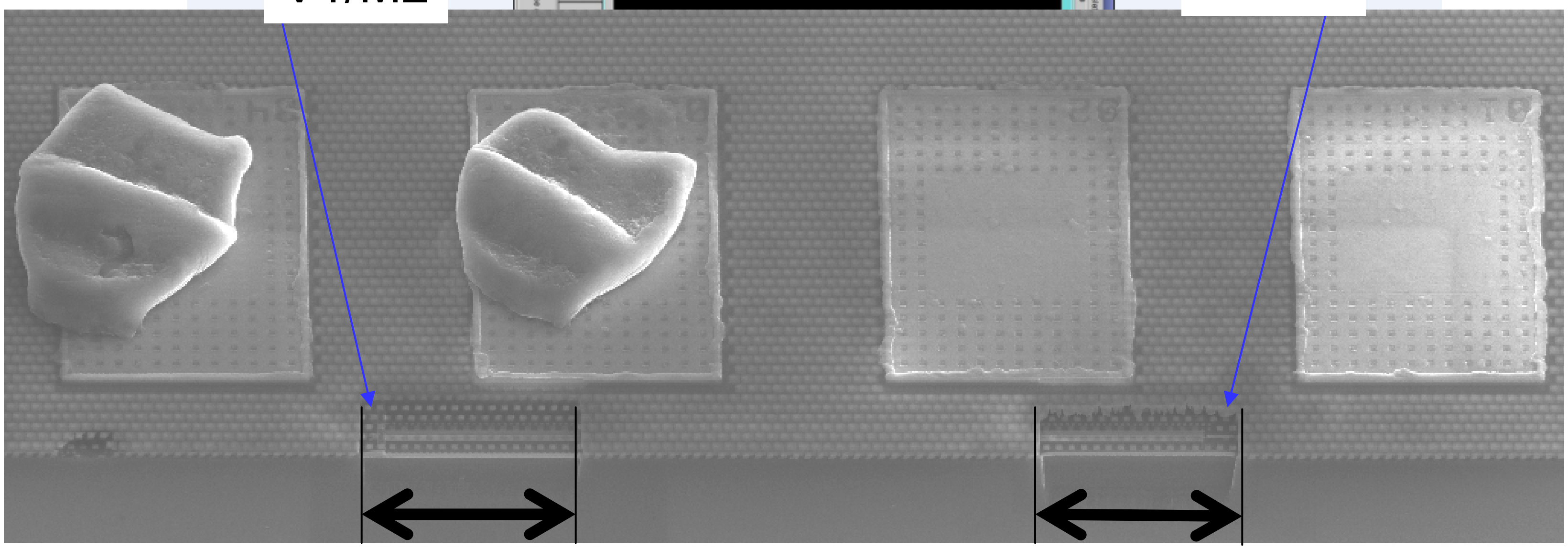


Test Structure (0.5 µm wide M2; 65 nm)

Acknowledgement:
Bryan Tracy
(Spansion)



SiN-based Capping
Carbon-based CVD oxide (low-*k*) Dielectric



50 µm segment
Cathode end

50 µm segment
Anode end

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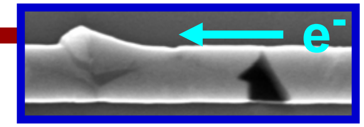
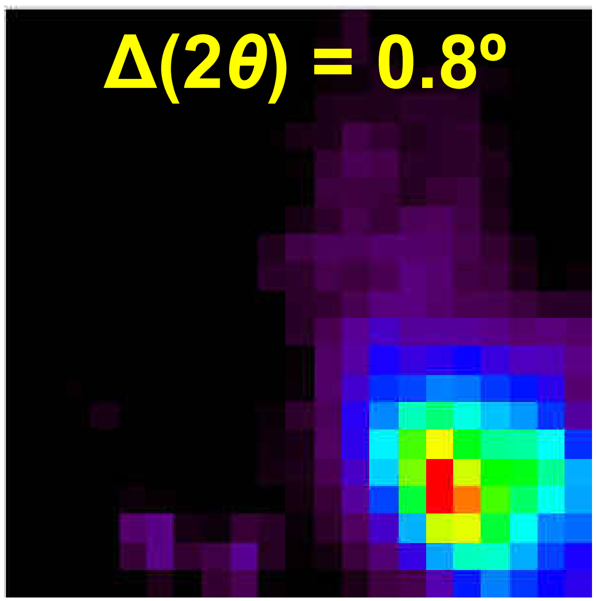


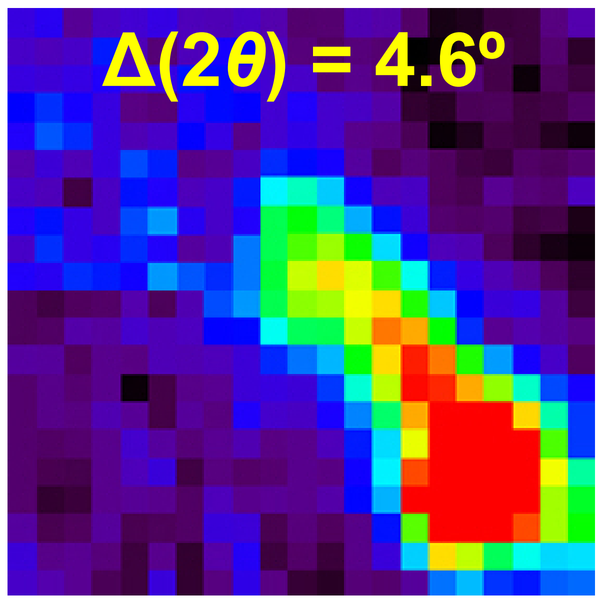
Experimental – EM-induced Plasticity (Laue Peak Streaking)

$\Delta(2\theta)$ vs time

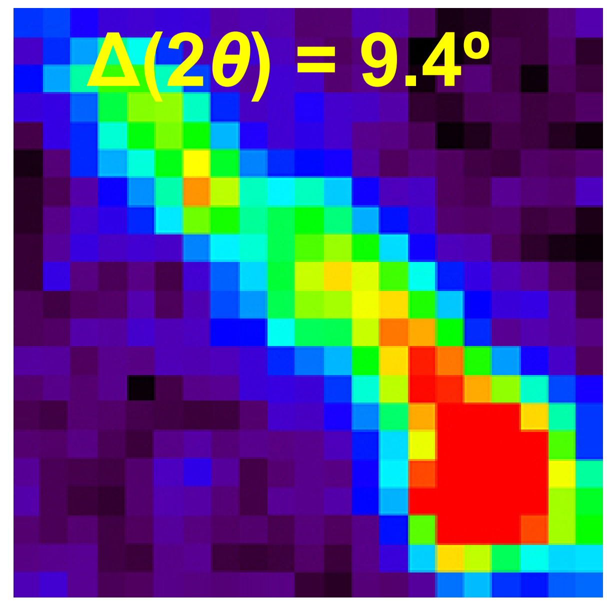
$(\bar{1}\bar{1}3)$ Peak



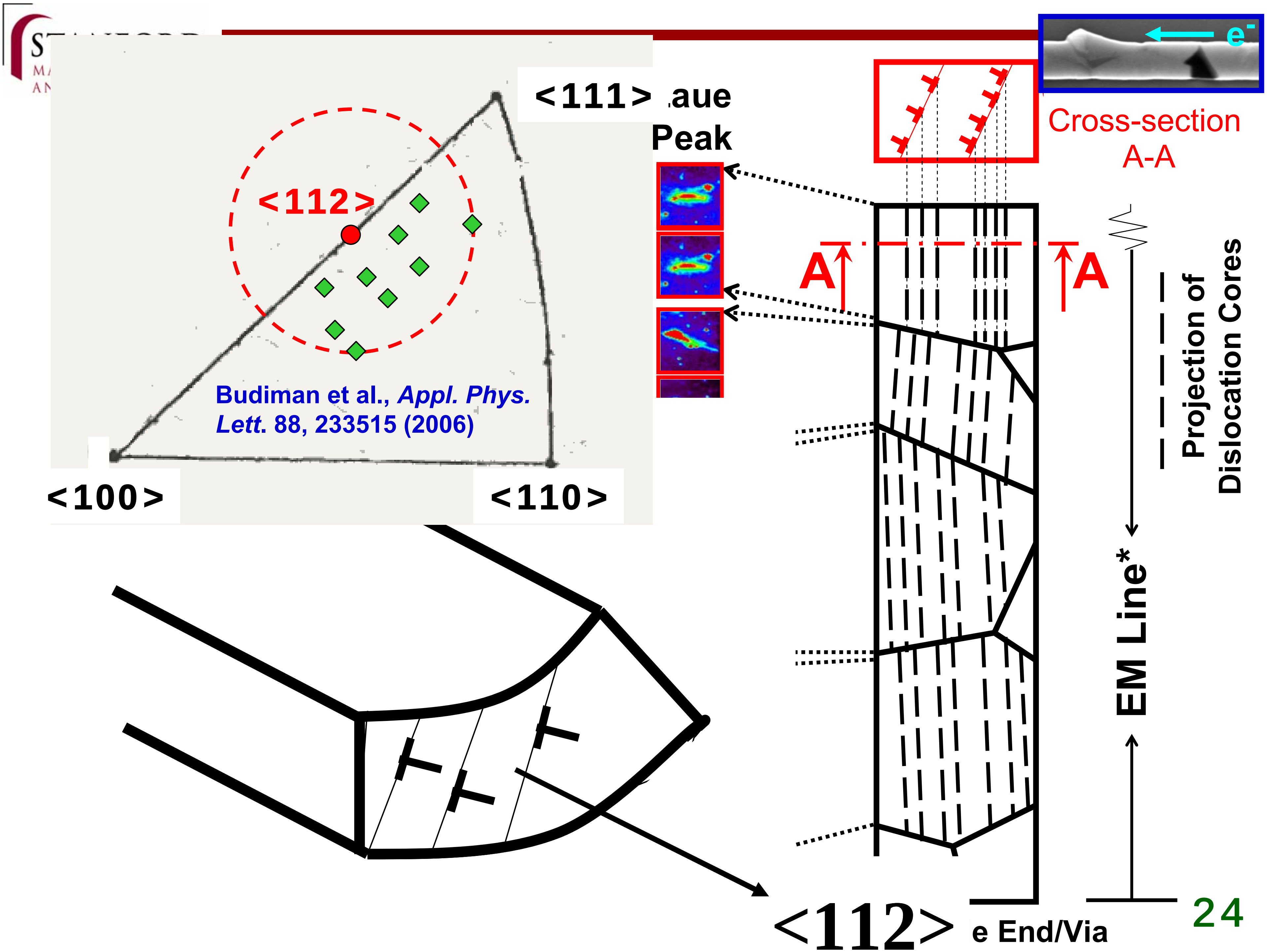
t = 0 hr
RT, j = 0
(Also T=300°C, j = 0)



t = 20 hrs
T = 300ºC, j = 2MA/cm^2



t = 36 hrs
T = 300ºC, j = 2MA/cm^2


<111>
aue
Peak
e-
Cross-section
A-A
<112>
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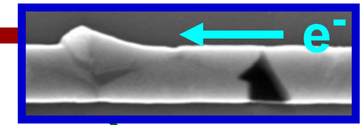
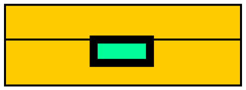
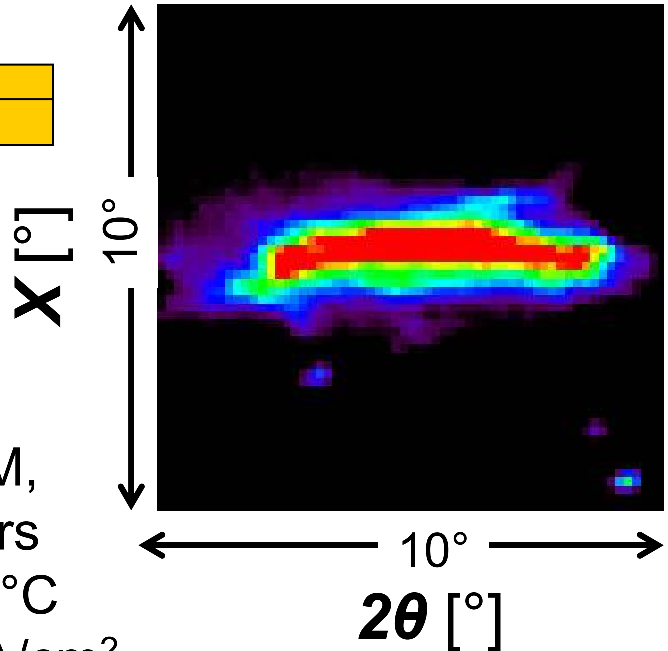
Budiman et al., *Appl. Phys. Lett.* 88, 233515 (2006)
<100>
<110>
Projection of Dislocation Cores
EM Line*
<112>
e End/Via

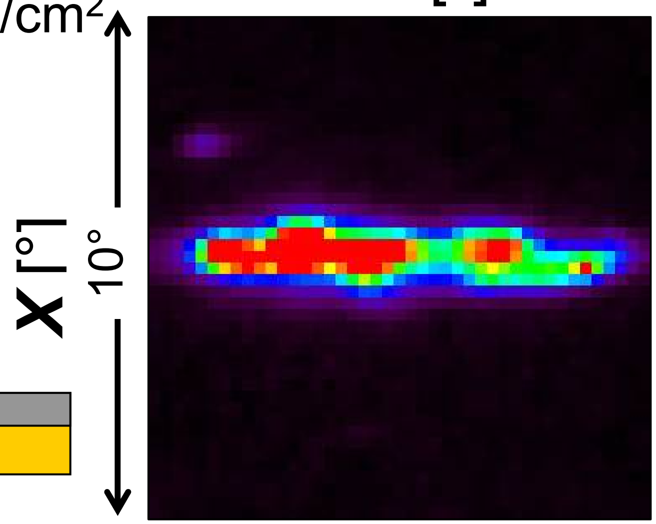


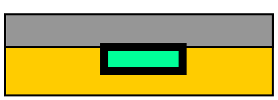
Experimental – Dislocation Density (ρ_{GND})





After EM,
t = 36 hrs
T = 300°C
j = 2 MA/cm²

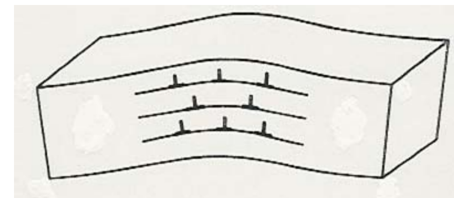




$$\boxed{\rho = \frac{1}{Rb}}$$

Cahn-Nye Relation

Pure bending

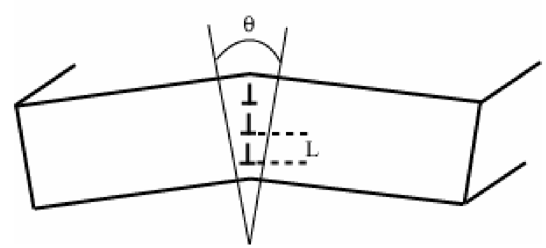


For Cu, Burgers Vector ***b*** = 2.546 Å

***R* = 2.31 μm**

Subgrain boundary

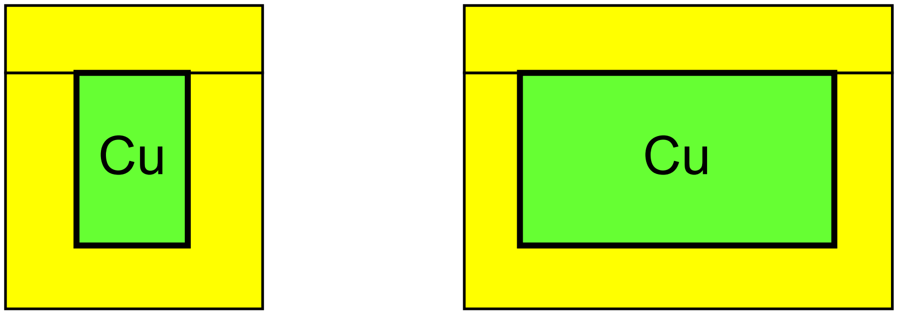
$$\boxed{\tan\theta = \frac{b}{L}}$$

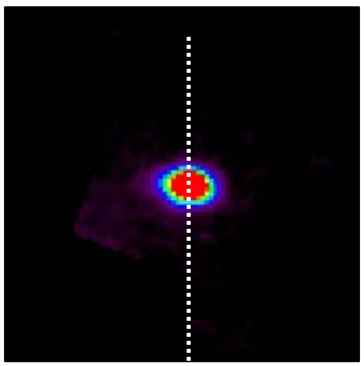


Density of GND's = 1.7x10^{15}/m^2

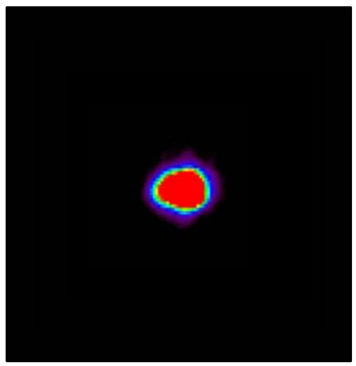
Samples A

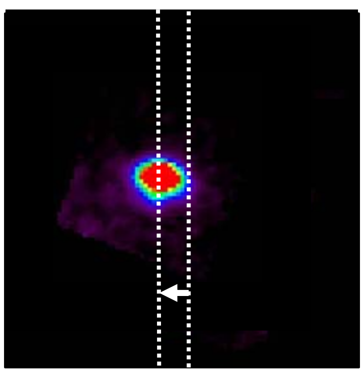
[Budiman *et al.*, APL 88, 233515 (2006)]



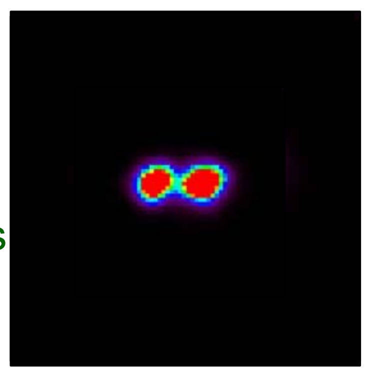


Initial
$t = 0$
$j = 0$





EM
t = 96 hrs
j = 3.1 MA/cm^2



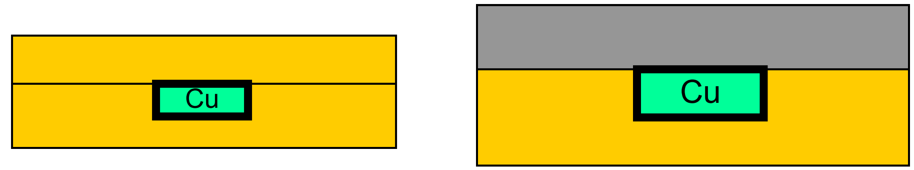
$\rho_{GND} \sim 10^{12}/\mathrm{m}^2$*

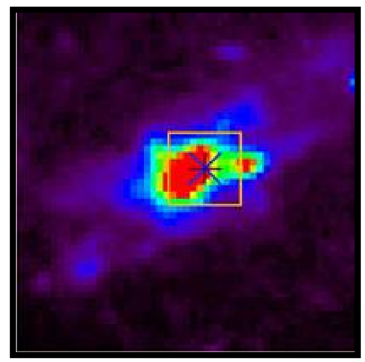
*typical annealed metals

$\rho_{GND} \sim 10^{13}/\mathrm{m}^2$

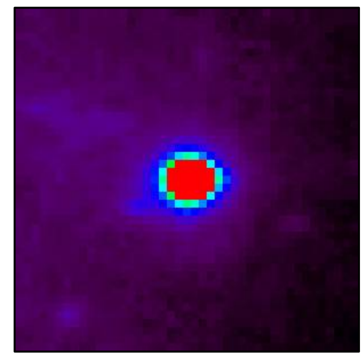
Samples B

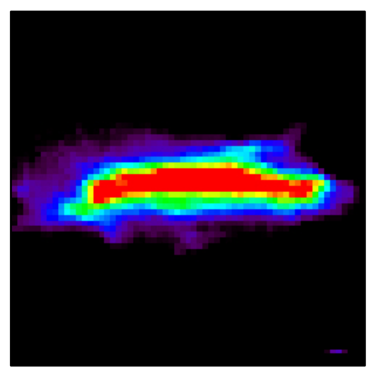
[Budiman *et al.*, IRPS 2007]



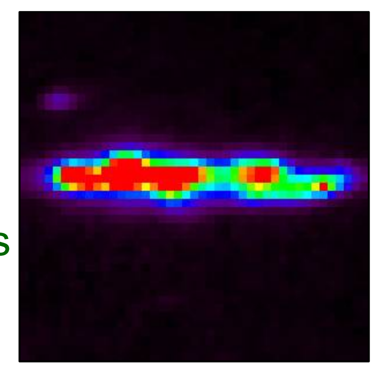


Initial
$t = 0$
$j = 0$





EM
t =36 hrs
j = 2.0 MA/cm^2

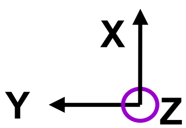


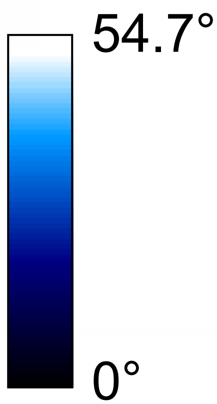
$\rho_{GND} \sim 10^{15}/\mathrm{m}^2$

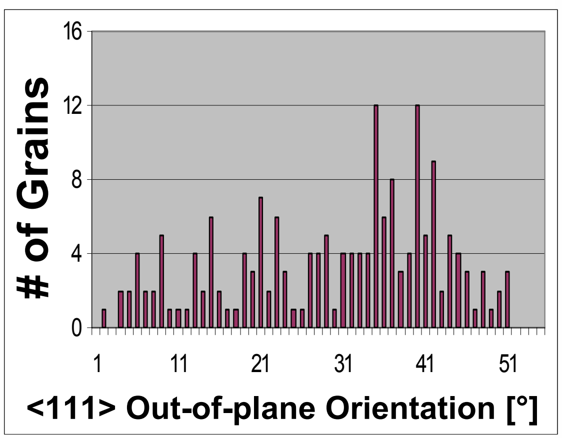
Samples A

[Budiman et al., APL 88, 233515 (2006)]

<111>
Out-of-plane
orientation

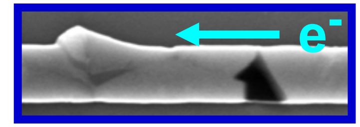




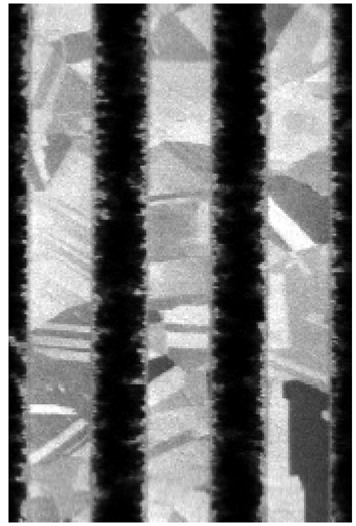


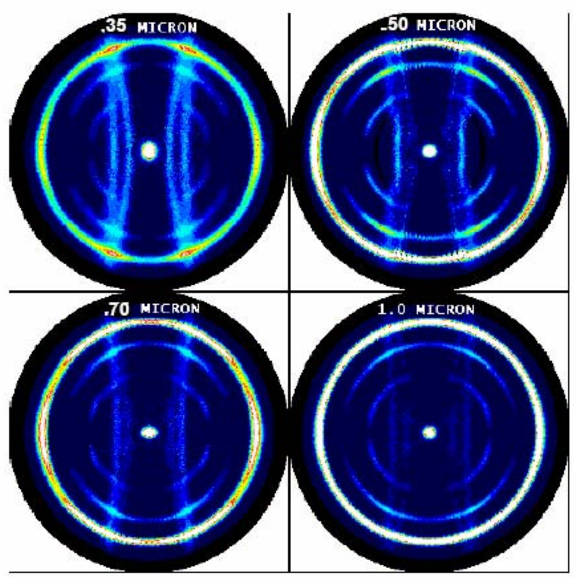
Weak (111) texture,
less plasticity

Samples B



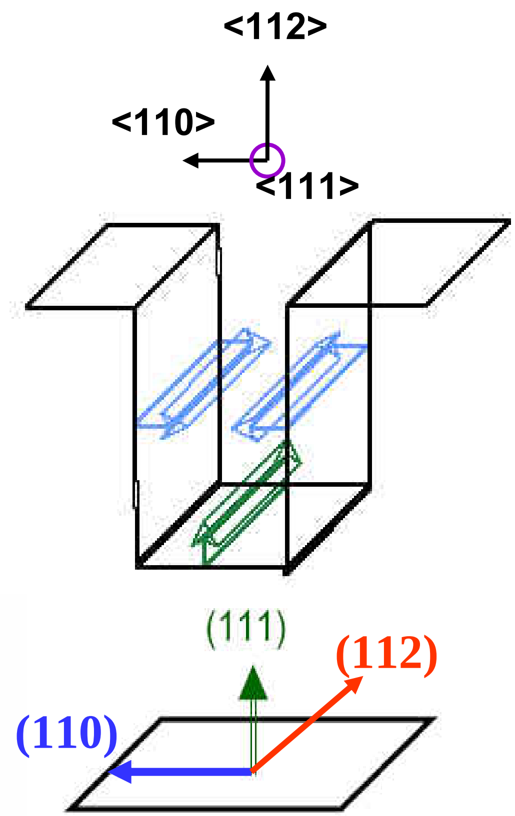
[Budiman et al., IRPS 2007, Besser *et al.*, Paik *et al.*]





Besser et al., *J. Elec. Matls.* **30**, No. 4, p. 320 (**2001**)

Strong (111) texture,
more plasticity



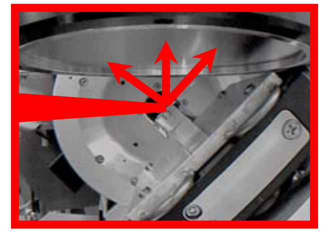
Besser et al., *J. Elec. Matls.* **30**, No. 4, p. 320 (**2001**)

Paik et al., *J. Elec. Matls.* **33**, No. 1, p. 48 (**2004**)

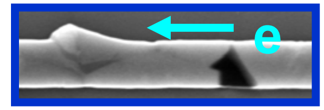
OUTLINE

THE TECHNIQUE:

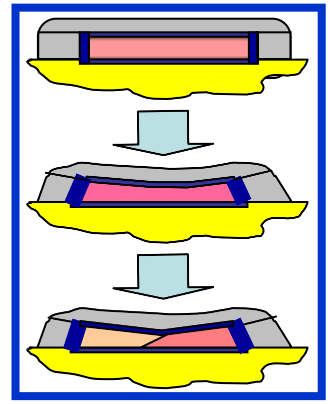
→ Synchrotron White Beam X-Ray Submicron Diffraction as Plasticity Probe for Study of Small Scale Mechanics



PLASTICITY IN ADVANCED INTERCONNECTS:

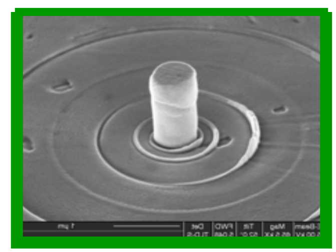


- ❑ The Basic Observation
  (Samples made by Intel Corp.)
- ❑ The Texture Observation
  (Samples made by AMD)
- ❑ The Practical Implications for EM Reliability Community in Industry

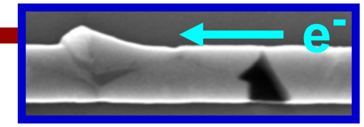


SMALL SCALE PLASTICITY IN CRYSTALS

- ❑ Size Effects in Au Nanopillars:
  → Smaller Pillar, Stronger Pillar!



CONCLUSIONS



BACKGROUND – EM & Plasticity

- EM Flux

$$J = C\frac{D}{kT}\left(Z^{*}e\rho j\right)$$

- Observed

$$J_{actual} = C\frac{D}{kT}\left(Z^{*}e\rho j^{\,n=1.5}\right)$$

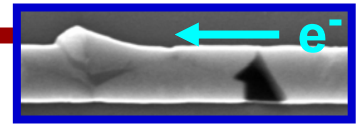
- Our hypothesis

$$J_{actual} = C\frac{D_{(j)}}{kT}\left(Z^{*}e\rho j^{\,n=1.0}\right)$$

Based on void growth-limited as demonstrated by Zschech et al., *Mat. Res. Soc. Proc*. **812**, F7.5.1 (2004)

$$D_{(j)} \rangle\rangle\rangle D$$

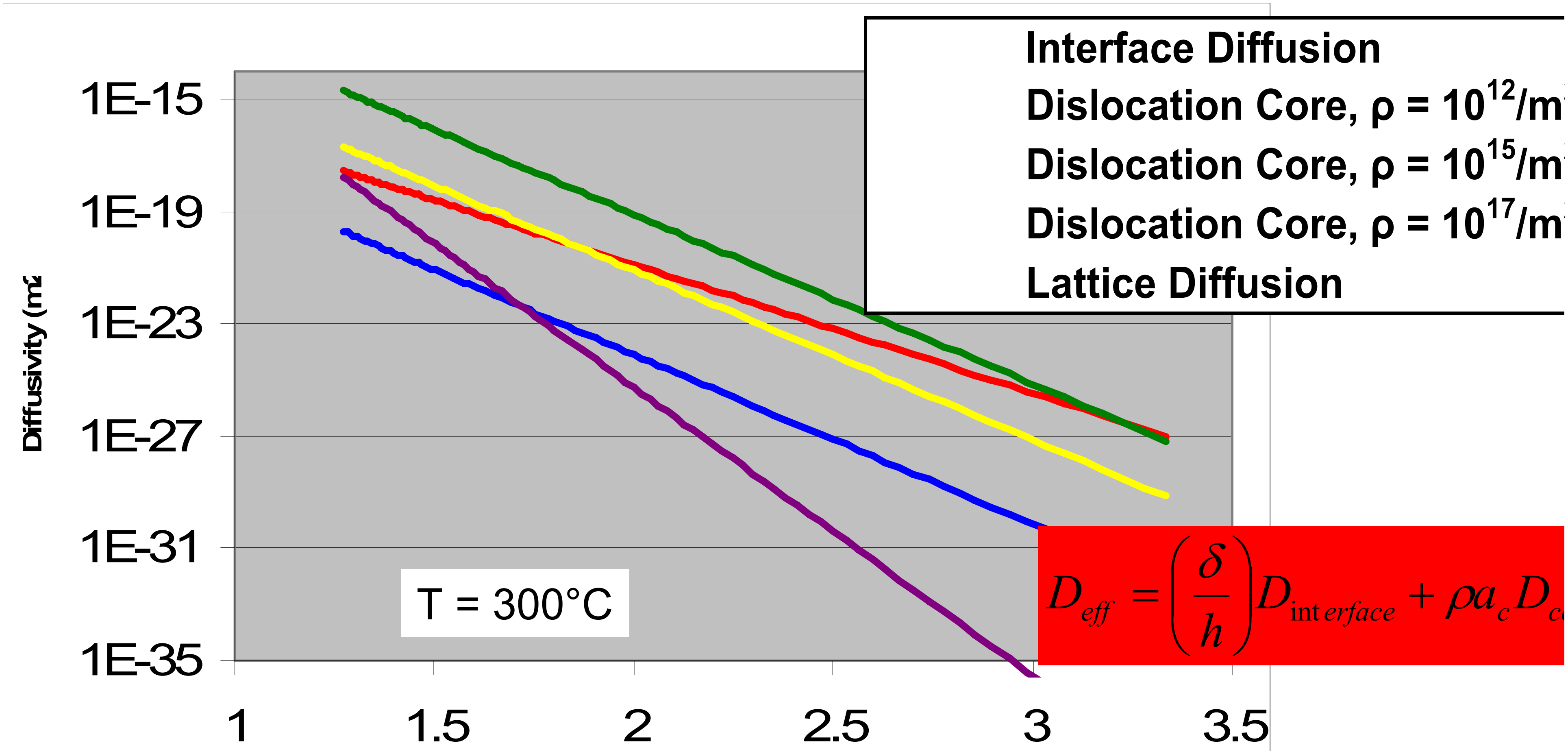
$$D_{eff} \rangle\rangle\rangle D_{\text{int}}$$



Dislocation Cores in EM – Lit. Review

- Frost, H.J., and Ashby, M.F., in *Deformation-Mechanism Maps: The Plasticity and Creep of Metals and Ceramics*. Pergamon Press, Oxford, 1982, p.21
  - Diffusion along dislocation cores is commonly included in model of diffusion-controlled deformation in bulk materials.
- Suo, Z. *Acta metall. mater*., 1994, **42**, 3581
  - EM-driven dislocation multiplication could lead to ρ high enough to affect EM damage processes (theoretical study).
- Oates, A.S., *J. Appl. Phys*., 1996, **79**, 163
  - Considered pipe vs lattice diffusion in Al at test conditions, but found no evidence of pipe diffusion; Suggested however that it may surpass grain boundary diffusion at use conditions.
- Baker, S.P., Joo, Y.-C., Knaub, M.P., Artz, E., *Acta mater*., 2000, **48**, 2199
  - In single crystal Al lines, the effect of $\rho = 10^{16}/m^2$ is comparable to grain boundary diffusion (experimental)

Interface vs Dislocation Core Diffusion



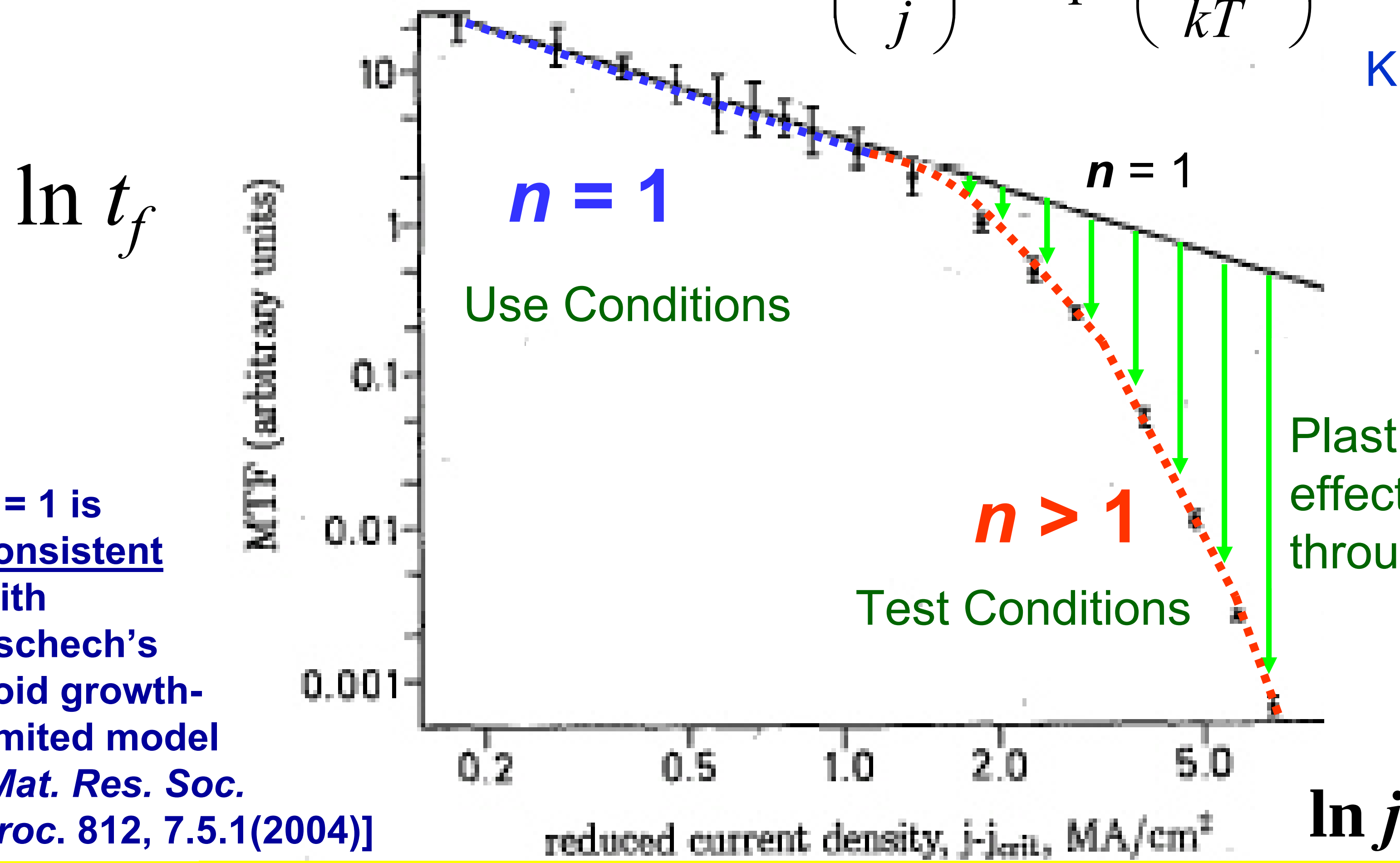
Diffusivities of Cu were calculated using values from:

1. Frost, H.J., and Ashby, M.F., in *Deformation-Mechanism Maps: The Plasticity and Creep of Metals and Ceramics*. Pergamon Press, Oxford, **1982**, p.21

2. Gan, D., Ho, Paul S., Pang, Y., Huang, Rui, Leu, J, Maiz, J., Scherban, T., *J. Mater. Res*., **2006**, **21**, No. 6, p.1512

Implications to EM Lifetime Prediction

Black's Law $t_f = A\left(\frac{1}{j}\right)^n \exp\left(\frac{E_A}{kT}\right)$



Kirchheim & Kaeber., *J. Appl. Phys*. **70**, p.172 (1991)

***n* = 1 is** **consistent** **with Zschech's void growth-limited model [*Mat. Res. Soc. Proc*. 812, 7.5.1(2004)]**

Use of n > 1 in extrapolation to use conditions will lead to an overestimation of device lifetime!!!

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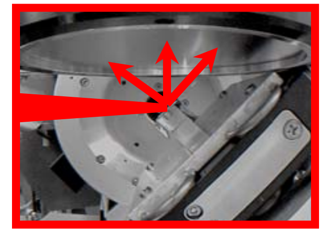

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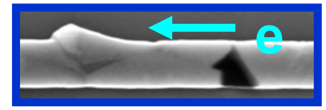

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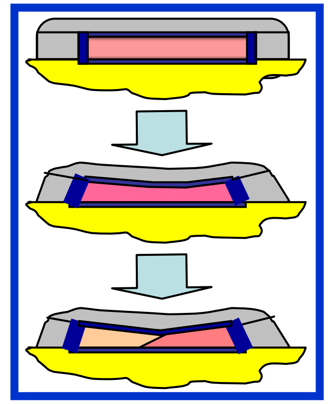

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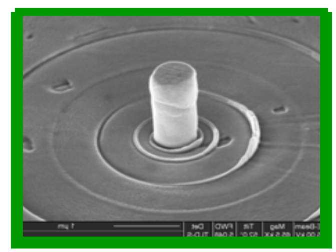
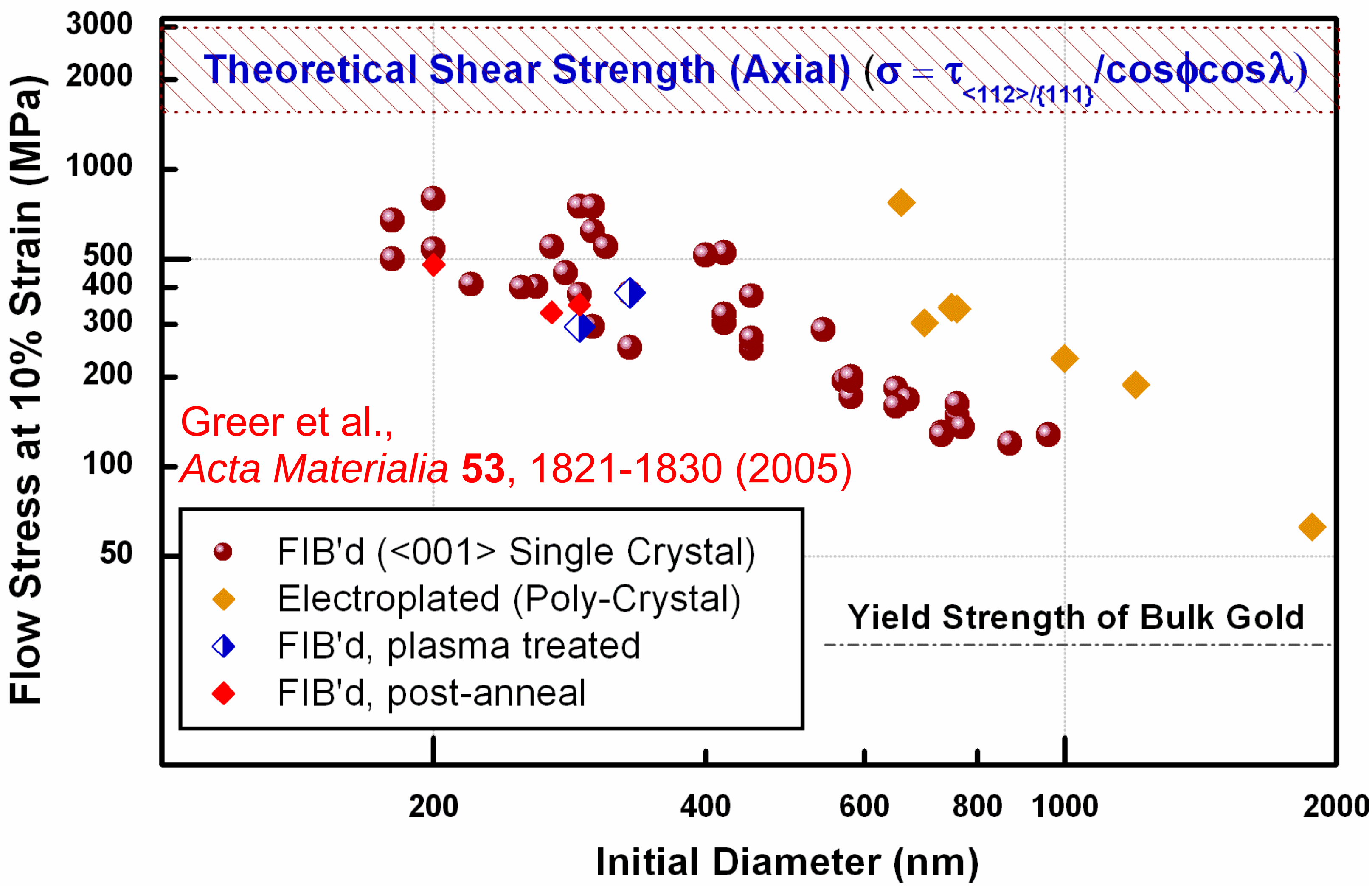
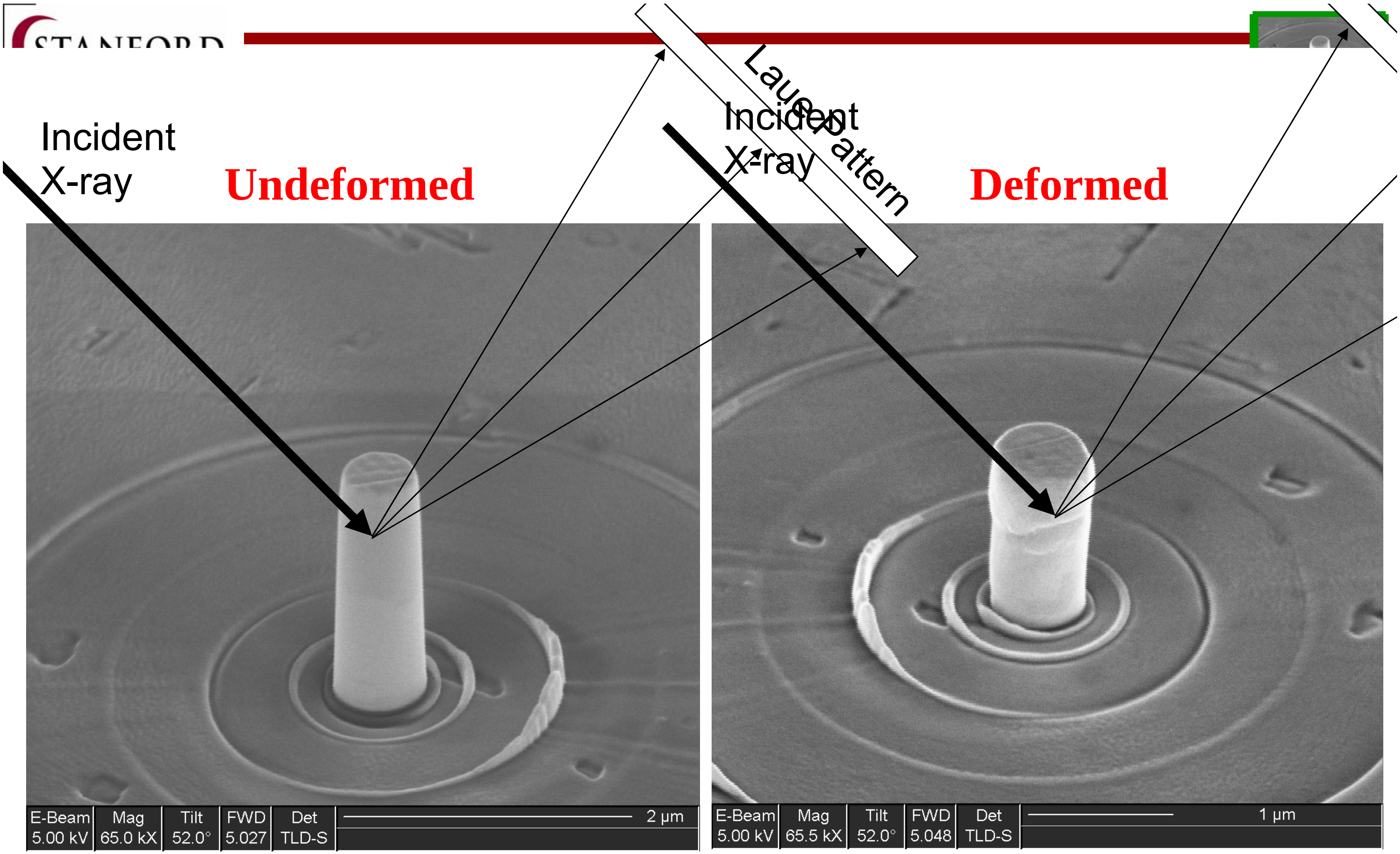


CONCLUSIONS

Size Effects in Compression of Small Single Crystals





Pillar 4 (undeformed)
Diam.: 0.58 μm
Length: 1.9 μm

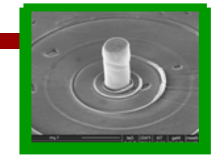
Total Strain ~35%

Pillar 4 (deformed)
Diam.: 0.67 μm

(111)-oriented Au Pillar

STANFORD
MATERIALS SCIENCE
AND ENGINEERING

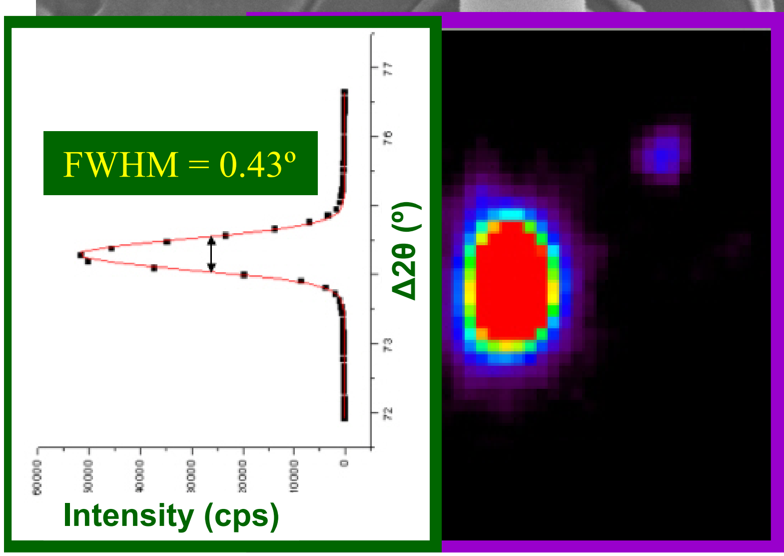
Absence of Strain Gradients



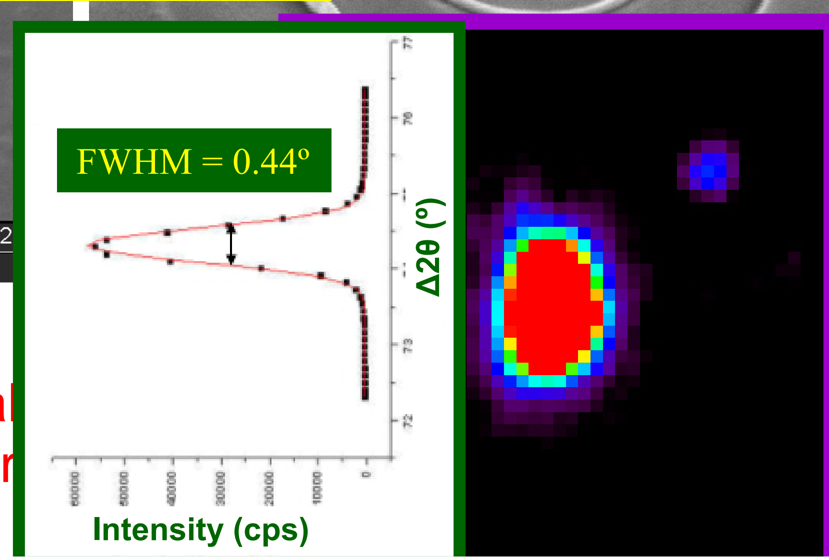
Undeformed | **Deformed**

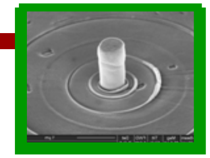
Not more than 2 GND's in the pillar after deformation!!

Consistent with earlier TEM Observation [Greer and Nix, Phys. Rev. B 73, 245410 (2006)]



Peal
Pillar

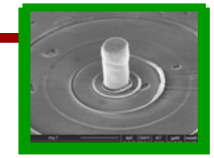




Possible Causes of Size Dependent Strength in Single Crystals?

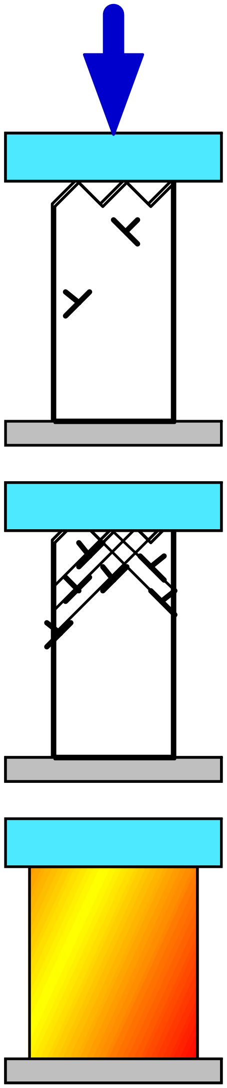
- ~~**Dislocation or subgrain hardening?**~~
  - <u>Not more than 2 GND's</u> in the pillar after deformation (X-Ray Submicron Diffraction)
  - <u>2 dislocations</u> not caused by the applied stress left in the pillar after deformation [TEM Observation, Greer and Nix, Phys. Rev. B **73**, 245410 (2006)]
  - Defect-free crystal from *in situ* TEM Observation [Minor *et al*., Nature Materials 5, 697 (2006)]

- Hardening of crystals by dislocation starvation and dislocation nucleation or source controlled?



Dislocation Starvation and Dislocation Nucleation or Source-Controlled Plasticity

[Greer & Nix, Phys. Rev. B 73, 245410 (2006)]



- Dislocations leave the crystal faster than they multiply.
- **New** dislocations have to be nucleated.
- Called **hardening by dislocation starvation**, occurs only in small volumes and not in bulk crystals.

CONCLUSIONS

1. White-beam x-ray submicron diffraction has proved to be a powerful **plasticity probe** for crystalline materials for the study of mechanics at small scales.

2. Plasticity in metal lines undergoing EM → **Important implications for reliability** community in industry.

3. Understanding the mechanics, and more specifically, the evolution of dislocations structures in nanodevices is the key before we can control and benefit from them – **nanomechanics**!

Acknowledgments

MECHANICAL PROPERTIES OF MATERIALS WITH NANOMETER SCALE MICROSTRUCTURES
U.S DOE, OFFICE OF BASIC ENERGY SCIENCES
GRANT NO (DE-FG02-04ER46163)

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ERNEST ORLANDO LAWRENCE BERKELEY NATIONAL LABORATORY
U.S DOE, OFFICE OF BASIC ENERGY SCIENCES
CONTRACT NO (DE-AC02-05CH11231)

SRC/INTEL/TASK ID: 945.001
JUN HE FOR VALUABLE DISCUSSIONS DURING 2006 GORDON RESEARCH CONFERENCE ON THIN FILMS & SMALL SCALE MECHANICAL BEHAVIOR

ADVANCED MICRO DEVICES, INC.
CO-OP/SUMMER 2006

THANK YOU