Current-Induced Fatigue in Chip Level Interconnects

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- Thermal Cycling due to Alternating Currents
- Damage Morphology
- Lifetime Behavior
- Crystallographic Orientation Effects
- Implications on Reliability
- Summary

Thermal Cycling

Energy transfer to a resistor:

$$P = i^2 R$$

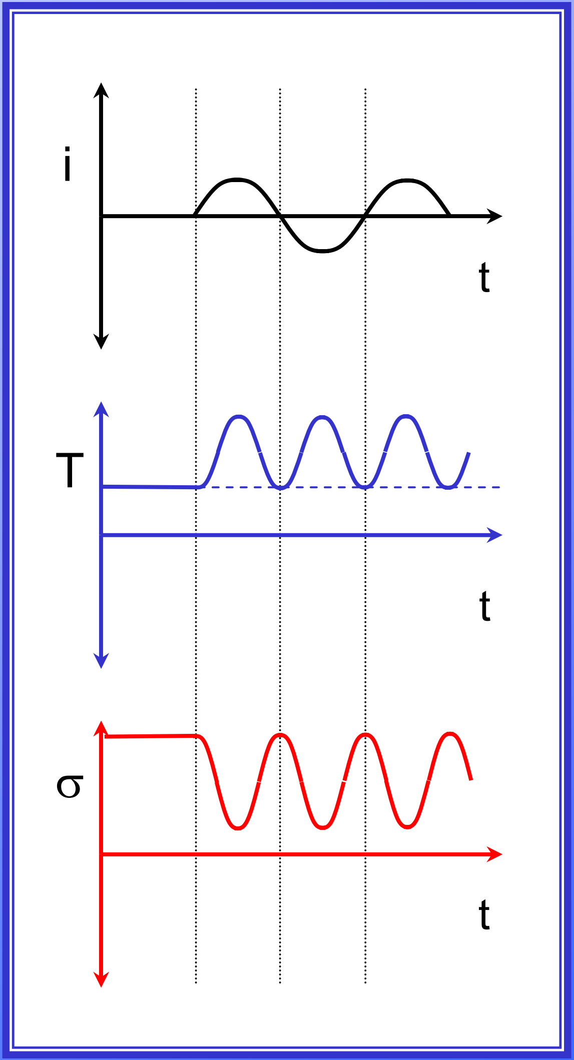
Electrical energy becomes heat:

$$\Delta T = \Delta Q / C$$

If heat conduction to substrate is good, then get thermal strain:

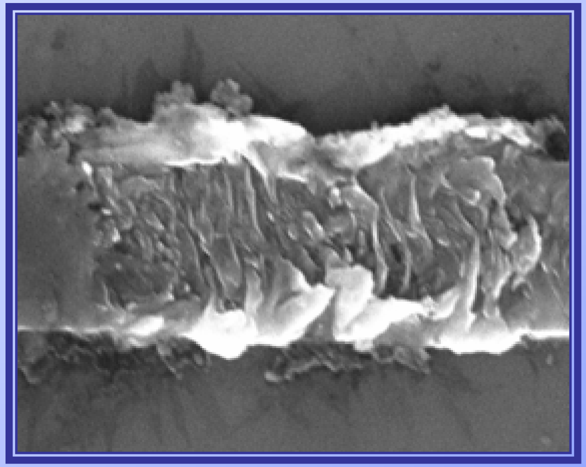
$$\varepsilon = \Delta\alpha \, \Delta T$$

$$\rightarrow \quad \Delta\sigma$$

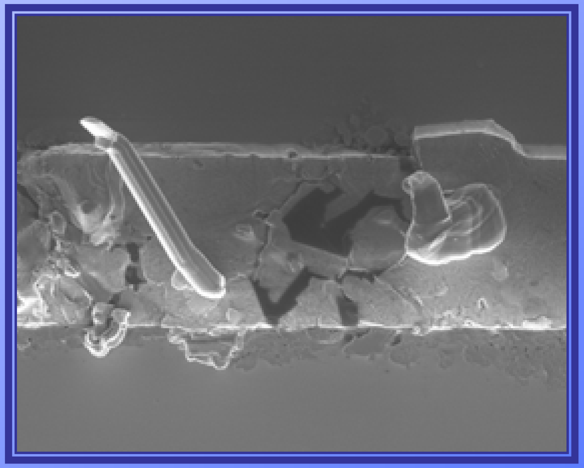


Interconnect Damage

A.C. versus D.C.



3 μm



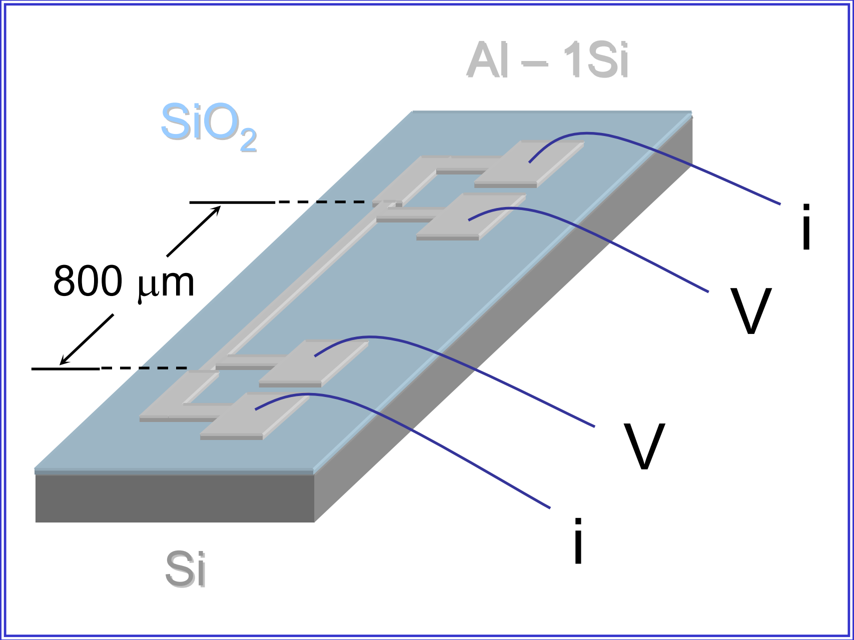
Severe topographic changes
Damage distributed over entire line length
Periodic surface "wrinkling"

More modest topographic changes
Damage confined to fewer sites
Void and hillock formation

Both tests:
Al-1Si/SiO_2/Si, unpassivated
j ~ 10 MA/cm^2
Sample nominally at room temperature

Experimental

Work done on both Cu and Al lines.
Here: results primarily from Al.
Gordon conference: Cu results



Lines sputtered, patterned and etched
Thickness = 0.55 μm
Widths = 1.3 to 13 μm
Most specimens unpassivated

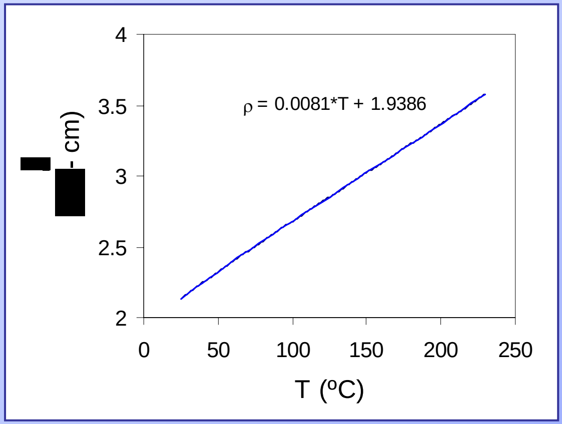
A.C. tests:
- 100 Hz, current control
- sinusoidal signal
- room environment

Lifetime measurements:
- to open circuit failure
- varied current density

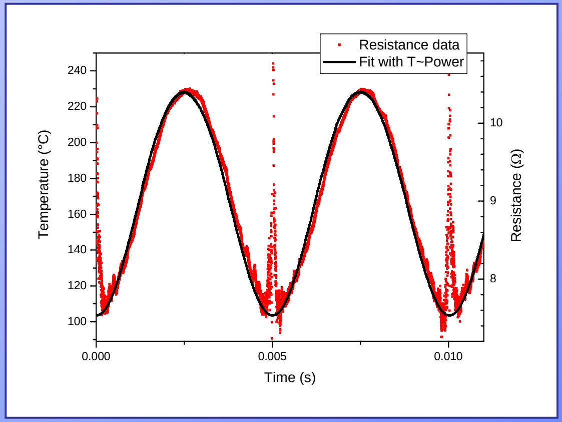
"Quasi" *in-situ* testing:
- EBSD
- AC test
- EBSD
- AC test

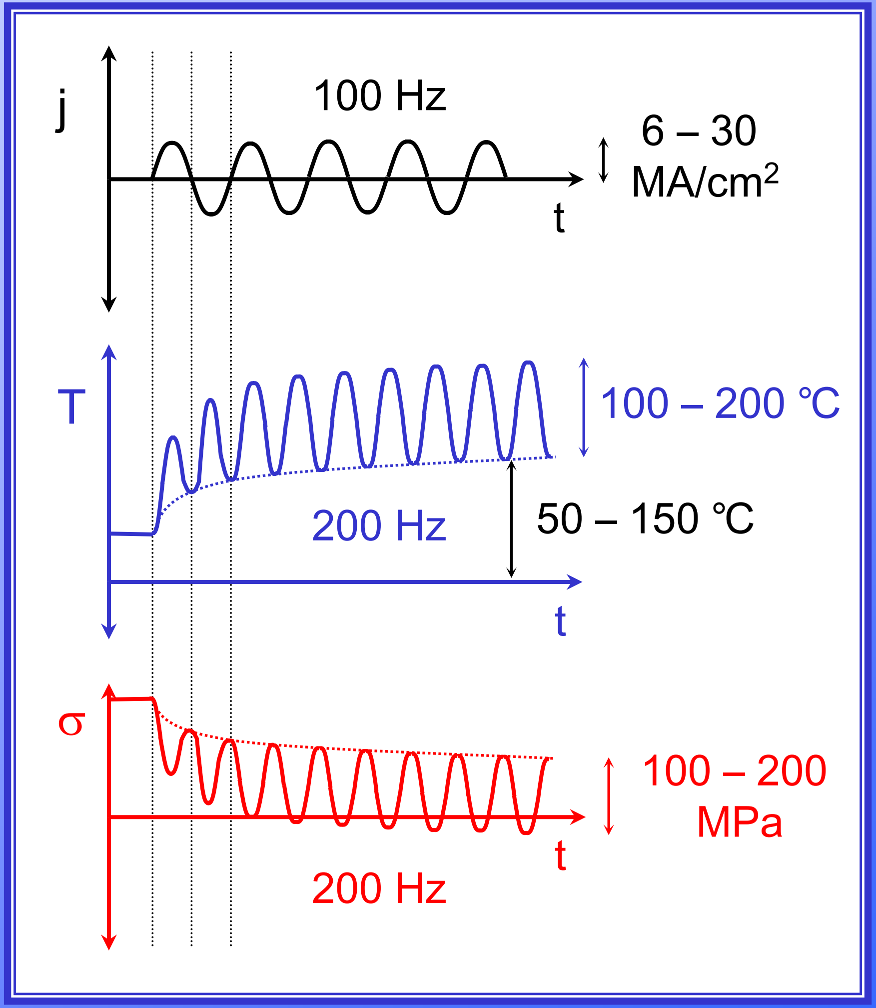
Joule Heating

Resistivity vs. Temp. Calibration

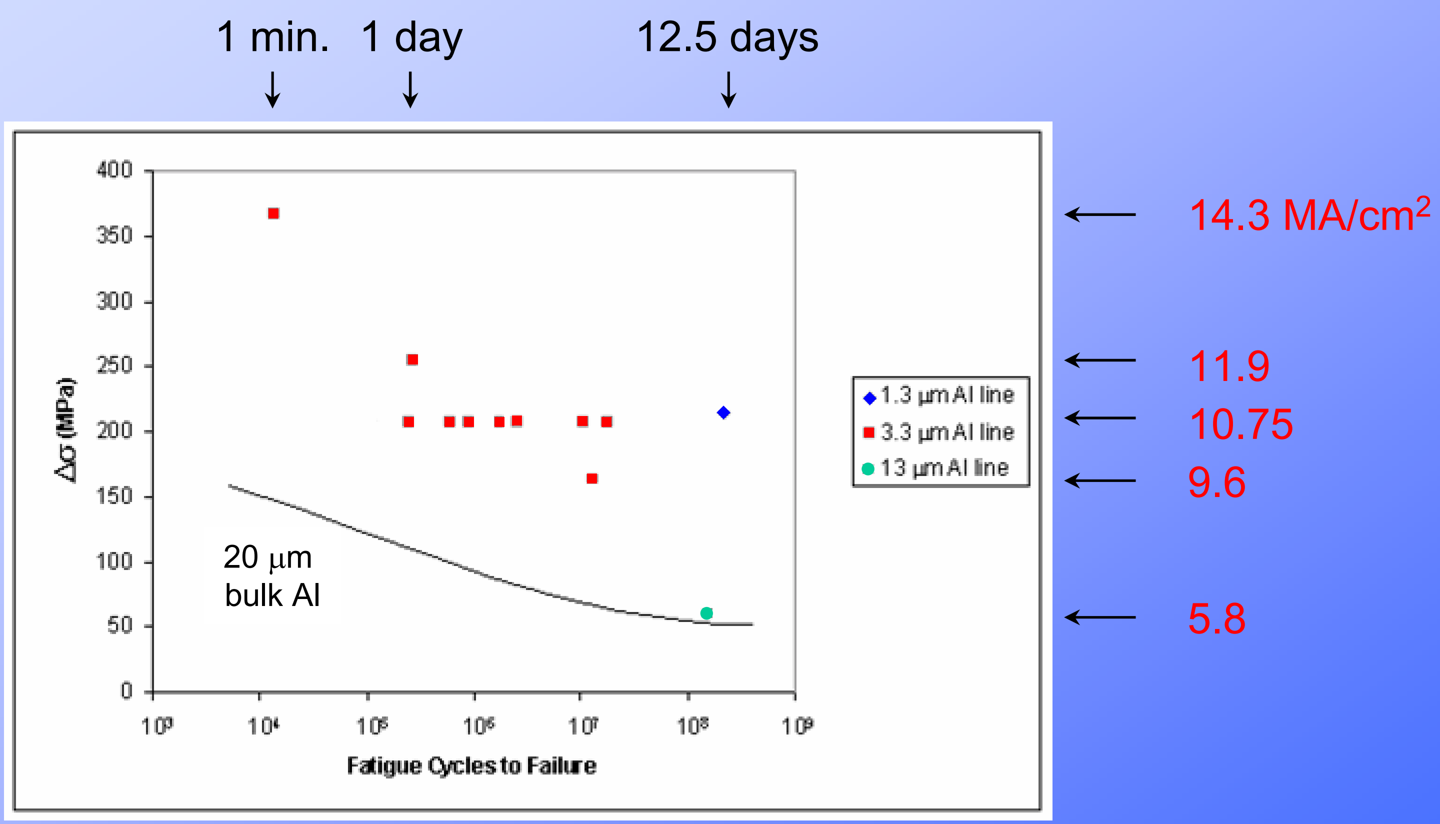


Time-resolved Resistance Measurement



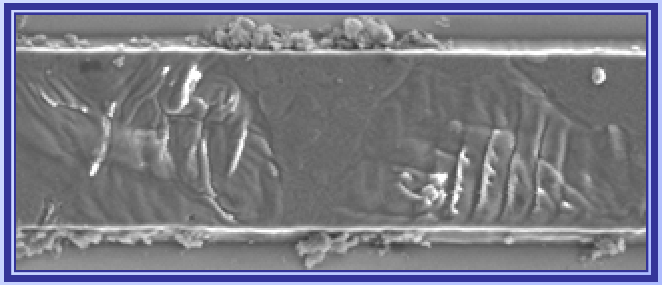


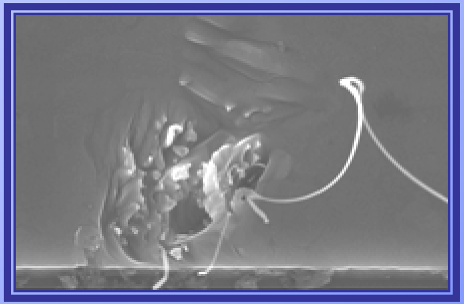
Lifetime Plot for A.C.-tested Al-1Si

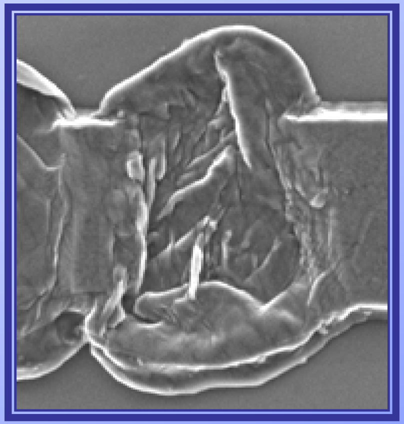


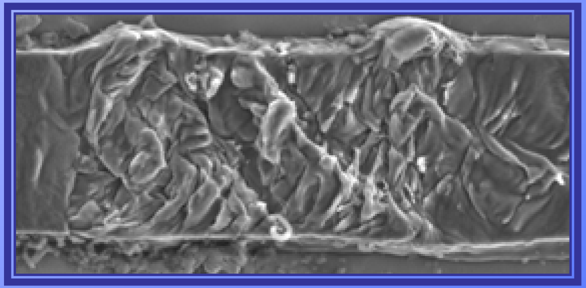
- Lifetimes to open circuit show fatigue-like behavior
- Stresses are higher, presumably due to film thickness and fine grain size effects
- Linewidth effect on lifetime, if any, still unclear

Examples of Damage



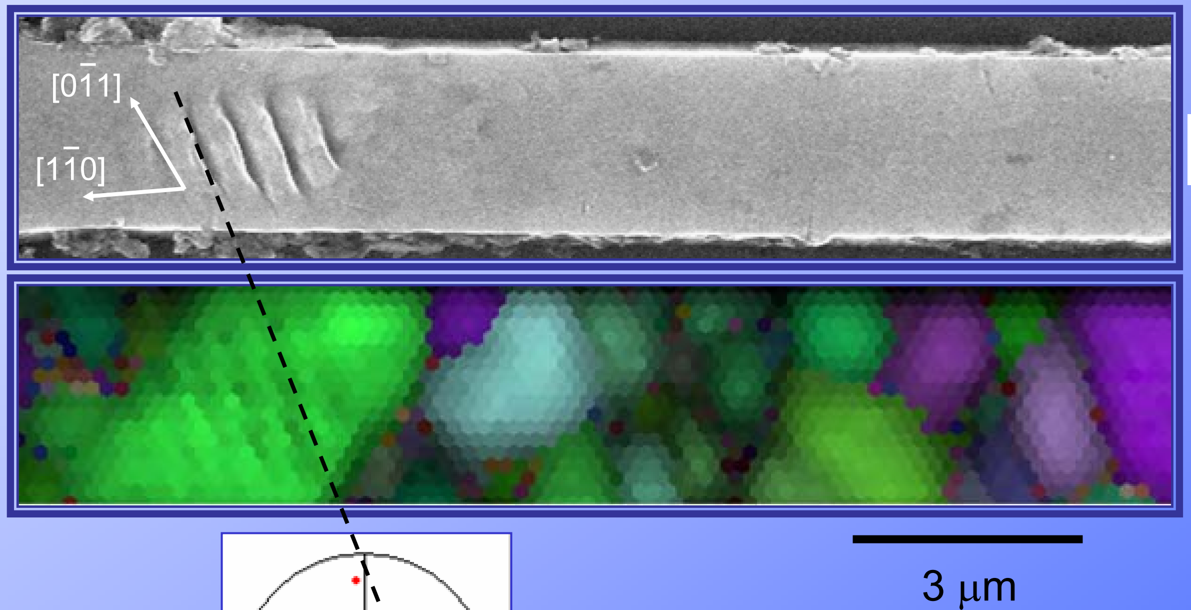




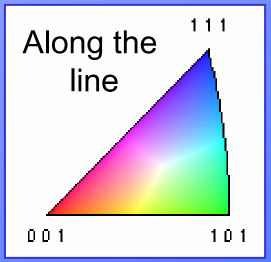


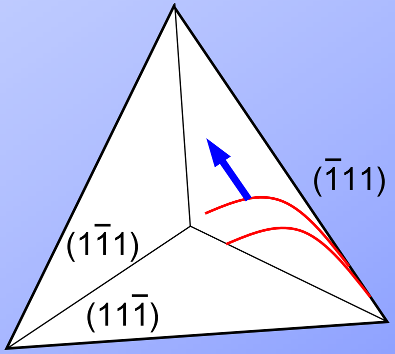
Damage is very site-selective, suggesting microstructural influence.
Small damaged regions become larger damaged regions.
Severe effects such as extrusion, whisker formation, and cracking observed.
Open circuit occurs only in more severely damaged regions.

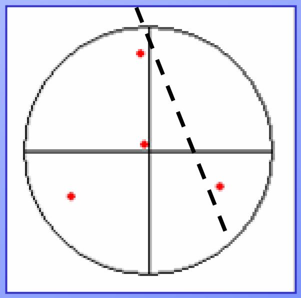
Topography



45 s at 12 MA/cm^2







Conventional glide can explain topography during early stages of testing.

Topography 2 – Site Specificity

Longitudinal loading

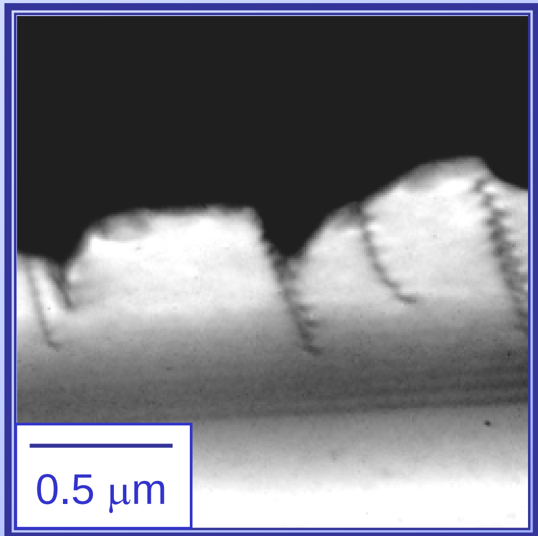
S.F. ~ 0.45   S.F. ~ 0.47

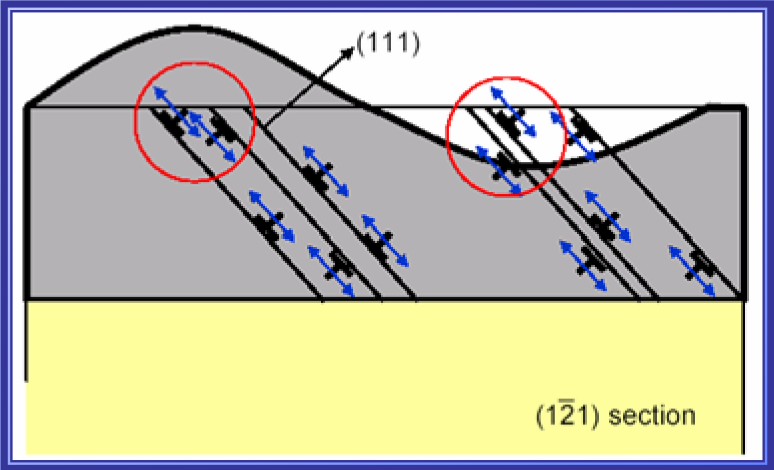
Transverse loading

S.F. ~ 0.41   S.F. ~ 0.44

- Grain that yielded did not have the largest resolved shear stress for either longitudinal or transverse loading.

Topography Summary

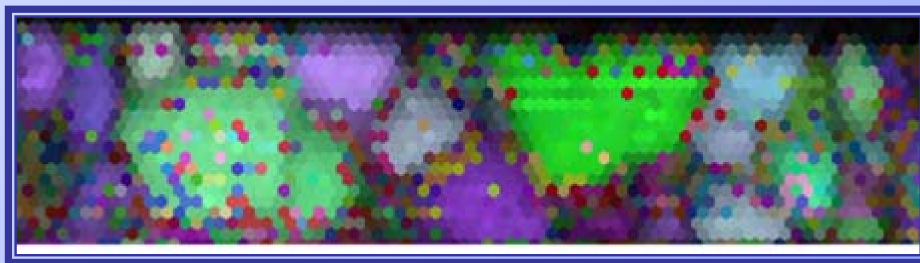




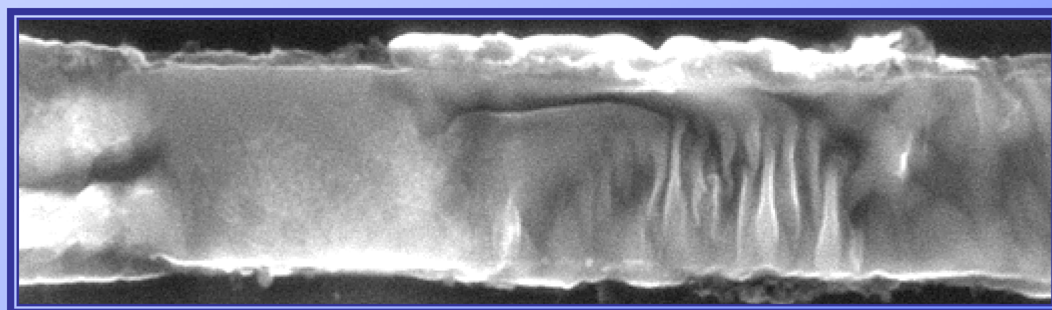
- Wrinkling is consistent with slip line traces associated with usual fcc slip systems of {111}⟨110⟩. These can form in under 60 s.
- Even after millions of cycles, no lower-energy dislocation structures were observed. Related to constrained volume available for deformation?
- Largest Schmid factor (assuming uniaxial loading) does not necessarily determine slip order.
- Must consider also effects of grain size and multiaxial stresses for predicting slip order.

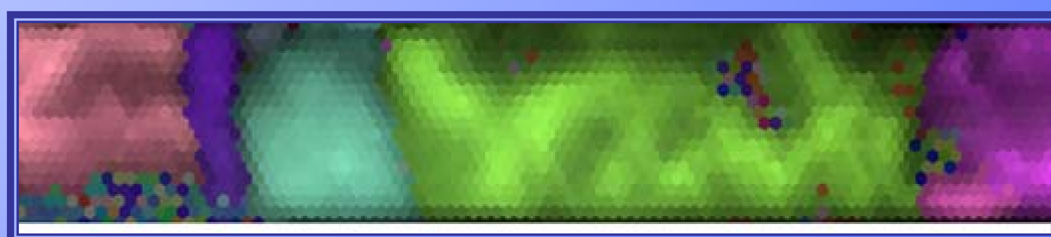
More than just Slip

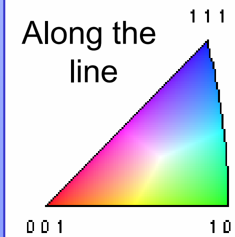
Prior to testing



60 s at
12 MA/cm^2



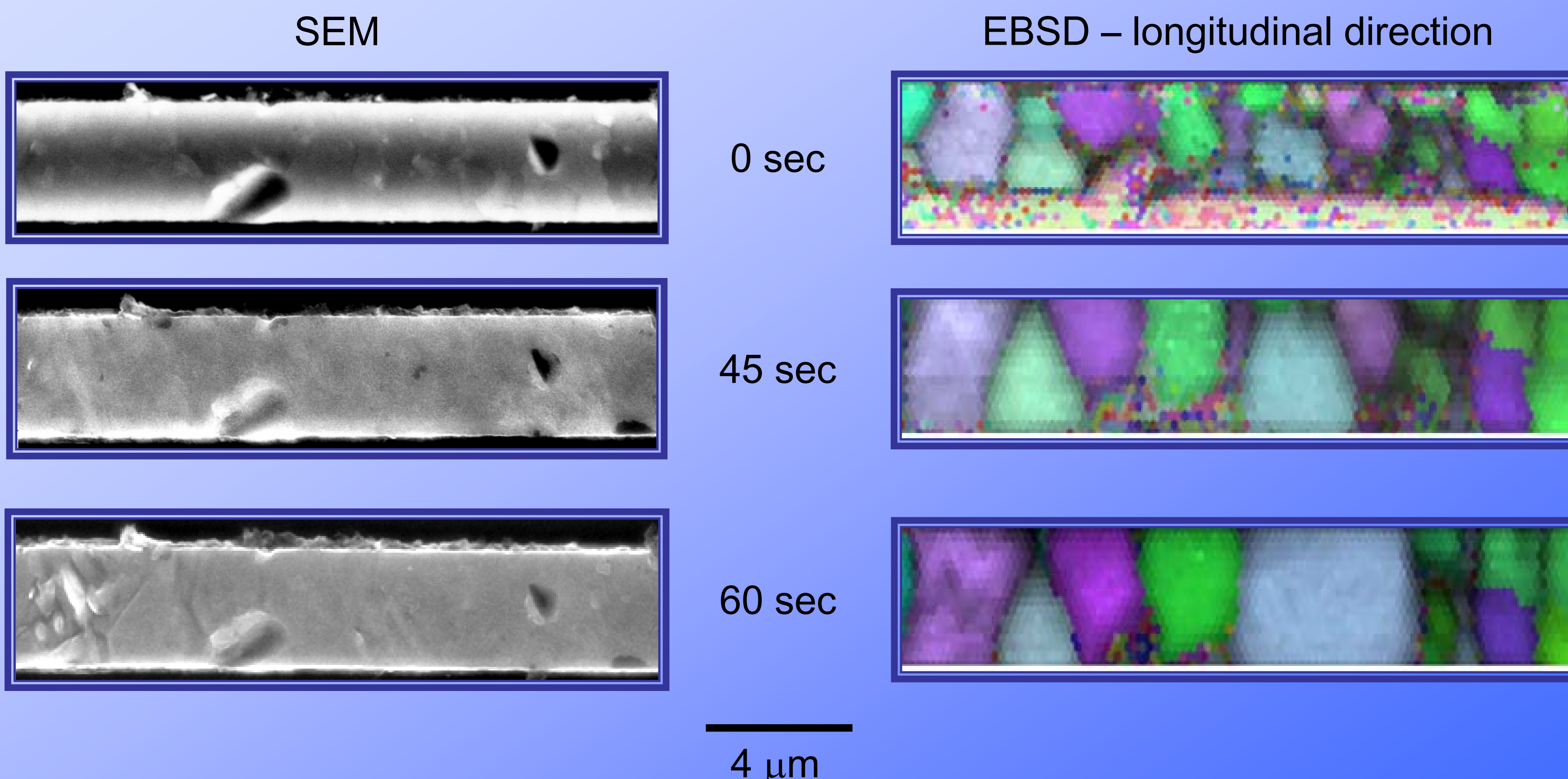




5 μm

Deformation accompanied by grain growth!

Grain Growth

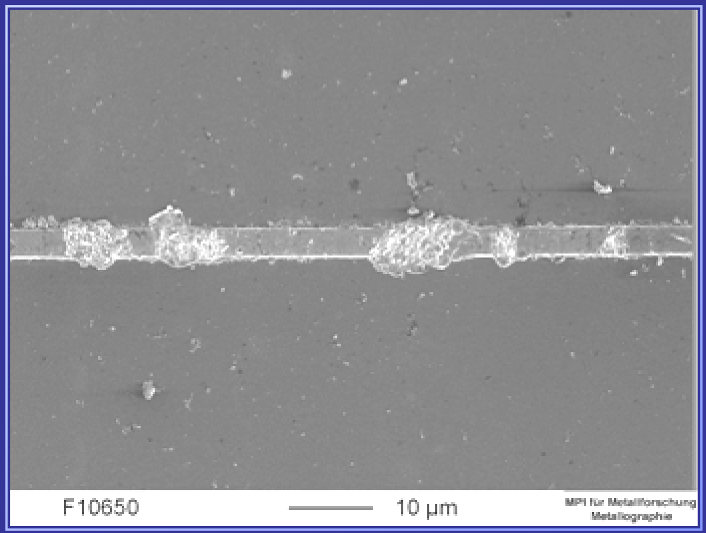


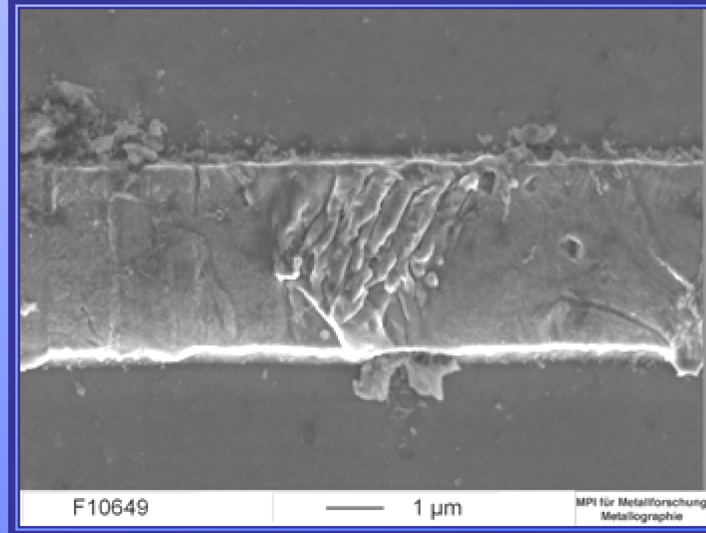
Observed growth in grains showing no slip lines.

Light blue grain shows onset of slip at 60 s, *after* significant growth.

Implications for Reliability

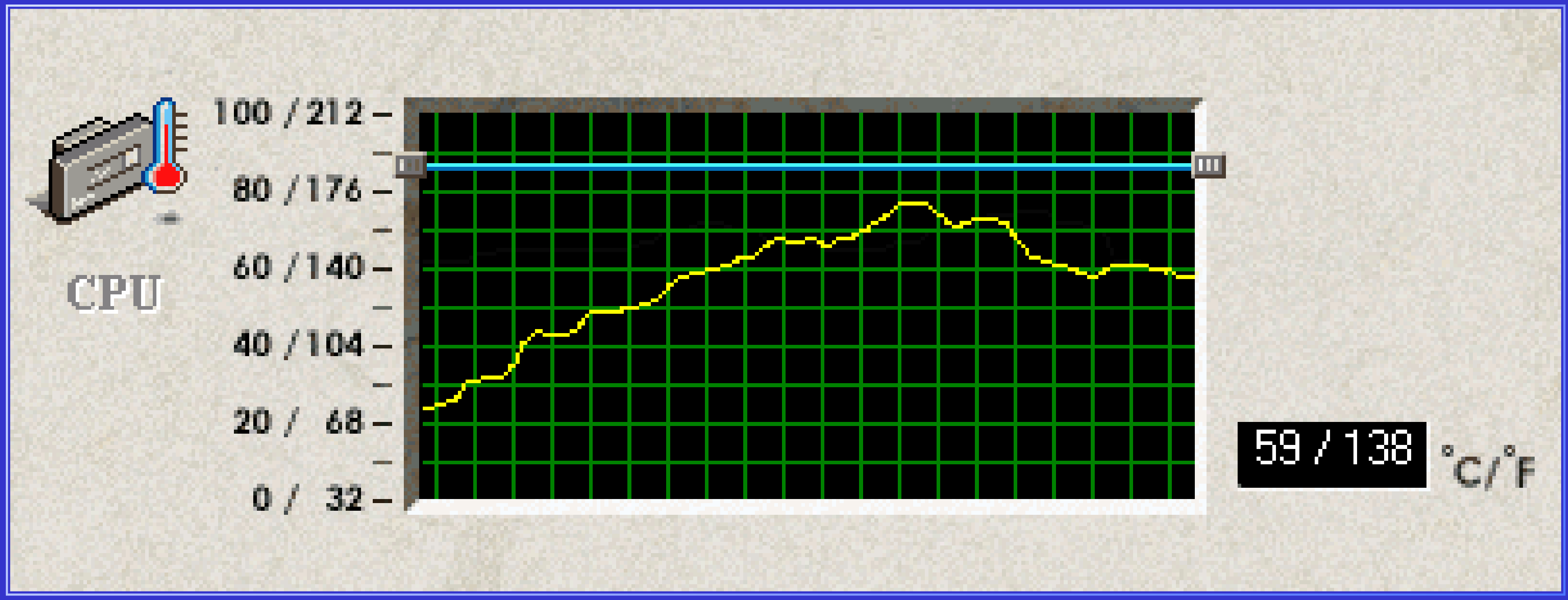
Coated with 2 μm photoresist (cured)
Tested in A.C. at 11 MA/cm^2
Photoresist stripped in acetone





Relatively soft encapsulant does not change damage morphology in Al.
Tests yet to be performed, but damage in unpassivated Cu is in many respects similar to that in Al…

Example of Low Frequency Cycling



Temperature variation of nearly 60C in one minute during normal cpu usage, as monitored by temperature sensor on motherboard.

Other examples:
Power cycling
Interconnect architecture

Summary

- A.C. damage distinctly different from D.C. damage
- Significant cycling of thermal stresses induces cyclic deformation
- Damage is site-specific
  - Local microstructure is important
- Topography largely attributed to dislocation activity
- Grain growth occurs in both Al and Cu lines
- Soft overlayers do not prevent damage
  - Cu/low-k systems may be susceptible
- Separation of temperature and current effects still underway
  - Pure fatigue versus EM-like behavior

Thoughts on Grain Growth

- Considerable driving force present, due to fine grain structure.
- Typically, growth accompanied by motion of high angle boundaries
  - We have this data, but have yet to analyze it.
- Probably not recrystallization
  - In bulk, cold-worked Al, occurs in tens of hrs at T > 300C.
  - PVD films that have little deformation-induced defects
- Strain-induced boundary migration?