Fatigue and Tensile Properties of Thin Films through Electrical Testing

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• Why an Electrical Test?
• Measurement Principle
• Microstructure
• Fatigue Lifetimes
• Strength

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Why Develop an Electrical Test?

- Method for testing “real” structures:
  - 150 nm-wide Cu, Ag (NIST, Sematech)
  - Testing such structures is difficult
  - Special specimen requirements for more common methods usually don’t match actual conditions.

Airgap microprocessor
Courtesy of International Business Machines Corporation.
Unauthorized use not permitted. 5/07.
Measurement Principle: Cyclic Joule Heating

- Four-point probe method
- Low frequency, high alternating currents
- No electromigration
- Controlled joule heating
- Thermal mismatch $\Rightarrow$ cyclic strain!

$\Delta \varepsilon_{\text{thermal}} = \Delta \alpha \Delta T$

(between metal and substrate)

Reference:
What about Non-Conducting Films?

- Use a proximity approach:

Thermal cycling occurs in film that doesn’t carry current.

Not yet demonstrated on non-conductors, though
Temperature from Resistance

- **R vs. T (calibration):**

\[
R(T) = R_0 + \Delta T \frac{dR}{dT}
\]

\[
\Rightarrow \Delta T = \frac{R(T) - R_0}{\frac{dR}{dT}}
\]

\[
\text{V and i vs. time:}
\]

\[
\text{T vs. time:}
\]
Fatigue Lifetime Curves
- Patterned Cu Lines

AC load plus unload cycles to failure

Temperature range, °C

Electroplated, damascene, narrow
PVD (e-beam), wide, uncovered
Fatigue Lifetime Curves

Strain Amplitude

Stress Amplitude
Estimates of Thin Film Ultimate Strength

Ultimate strength:
- Use Basquin equation, where

\[ \sigma_a = \frac{\Delta \varepsilon_e E}{2} = \sigma'_f \left(2N_f\right)^b \]

\[ \sim \sigma_{UTS} \]

- \( \sigma_a \) = stress amplitude
- \( E \) = Young’s modulus
- \( \Delta \varepsilon_e \) = elastic strain range
- \( \sigma'_f \) = fatigue strength coefficient
  \( \sim \) ultimate strength, \( \sigma_{UTS} \)
- \( b \) = fatigue strength exponent
- \( N_f \) = number of reversals to failure
UTS Measurements on Aluminum

Extrapolate to one reversal to estimate strength

\[ \sigma_{UTS}(\text{Al}) = 250 \pm 40 \text{ MPa} \text{ electrical} \]

\[ \sigma_{UTS}(\text{Al}) = 239 \pm 4 \text{ MPa} \text{ microtensile} \]

Tests performed on specimens fabricated on same wafer

Approach needs more qualification

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Microstructural Changes

- SEM/EBSD, test for $t_1$, SEM/EBSD, test for $t_2$, ...
- Al-1Si, $t = 0.5 \, \mu m$, $w = 3.3 \, \mu m$
- $j_{rms} = 12 \, MA/cm^2 \Rightarrow \Delta T \approx 200 \, ^\circ C$, $\Delta \varepsilon \approx 0.4 \%$
- $t_i = 0, 10, 20, 40, 80, 160, 320, 697 \, s$
Commentary:
Standardization of Small-Scale Tests

• Concern:
  – Different methods usually require different processes
  – For thin films, even slight variations in processing can cause dramatic changes in microstructure (& properties)

• Suggested Action:
  – Include microstructural parameters when reporting results

• Concern:
  – Even with films from same wafer, different specimen needs can change mechanical constraint

• Suggested Action:
  – Exercise caution when comparing one type of test to another
Summary

- An electrical method for applying cyclic thermal strain to patterned thin films on substrates has been developed.

- This approach does not require special specimen geometries.
  - wide range of structure dimensions;
  - buried structures → properties under constraint;

- Test naturally provides fatigue lifetime data

- Ultimate strength of patterned thin films can be estimated through use of modified Basquin equation.

- Test method requires more demonstration and refinement on non-conductors, unusual film patterns, buried structures

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