Microstructure Evolution During Alternating-Current Induced Fatigue

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Cyclic Thermomechanical Stresses in Thin Films

Experimental

SEM and *Quasi in-situ* EBSD Results

Analysis of Thin Film Deformation

Implications on Reliability

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National Semiconductor Metrology Program, NIST Office of Microelectronics Programs
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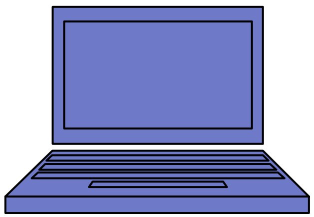
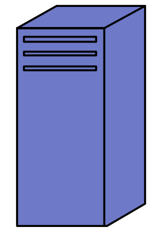
Cyclic Thermomechanical Stresses – Need for Research

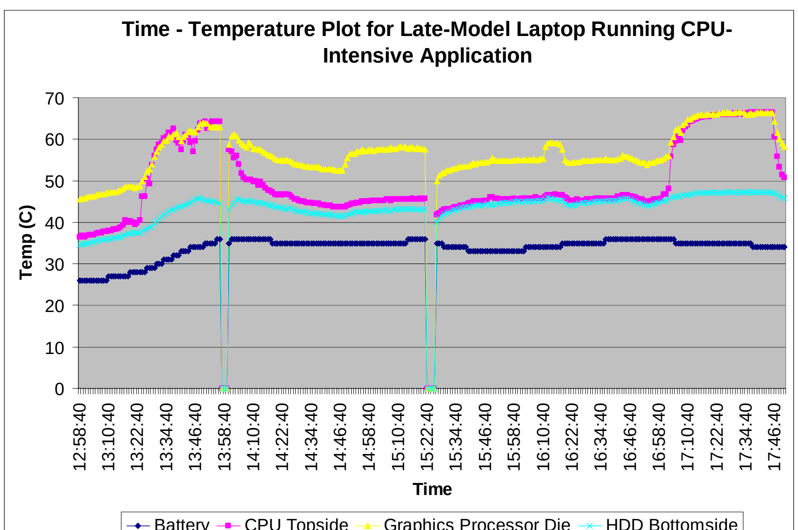
- *As identified by 2003 ITRS, 2004 NIST Workshop on Reliability Issues in Nanomaterials:*
  - Thermomechanical fatigue in chip- and package-level interconnect systems is a genuine concern for future generations
  - Detecting, testing, modeling, and control of failure mechanisms is necessary
    - We address these concerns.

Cyclic Thermomechanical Stresses – Real-world Examples

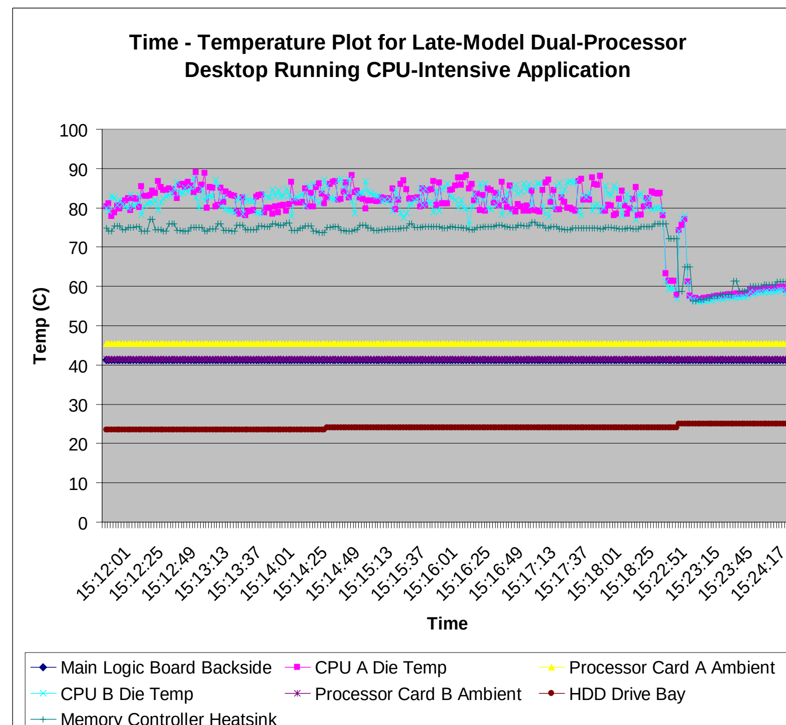
- *Big temperature excursions!*







$\Delta T \sim 50°C$



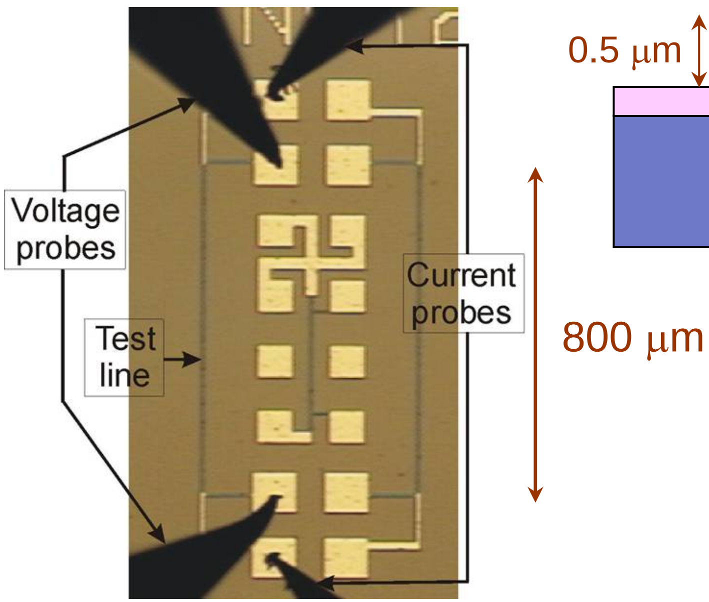
ASME IMECE 2004, Anaheim, CA

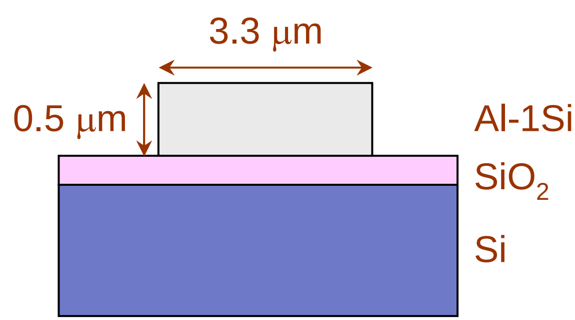
Experimental
– Time-varying Electrical Stressing

- Thermomechanical fatigue testing
- 4-point probe method
- Low frequency, high current density, *j*
- Controlled Joule heating

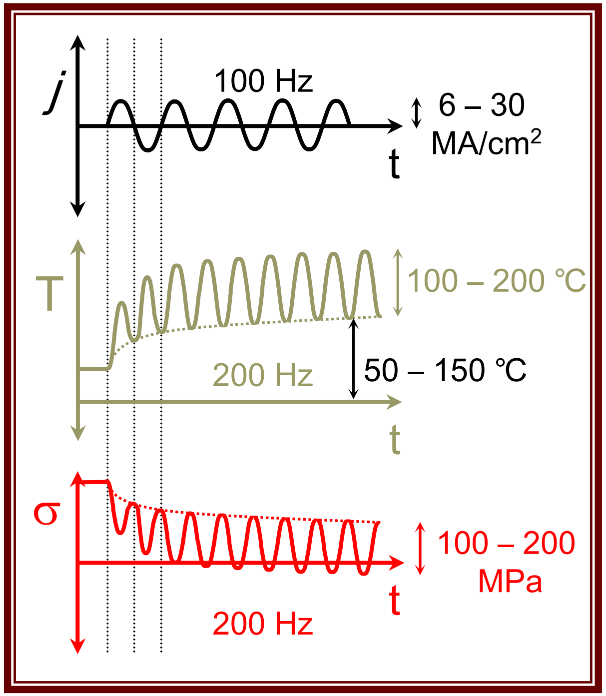
R. Mönig, R. R. Keller, C. A. Volkert, *Rev. Sci. Instrum.* 75, 4997, (2004).

$\varepsilon_{thermal} = \Delta\alpha\ \Delta T$ (= 0.002 for Al)
(between metal and substrate)



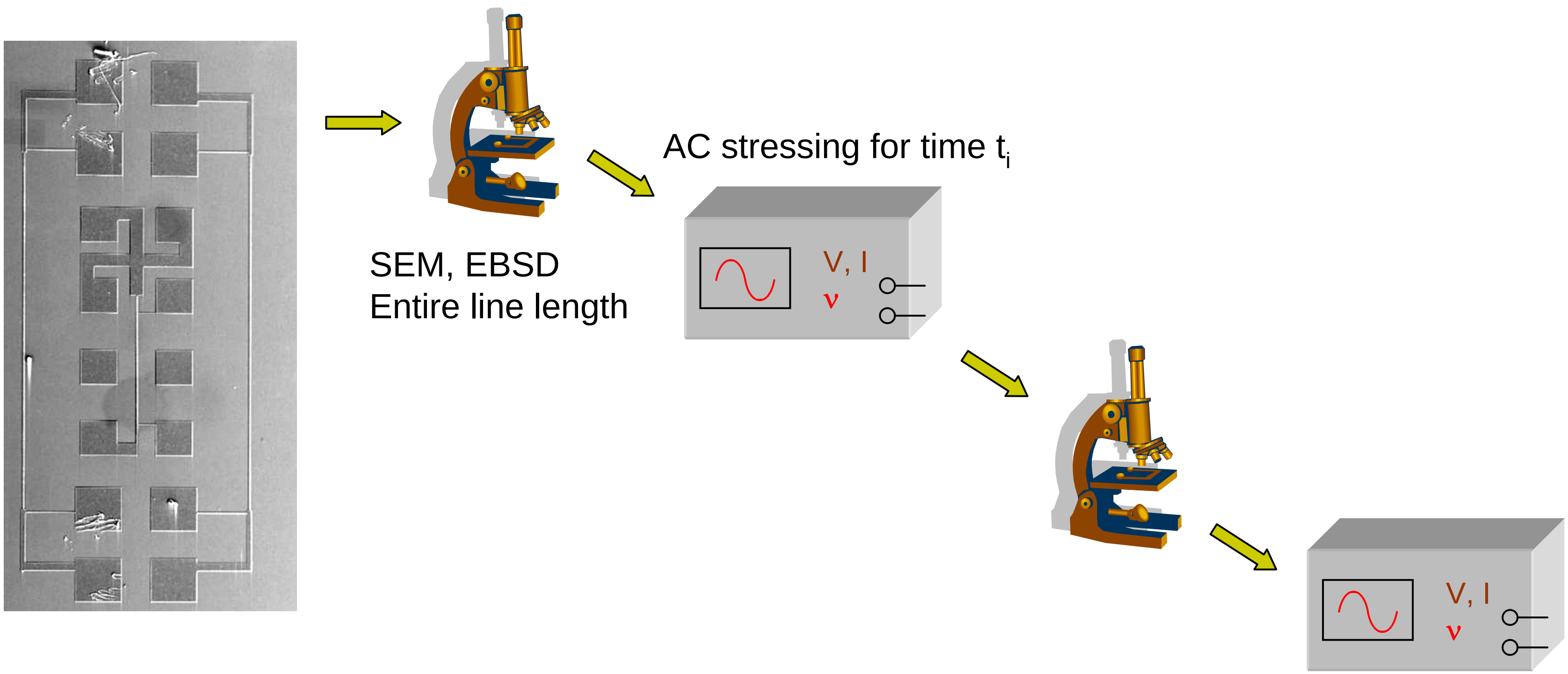


$\Delta\sigma$ = 100 to 200 MPa
~ σ_{ys} for Al and Cu



Experimental
– *Quasi in-situ* Electron Backscatter Diffraction

- *Observe, test, observe, test, … , monitoring of one specimen:*
- *Observed after t = 0, 10, 20, 40, 80, 160, 320, failure (697) s of accumulated stressing time.*

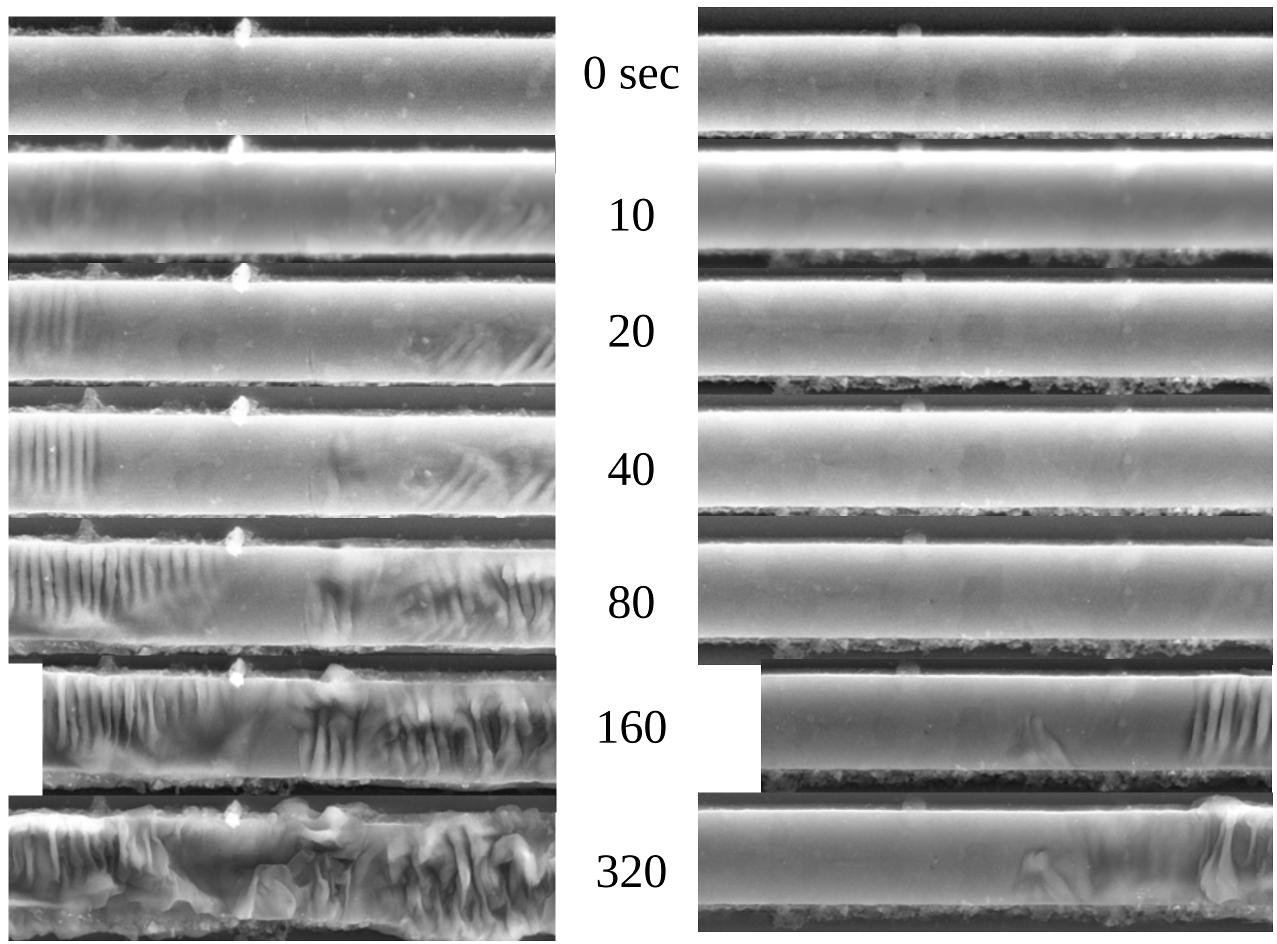


Results – Damage Evolution (SEM)

- *Surface damage highly localized:*

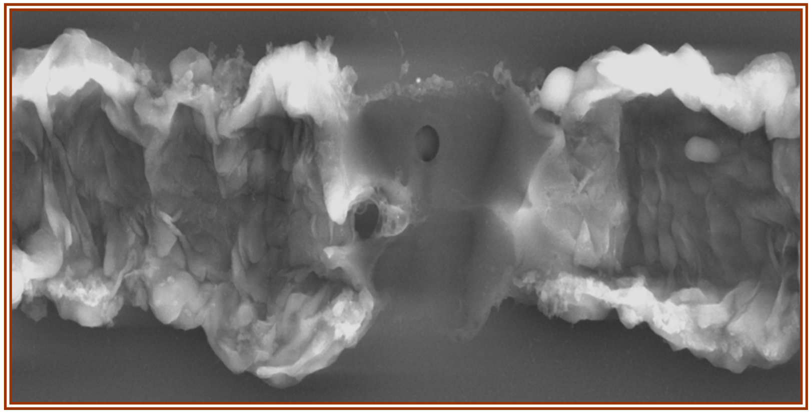
Plan-view SE images
Linewidth = 3.3 μm

Progressive damage, typical of fatigue.

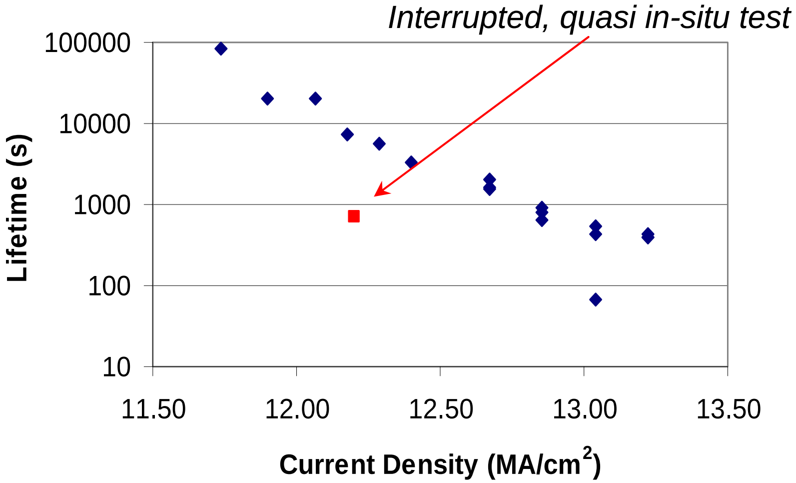


Results – Final Failure

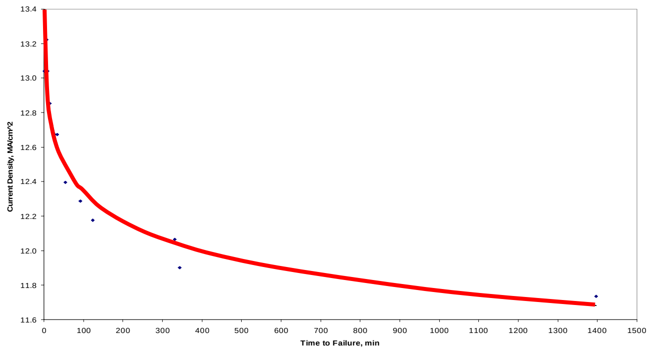
Open circuit at 697 s:



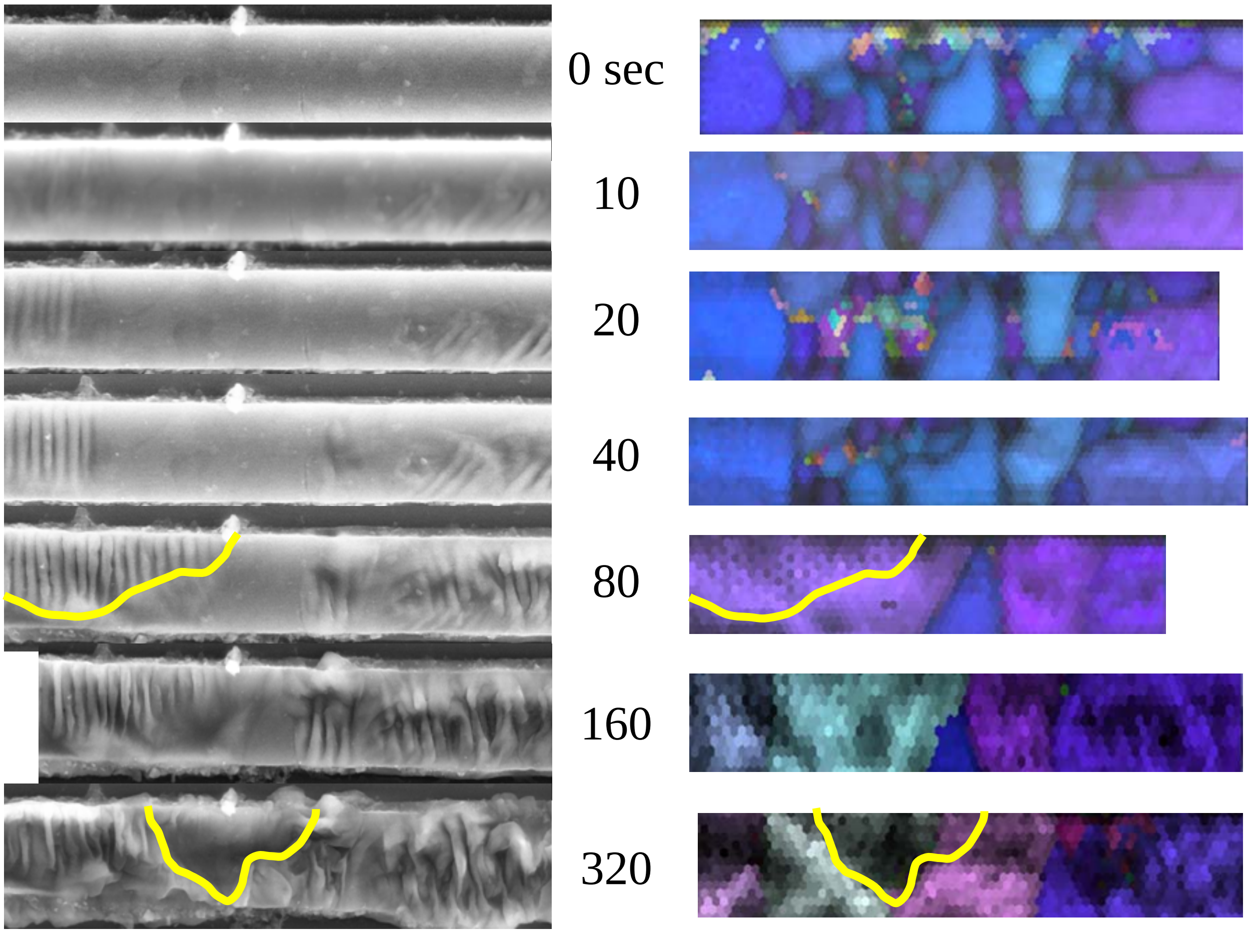
Lifetime data:



Similar to fatigue S-N curve:

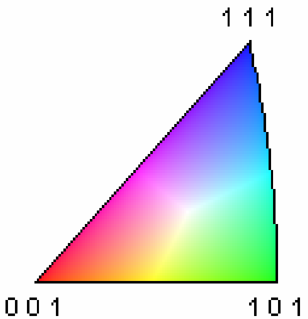


Results – Damage Evolution (SEM + EBSD)



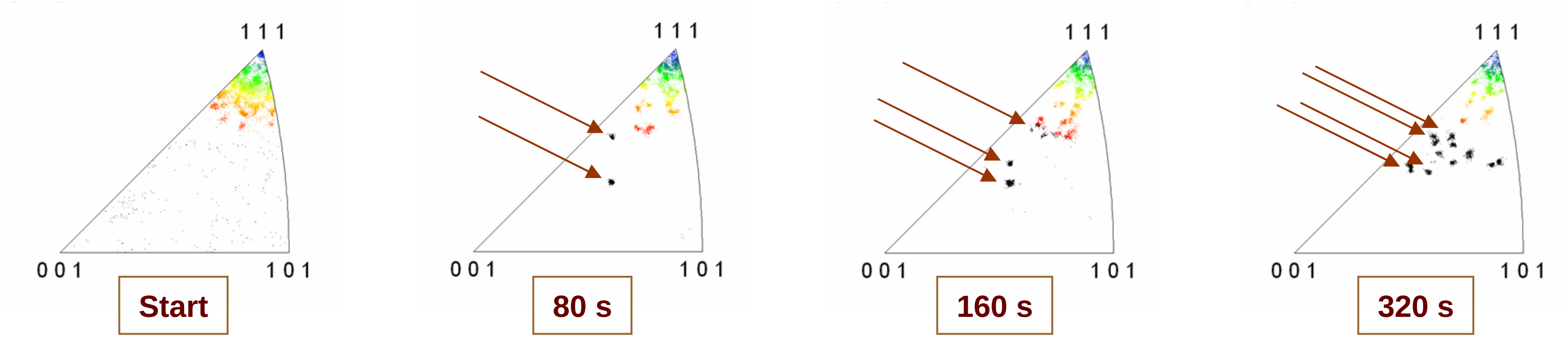
Damage localization corresponds to grain structure.

Growth of damage corresponds to growth and re-orientation of grains!

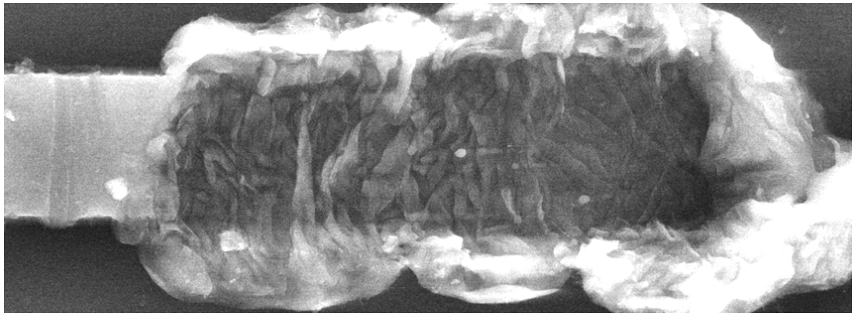


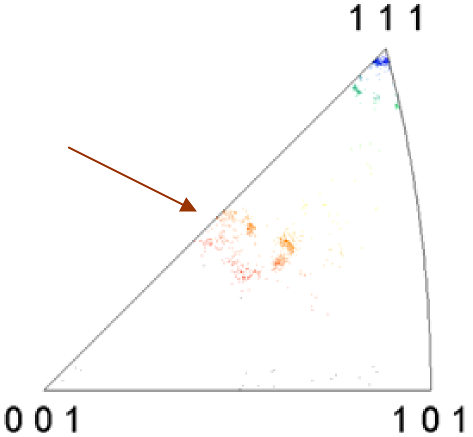
Results – Grain Re-orientation

- *Surface normals move away from <111> with stressing:*



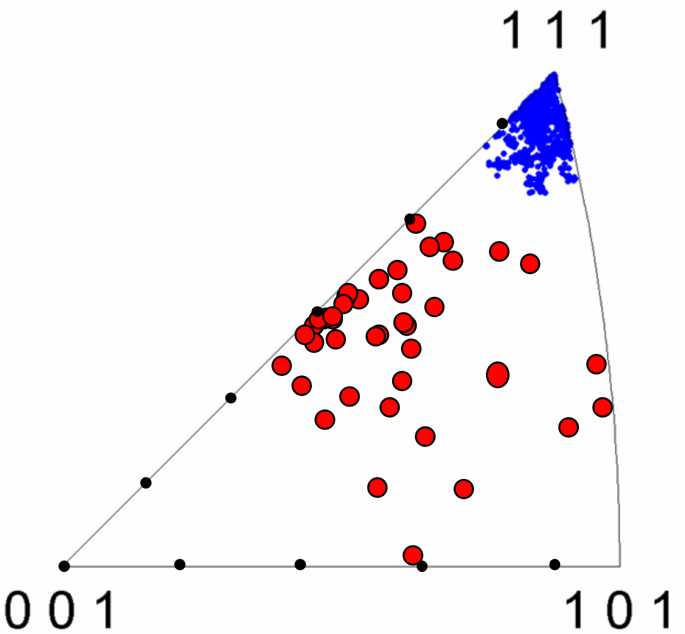
Severely deformed area:

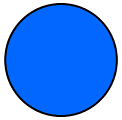




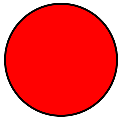
Re-orientation Summary for Entire Line

- *All severely deformed areas show drastic re-orientation*
- *Sometimes in excess of 35°!*





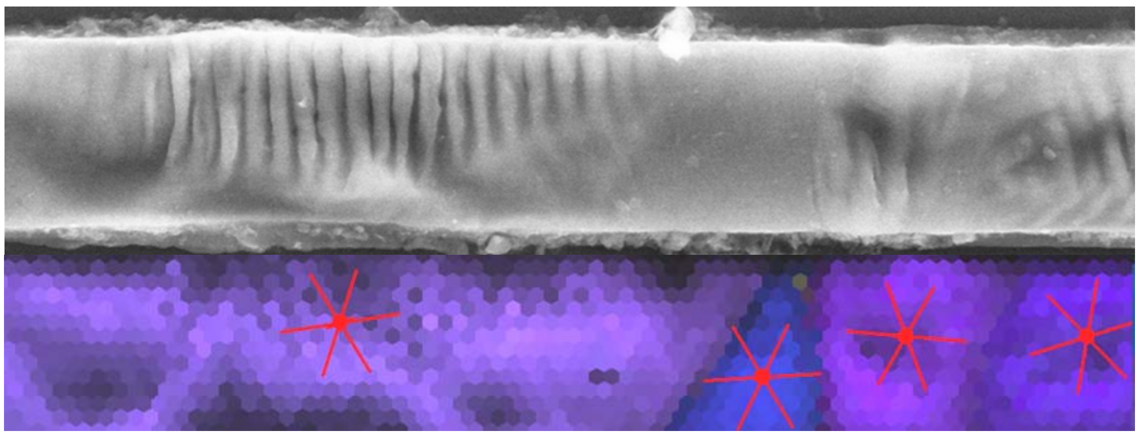
As-deposited starting normal orientations. Within 10 degrees of (111).

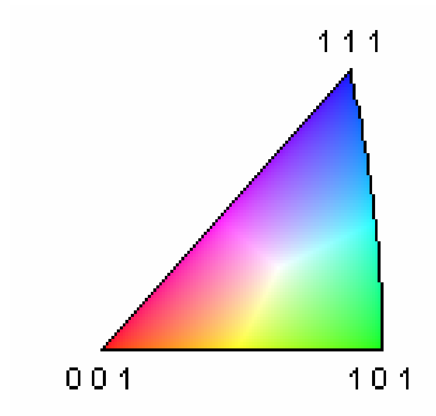


New normal orientation of severely deformed structures after failure.

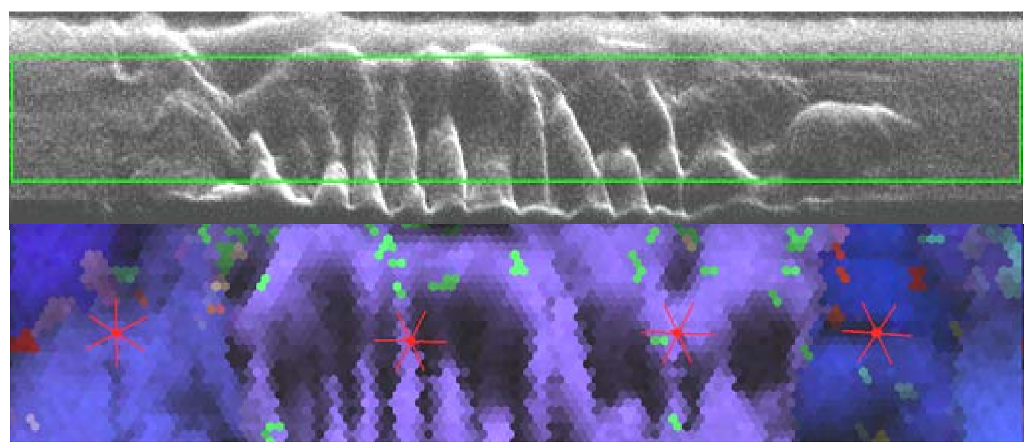
Analysis
– Damage by Dislocation Processes

- *Topography consistent with multiple slip:*



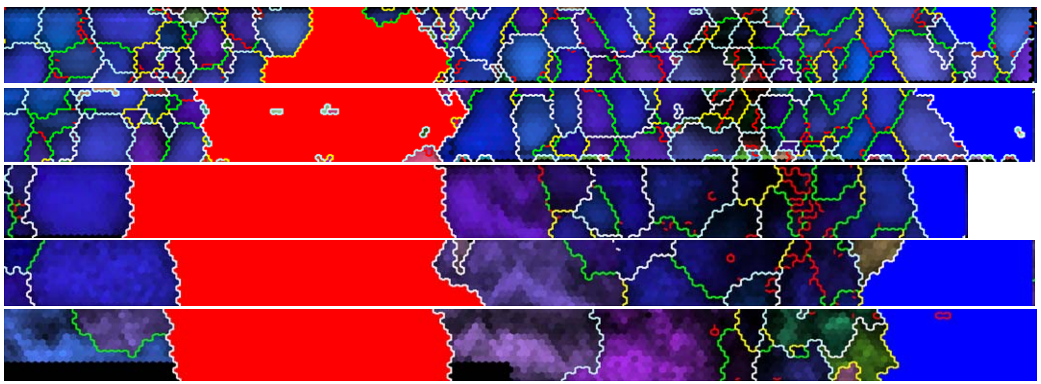


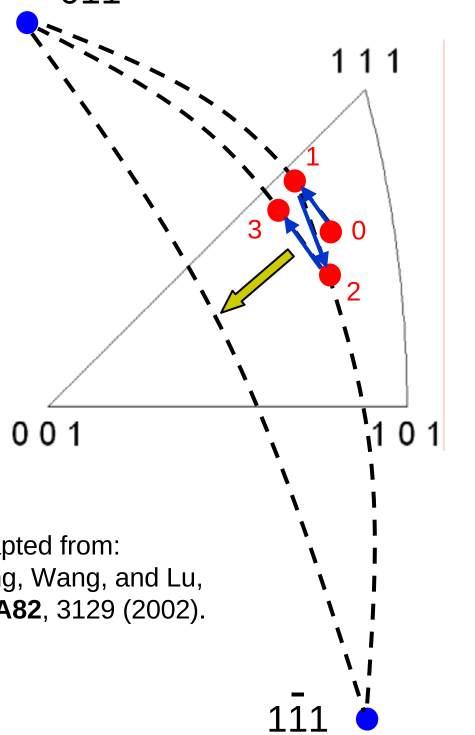
denotes (111) slip traces

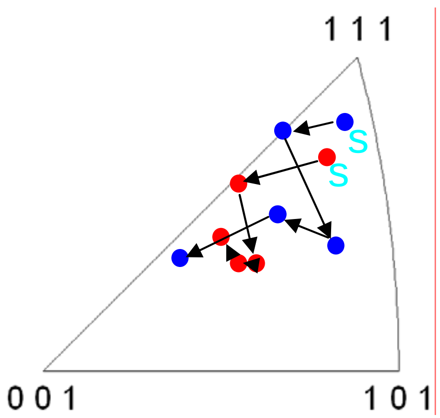


Analysis –
Progression of Re-orientation with Cycling

- *Surface normals move away from (111)*







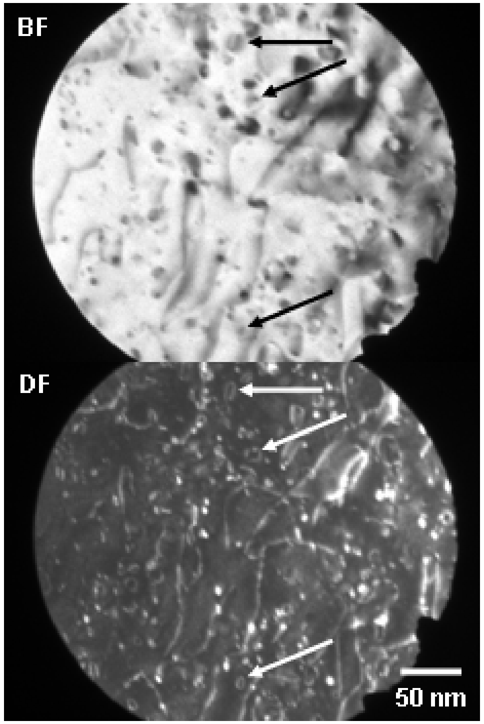
- Irreversible rotation accumulated during cycling.
- Extent depends upon magnitude of τ_{CRSS} and number of cycles.
- Net rotation can amount to tens of degrees.

Adapted from:
Li, Li, Zhang, Wang, and Lu,
Phil. Mag. **A82**, 3129 (2002).

Temperature

- *Recrystallization?*
  - No!
  - 50% $T_{recrystallization}$ (1 h) ~ 240 to 320 °C
  - Prismatic loops ⇒ sustained T_{max} < ~150 °C
  - Consistent with time-resolved R
  - More deformation with increased cycling: inconsistent with new grains.
- *<u>Higher average temperature:</u> may be safer from thermomechanical fatigue point of view*
  - Lower R ratio, lower stress
- *However! Can form whiskers…*

TEM: loops



Characteristic Diffusion Distances

- *Distance estimate:*

$$x = \sqrt{Dt}$$

t = 0.005 s in one temperature cycle

	D (m^2/s)	*x*
Grain Boundary	10^{-15}	*1.5 nm*
Lattice	10^{-18}	*0.05 nm*
Thermal	10^{-4}	*500 μm*

Reliability

- *Electromigration: Negligible!*
  - *t* (1/2 current cycle) = 0.005 s:
    - total diffusion distance ~1 nm or less

- *Passivation integrity: Depends…*
  - Compliant dielectric (hard-baked photoresist) does *nothing* to suppress damage;
  - Rigid, poorly adhering dielectric (nitride) bowed and delaminated;
  - Rigid, well adhering dielectric (oxide): in progress.
    - Expect damage to be suppressed.

Summary

- *Developing electrical-based test method for thermomechanical fatigue of patterned structures;*
  - Based on controlled Joule heating;
- *Observed highly selective damage formation;*
  - Dependent on grain structure;
- *Damage:*
  - Severe surface topography;
  - Grain growth;
  - Grain re-orientation;
- *Reliability issues?*

Thank you so much!