Electromigration Study of Pure Sn Conductors

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Purpose/Charter

• “Green” Computer
  – Pb may (will) be banned from use in the next decade in electronic components
    • Unfortunately it is a wonderful material for solder joining, there ain’t nothin’ better
  – Sn is a “green” metal
    • Not as well characterized as Pb
      – Strange stuff
    • Has significant problems that Pb does not
      – Sn “Pest”
      – Extreme fast diffusion of Noble and transition metals
  • Anisotropy
    – Mechanical and electrical
Interesting Initial Results

- Engineering
  - j x l Determination
  - Immortality
  - Activation Energy

- Science
  - Resistance Decay
Sn Characterization

- **Blech Length effect**
  - Literature is very inconsistent
    - Wide variation in jxl product
- **Effect of contacted metals**
  - Cr
    - No solid solubility (<.0001%)   
    - No IMC formation
  - Ni
    - No solid solubility (<.005%)   
    - IMC formation
  - Oxide
Failure Physics
(Metallization Driving Forces)

\[ F = \left( \sum_{i} F_i \right) = F_{em} + F_{tm} + F_{\sigma} + F_S \]

\[ \vec{F}_{em} = Z \ast e \rho \vec{j} \]

\[ F_{\sigma} = \Omega \frac{d\sigma}{dx} \]

\[ F_{tm} = \frac{Q^* dT}{T} \frac{dx}{dx} \]

\[ F_S = \frac{kT dC}{C} dx \]
Mass Transport Equation

\[ J = \frac{DC}{kT} \left( Z * e \rho j - \Omega \frac{d\sigma}{dx} \right) \]

Due to electromigration and stress gradient,

Stress gradient builds to oppose electromigration.
Blech Condition

\[ J = \frac{DC}{kT} \left( Z^* e \rho j - \Omega \frac{d\sigma}{dx} \right) = 0 \]

*If there is a blocking boundary condition, electromigration stops completely at steady state*
A Blech Length will be defined for any current density.

\[ j \times l_{Blech} \leq A_{Blech} \]
Consequences for C4 Electromigration Testing

• “Black’s Law” isn’t
  – Only valid for nucleation dominated failure far from the steady state

• The static steady state condition is very near the use condition in solder ball technology
  – More important to go to lower than higher current density

We may luck out and have solder ball Immortality
Blech Product Determination

- First Experiments with Sn/Cr
  - Successively lower j to find when Blech Condition is satisfied
  - Initial thoughts were that Blech Product for Sn would be substantially less than for Al or Cu
    - lower yield strength
    - Higher $z^*$

*If Blech Product is on the order of 100 we may be able to design immortality*
Test Structure
Resistance vs Time

Sn Cr 1mA 150C Device 2-8

Therefore the Blech Product is less than 250
Extrusion

Before

After ~20 hours at 5 mA

Therefore Blech Product is less than 1250
Sn Cr 0.5 mA 150C then 170C

Therefore the Blech Product is > 100
Length Effect?

- Failures can occur at 1 mA @ 150C
  - Sample dimensions
    - 2 X 4 X 200 µm
    - \( j = 1.25 \times 10^4 \text{ A/cm}^2 \)
  - \( jl < 250 \text{ A/cm} \)
- Failures do **NOT** occur at 500 µA
  - \( jl > 125 \text{ A/cm} \)
  - For 125 µm solder ball, \( j_{\text{crit}} = \sim 10,000 \text{ A/cm}^2 \)
    - **Immortality below** 1.2 A
  - For 75 µm solder ball, \( j_{\text{crit}} = \sim 15,000 \text{ A/cm}^2 \)
    - **Immortality below** 650 mA
Back Flow

• Merely exceeding the Blech Length of a value of $j$ is not sufficient
  – If the length of the sample is twice $l_B$, the driving force for failure is reduced by half near end of life and failure times are increased proportionally

• Apparent current density exponent $(j^{-n})$ will be incorrect
  – Extrapolations to use condition unrealistic
Back Flow

• Experiments at higher current density may be irrelevant
  – Failure by Sn electromigration may not be possible at use conditions
  – For $j_l = 12.5 \text{ ma/} \mu\text{m}$ the Blech current density for a 125 $\mu\text{m}$ C4 is $\sim 0.1 \text{ ma/} \mu\text{m}^2$ ($10^4 \text{ A/cm}^2$)

$$\int_{0}^{l} j(x) \, dx \leq 12.5 \frac{mA}{\mu m}$$

Actually
Test Structure II

Like TS I but with different boundary conditions
“Reservoir Effect” on RHS
Activation Energy

• From Drift Velocity
  – 5 temperatures
    • 90°C, 110°C, 130°C, 150°C, 170°C
    • Wide temperature range
    • Down to operational use condition
  – 10 mA
    • Order of magnitude higher than Blech Current for this structure
    • No contribution from back stress gradient
  – Samples allowed to relax fully before measurement
Activation Energy

Sn Electromigration (Drift Velocity)
0.96 +- 0.05 eV

Upper 95% Confidence Limit
Lower 95% Confidence Limit
Activation Energy

\[ \Delta H = 0.96 \pm 0.05 \text{ eV} \]

– No Evidence of Grain Boundary Contribution

– Literature
  - Lattice 0.99 and 1.1 eV
  - Grain Boundary 0.41 to 0.51 eV
Other Configurations

- Similar Behavior wrt Blech Product
  - Sn on Ni
  - Sn on Oxide
  - Sn – 0.7 % Cu alloy
Interesting Initial Results

• Engineering
  – j x l Determination
    • Immortality
  – Activation Energy

• Science
  – Resistance Decay
Resistance Decay

Decay time is a function of the current
Resistance later rises due to damage/edge motion
Decay

<table>
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<tr>
<th>I</th>
<th>tau</th>
<th>A</th>
<th>Vo</th>
<th>Ro</th>
<th>V inf</th>
<th>R inf</th>
<th>DV/Vo %</th>
<th>Delta</th>
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<td>0.00667</td>
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<td>1214  4.50E-04</td>
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<td>0.0182</td>
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Substantial uncorrelated variation in initial resistance and in delta R
$1/j^2$ Dependence

![Graph showing Cr Underlay Decay with the equation $y = 9927.4x^{-1.926}$]
Other Results

• Not due to temperature alone
  – Samples sitting at 150 C for up to 2 months before application of DC
    • Joule heating is too small
  – AC tests show only minimal changes (<0.5%)
    • Frequency dependent
      – 1 KHz a small possible effect
        » (probably due to temperature)
      – 10 KHz, 100 KHz no effect
Why?

• Sn is anisotropic
  – 40% difference in resistivity
    • (14.3 to 9.9 $\mu\Omega\cdot$cm)
  – 20% difference in elastic modulus
    • $C_{11} = 7.23$ and $C_{33} = 8.84 \times 10^{11}$ dyne/cm$^2$
Why?

• Electromigration induced stress gradient produces driving force inducing re-orientation of Sn structure to minimize strain energy.

• Final orientation is lower resistance
Effect of Structure

• Effect prominent on Sn/Cr and Sn/Ni
• Much less on Sn/SiO₂
• Texture (Ken Rodbell) is very different in as deposited condition
  – Sn/SiO₂ already aligned with lower resistivity orientation
• Before and after Sn/Ni showed change in ρ and change in preferred orientation
What?

• How does this come about?
  – Decay $\tau$ suggests grain boundary processes
    • Consistent with $\sim$0.4 eV
  – Grain boundary diffusion?

• More work needs to be done
Comment:
Mass Transport with Soret Effect

\[ J = \frac{DC}{kT} \left( Z^* e \rho j + \frac{Q^*}{T} \frac{dT}{dx} - \Omega \frac{d\sigma}{dx} \right) \]
Mass Transport with Soret Effect

• Soret diffusion can have a profound effect on the behavior
  – Comparable to the electromigration driving force in Sn
  – Bizarre current density effects can be expected

• Any projection of reliability must be made in terms of the temperature gradients
  – Must be restricted/eliminated/specified in design rules
I get by with a little help from my friends

Ken Rodbell
Henry Nye
Cev Noyan
Conal Murray

Steve Kilpatrick
Tom Shaw
Mike Sullivan

Stephanie Chiras
Bob Rosenberg
Michael Lane