Electromigration
Test Structure Design

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Outline (Electromigration Test Structure)

1. Background of Electromigration
2. Critical Points of EM Test Structures
3. Design Electromigration Test Structure
4. Calculation and Analysis of EM Test Structure
   (with Excel and Simulation Tool)
5. Conclusion

1. Background of Electromigration (EM)

- Electromigration: Metal atoms swept out of position by high current density → failure (void/extrusion)
- Black's Law (Mean time to failure of a wire)

$$MTTF = \frac{A}{J^2}\exp(\frac{E_a}{kT})$$

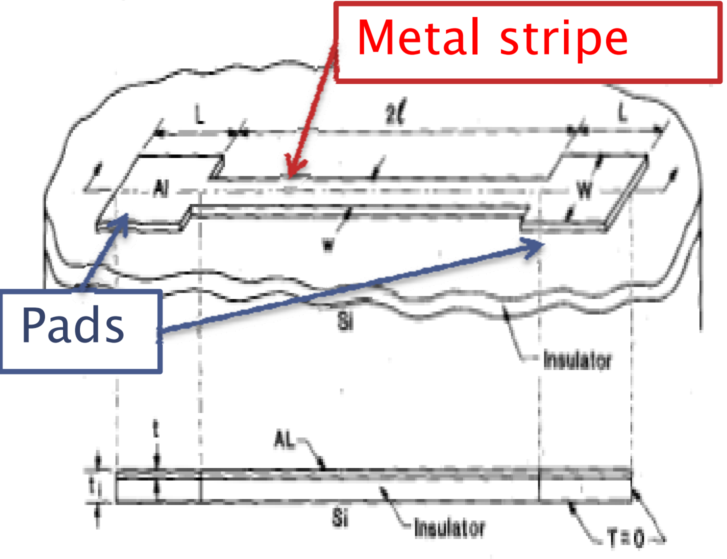
J = current density
T = film temperature
A = cross-section of interconnect area
Ea = activation energy (=0.7eV for Al)
K = Boltzmann's constant

Note: Current density and temperature are decaying factors

- With EM Test Structure, one can do …
  - Find maximum current density that can be used in interconnects of technology
  - Expect device lifetime by stressing test structures at elevated temperature and high current density
    - Focus on J and T in EM Test Structure

2. Electromigration Test Structure

↓Dog-bone EM Test Structure



- Thermally narrow stripes terminated in wide pads
- Voltage-sensing taps for Kelvin (resistance) measurement

- **By stressing at high current density to reduce test time**

1. Power dissipated by resistance of line is high

2. Temperature rise becomes high

3. When e⁻ flows from cold to hot, metal breaks down and creates voids (open)

4. Failure * This failure doesn't happen under use condition. **(PROBLEM in Test)**

- To avoid heat by high current density, good heat sinking technique is necessary in order to reduce temperature gradient

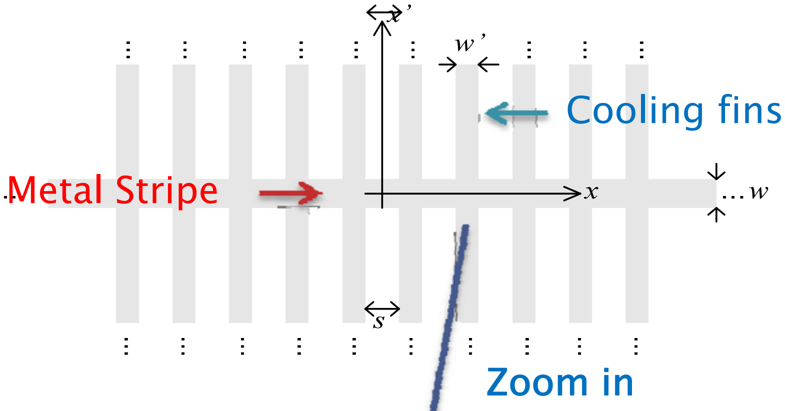
- **Purpose: design test structure to sustain high current density but minimize temperature gradients**

3. EM Test Structure
(Dog-bone EM Structure with Cooling Fins)

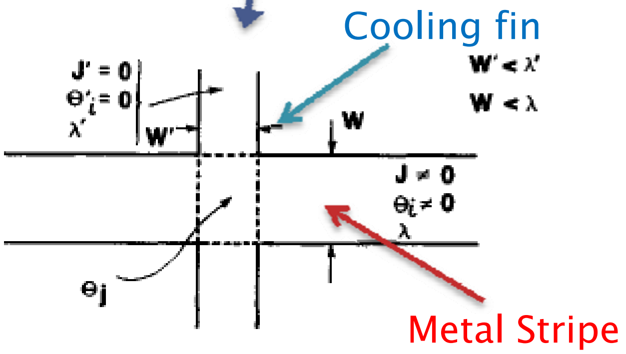
- Solution to reduce temperature gradient is …
  - Apply Cooling fins to stripe

- Want to prove this mathematically
  1. Calculate current density
  2. Calculate Temperature Gradient
  3. Estimate optimum space between cooling fins

Reference C.G. Shirley 1985



Schematic diagram of cooling fins

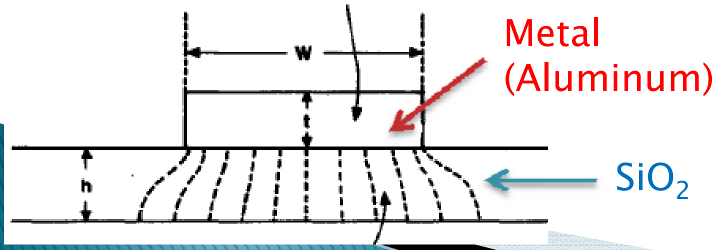


Schematic diagram of close-up test structure

3. Design EM Test Structure (Current Density)

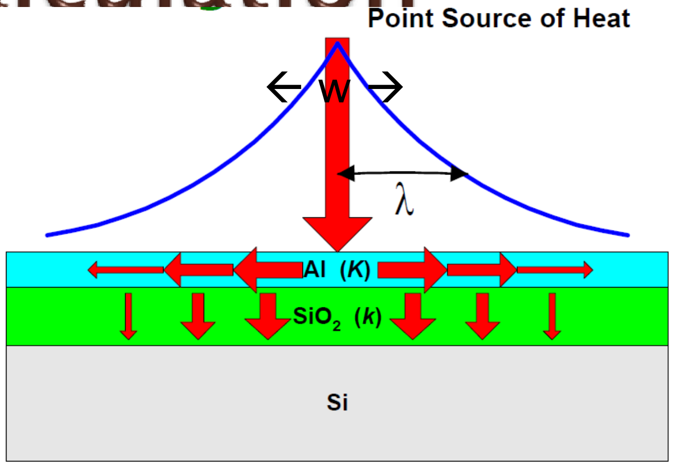
- For accelerated test, we want as high current density as possible to <u>reduce testing time</u>
  - But, be careful with high temperature gradient.
- Limitations of EM test structure
  1. Thermal Runaway Current Density ($J_{max} = 10^7 A/cm^2$)
  2. Temperature Gradient $d\Psi/dx$ as small as possible

Under use condition, $J_{use} = 2 \times 10^5 A/cm^2$
Under stress condition, $J_{stress} = 10^6 A/cm^2 < J_{max}$



*all numbers here are approximated in t = h=1um technology

4. EM Test Structure Calculation

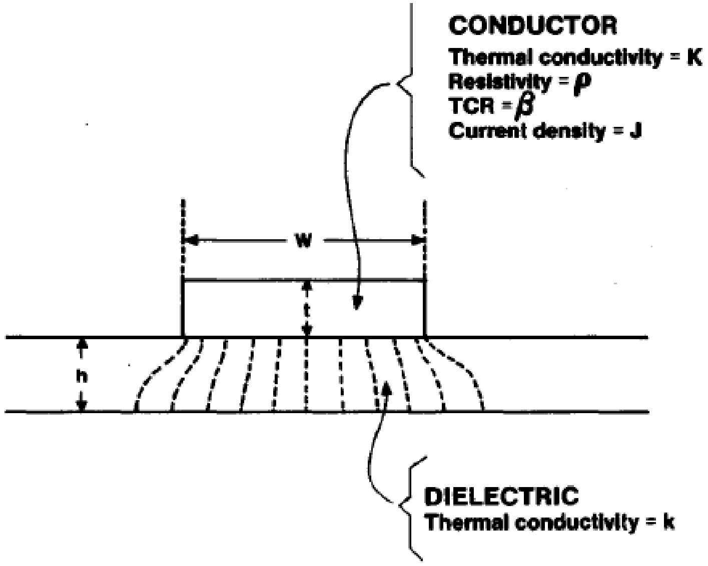


Assumptions

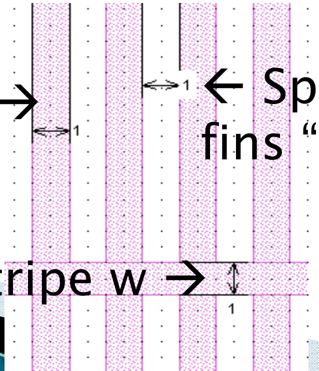
narrow stripe criteria (w, w'<<λ)

- w = w' = t = h = 1um
- This simplifies calculations a lot ☺

- **Calculation Steps**
  1. Find λ (thermal decay length) $\lambda = \sqrt{\frac{K\,th}{k\,\delta}}$ <to satisfy narrow stripe criteria>
  2. Find current density
     - dependent of λ, s
  3. Find temperature gradient ($\frac{d\psi}{ds}$)
     - dependent of λ, s, J



Cross section of a conductor stripe
Reference C.G. Shirley 1985



Cooling fin w' →

← Space b/w fins "s"

Stripe w →

Show Excel Spreadsheet

Microsoft Office
cel 97-2003 W

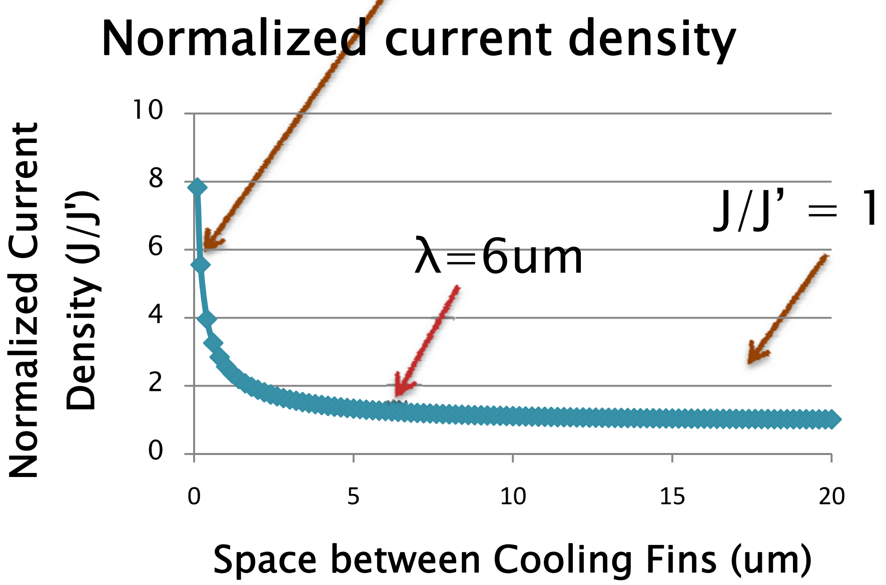
4. Current Density vs Space b/w Cooling fins Plot

- Normalized Current Density

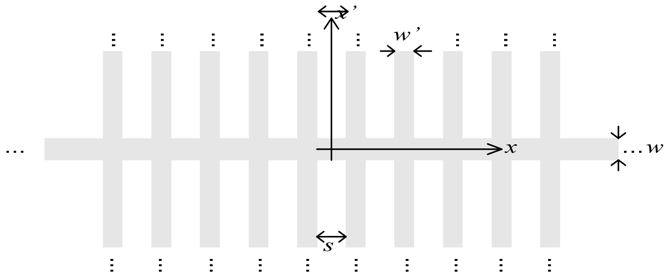
$$\frac{J}{J_{s\to\infty}} = \sqrt{\frac{1+\coth\left(\frac{s}{2\lambda}\right)}{2}}$$

•coth(x) converges to 1 as x → ∞

- As space increases, current density goes down.



•Limited by Technology
•DRC checks for min. space



4. Temperature Gradient vs Space b/w cooling fins plot

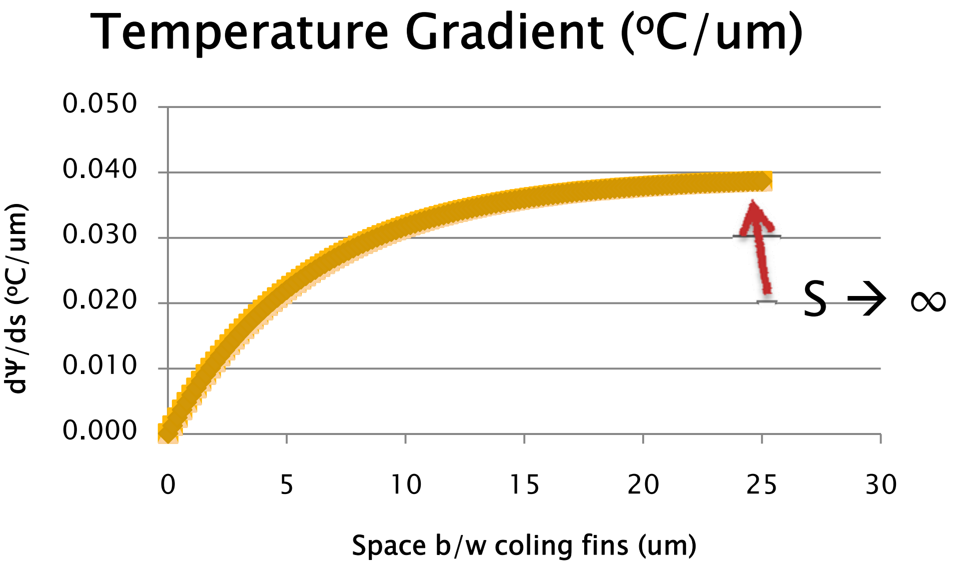
- Temperature Gradient Eqn. with generic “s”

$$\frac{d\psi}{ds} = \frac{J^2 \rho_s \lambda}{K\left[1+\coth\left(\frac{s}{2\lambda}\right)\right]}$$

- Temperature Gradient Eqn. as s → ∞

$$\frac{d\psi}{ds} = \frac{J^2 \rho_s \lambda}{2K} = 0.0393^o C / um$$

- **As s increases, temperature gradient increases.**

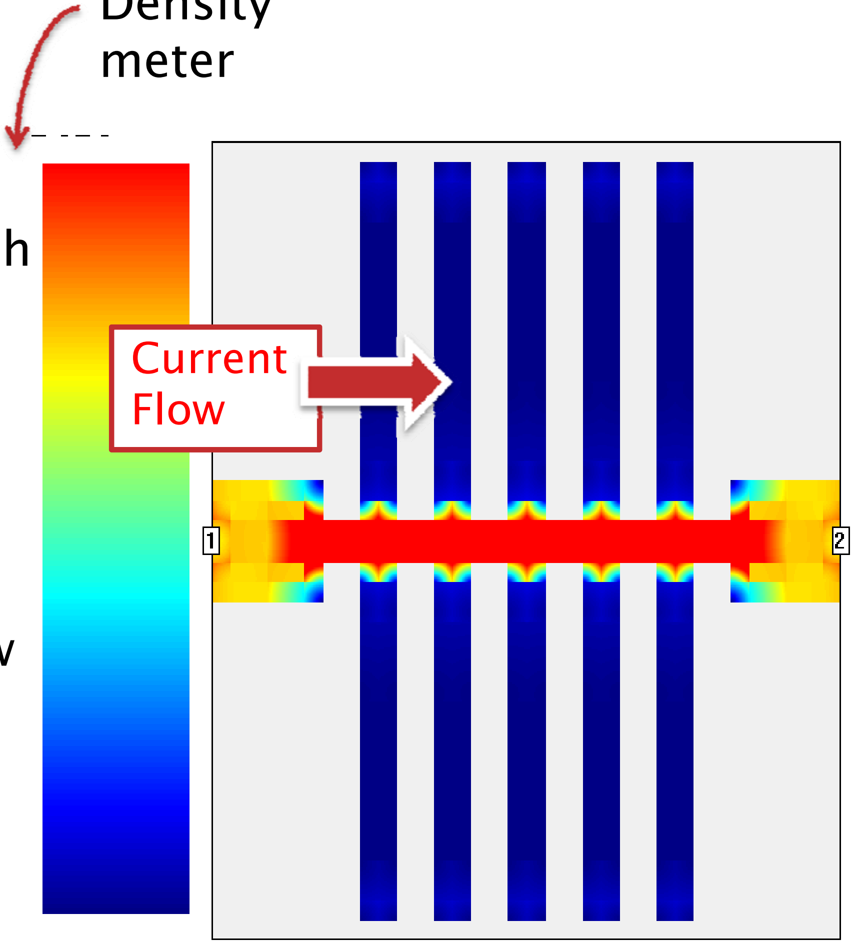


$J = 10^6 A/cm^2$
$\rho_s = 2.82 * 10^{-6} \Omega/cm$
$\lambda = 6.077 um$
$K = 2.18\ W/^oC\ cm$

4. CD Simulation

- Sonnet Lite Software (Limited Version) f = 1kHz
- Want to see current density effect due to the space, width of cooling fins

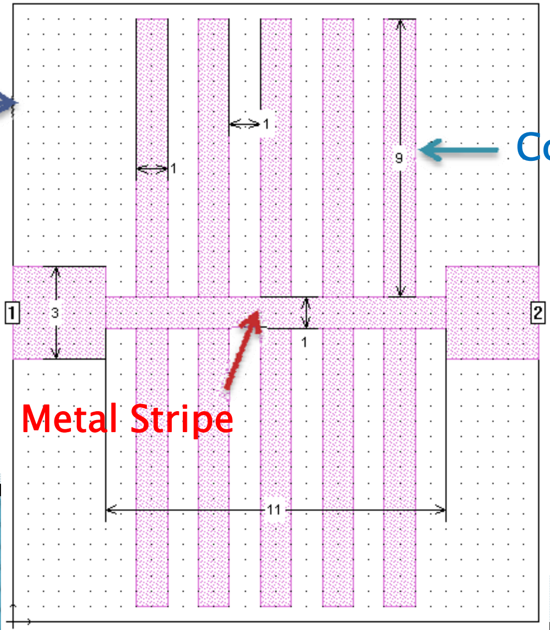
Current Density meter



High J

Low J

EM Test Structure w/ fins



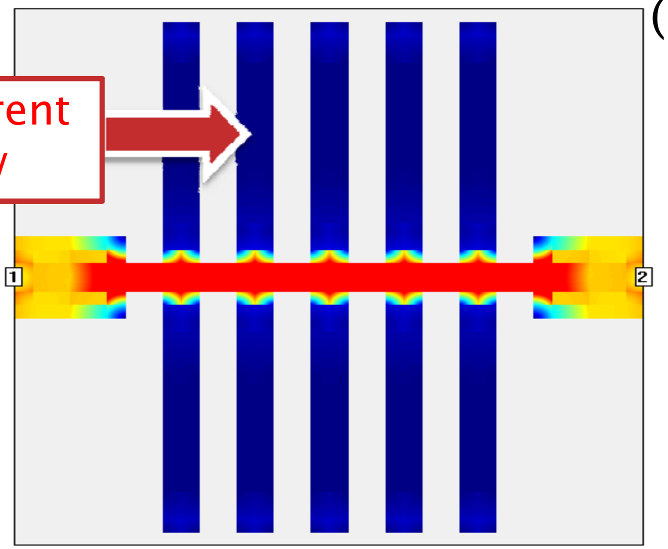
Metal Stripe

Cooling fin

←Aluminum Strip/Cooling fins/taps w=w'=s=1um diagram on Sonnet Lite

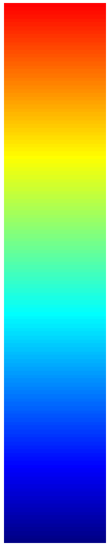
4. Current Density Simulation

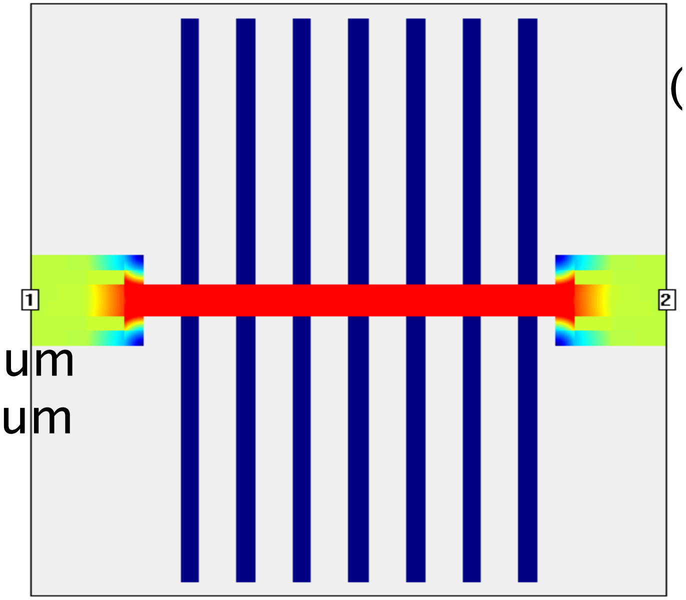
(1)w=w'=s= 1um



Current Flow

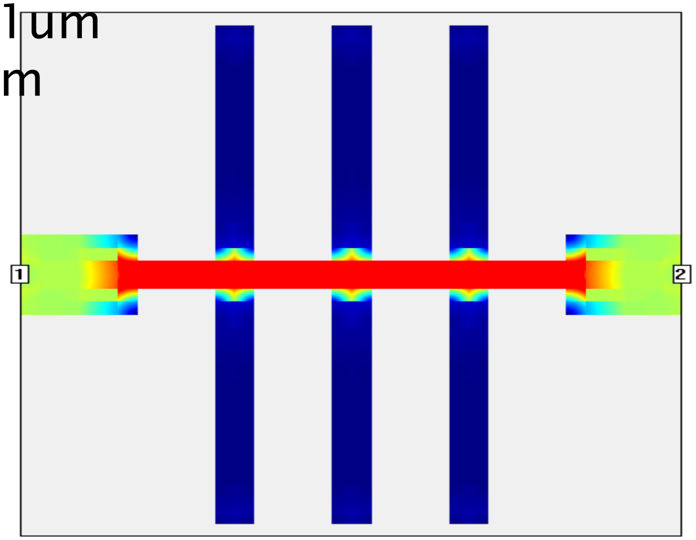
Current density



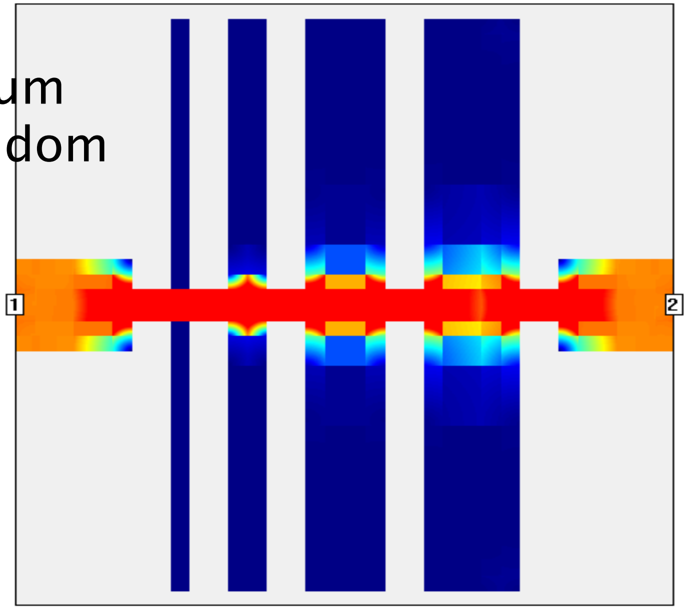


(2)w=s=1um
w'=0.5um

(3)w=w'=1um
s=2.5um



(4)w=s=1um
w' =random



5. Conclusion

- In accelerated test for EM, high current density is necessary to reduce test time.
- In order for a normal dog-bone EM test structure to have high current density, temperature gradient is a big problem for formation of voids.
- By adding cooling fins, temperature gradient is reduced (proved mathematically)
  - To get high current density and low temperature gradient, space needs to be as small as possible.
  - However, the size of spacing between cooling fins is limited by technology
  - pick $s = \{ s_{min}$ (set by DRC)$< s < \lambda = 6um \}$ i.e. $s = 1um$

References

1. C. G. Shirley, "Steady-State Temperature Profiles in Narrow Thin-Film Conductors," J. Appl. Phys., Vol. 57, pp. 777-784, 1985
2. J. R. Black, “Electromigration – A Brief Survey and Some Recent Results,” IEEE Transactions on Electron Devices Volume 16, Issue 4, Apr 1969 Page(s):338 – 347
3. ECE510 Applied Reliability Lectures

END

- Questions?