Electromigration in Flip Chip Solder Joints

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3. Electromigration in flip chip solder joints
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   • Effect of composite solder joints

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Support : NSF, SRC
Co-workers : Prof. Chang-yi Liu, National Central University, Taiwan; Prof. Taek Yeong Lee, Hanbat National University, Korea; Dr. Everett Yeh, Intel, Santa Clara, CA; Dr. Woojin Choi, Intel, Chandler, AZ; Ms. Hua Gan, Mr. Albert Wu, Mr. Jong-ook Suh, Miss Emily Ou, Miss Annie Huang, UCLA
63Sn/Pb Electromigration Example

Bump Connected to Positive Terminal on Substrate (bottom)

\[ J = 6 \sim 8 \times 10^3 \text{ amp/cm}^2 \]
\[ T = 150 \, ^\circ \text{C}, \, t = 100 \text{ hrs} \]

Why does electromigration in solder joints become a reliability problem?

Calculation of Diffusivities

\[ D_L = 0.5 \exp\left(-\frac{34 \, T_m}{RT}\right) \]
\[ D_{gb} = 0.3 \exp\left(-\frac{17.8 \, T_m}{RT}\right) \]
\[ D_s = 0.014 \exp\left(-\frac{13 \, T_m}{RT}\right) \]


\[ T_m : \text{Melting point of Metal} \]

LogD vs. \( T_m/T \) for FCC metals

Not due to diffusion!
## Different Diffusion Mechanisms

<table>
<thead>
<tr>
<th></th>
<th>Melting point (°K)</th>
<th>Temperature ratio 373°K/Tm</th>
<th>Diffusivities at 100°C [373°K] (cm²/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu</td>
<td>1356</td>
<td>0.275</td>
<td>Surface $D_s=10^{-12}$</td>
</tr>
<tr>
<td>Al</td>
<td>933</td>
<td>0.4</td>
<td>Grain Boundary $D_{gb}=6\times10^{-11}$</td>
</tr>
<tr>
<td>Pb</td>
<td>600</td>
<td>0.62</td>
<td>Lattice $D_l=6\times10^{-13}$</td>
</tr>
<tr>
<td>Eutectic SnPb</td>
<td>456</td>
<td>0.82</td>
<td>Lattice $D_l=2\times10^{-9}$ to $2\times10^{-10}$</td>
</tr>
</tbody>
</table>

Electromigration in Al is dominated by *grain boundary* diffusion

Electromigration in Cu is dominated by *surface* diffusion

Electromigration in solder is dominated by *lattice* diffusion

*Fast lattice diffusion is not the reason of EM failure in solder joints*
If \( J = 0 \), there is no net electromigration flux.

\[
J = -C \frac{D}{kT} \frac{d\sigma\Omega}{dx} + C \frac{D}{kT} Z^* eE
\]

\[
\frac{\Delta \sigma \Omega}{\Delta x} = Z^* e \rho j
\]

**Critical product**

\[(j \Delta x)_{\text{critical}} = \frac{\Delta \sigma \Omega}{Z^* e \rho}\]

If \( j \Delta x < (j \Delta x)_c \) \( \rightarrow \) No electromigration damage
Electromigration in Al short strips on TiN

By Dr. Alexander Straub, MPI Stuttgart, Germany, July 1999

Line width : 10µm, Line Thickness : 100nm,
Current density $10^6$ A/cm², Temperature : 225°C
## Small Critical Product in Solders

\[
(j \Delta x)_c = \frac{\Delta \sigma \Omega}{Z^* \varepsilon \rho}
\]

\[
(j \Delta x)_c = \frac{Y \Delta \varepsilon \Omega}{Z^* \varepsilon \rho}
\]

\[\Delta \sigma = Y \Delta \varepsilon, \quad \Delta \varepsilon = 0.2\% \text{ at elastic limit}\]

<table>
<thead>
<tr>
<th>Material</th>
<th>Y (GPa)</th>
<th>Z*</th>
<th>(\rho (\mu\Omega \text{-cm}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solder</td>
<td>~30</td>
<td>~30</td>
<td>~22</td>
</tr>
<tr>
<td>Al</td>
<td>~69</td>
<td>2~4</td>
<td>~2</td>
</tr>
<tr>
<td>Cu</td>
<td>~110</td>
<td>2~4</td>
<td>~2</td>
</tr>
</tbody>
</table>

\[
(j \Delta x)_{c_{\text{solder}}} = \frac{Y \Delta \varepsilon \Omega}{Z^* \varepsilon \rho} \approx 5 \times 10^{-3} (j \Delta x)_{c_{\text{Cu/Al}}}
\]

- Constant \(\Delta x\), the current density needed to fail solder is **2~3 orders smaller** than that needed to fail Al or Cu.
- If Al or Cu fails at \(10^5\) to \(10^6\) A/cm\(^2\), solder will fail at \(10^3\) or \(10^4\) A/cm\(^2\).
Current crowding in a flip chip solder joint

The design rule is 0.2A per bump, so for a bump of 100µm × 100µm
The average current density is $0.2 \times 10^{-4} \text{ A/cm}^2$ or $0.2 \times 10^4 \text{ A/cm}^2$

The unique geometry of a solder joint leads to current crowding

$J = I/A$, $A_{\text{Al}} \ll A_{\text{solder}}$

Solder is the weakest link due to current crowding
Time - Potential Curve

Resistance does not change much

![Graph showing potential vs. time with a note that resistance does not change much.]

<table>
<thead>
<tr>
<th></th>
<th>Al or Cu Interconnects</th>
<th>Solder Bumps</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cross-section</td>
<td>0.5x0.2 μm²</td>
<td>100x100 μm²</td>
</tr>
<tr>
<td>Resistivity</td>
<td>1.7-2.6 μm·cm</td>
<td>11.5-22 μm·cm</td>
</tr>
<tr>
<td>Resistance</td>
<td>1 to 10 ohm</td>
<td>10⁻³ ohm</td>
</tr>
<tr>
<td>Current</td>
<td>10⁻³ amp</td>
<td>1 amp</td>
</tr>
<tr>
<td>Current Density</td>
<td>10⁶ A/cm²</td>
<td>10³ to 10⁴ A/cm²</td>
</tr>
</tbody>
</table>
Unique characteristics of electromigration in a flip chip solder joint

- Typically, it is a two-phase eutectic alloy
- It has UBM on chip side and bond-pad on substrate side:
  - chemical force interacts with electrical force
- Flip chip solder joints are under thermal stress:
  - mechanical force interacts with electrical force
- Its geometry leads to current crowding
- Solder joint is low resistance as compared to Al and Cu interconnects:
  - it is insensitive to resistance change and hard to detect failure by resistance change
- Pb-free vs. Pb-containing solders
- Thick UBM vs. thin film UBM
- Composite solder joint – interdiffusion is an issue
Test Samples

Flip chip solder joints (from Flip Chip Technologies)

**UBM:** Thin film Al/Ni(V)/Cu
**Solder:** Eutectic SnPb and eutectic SnAgCu
**Test condition:** 125 to 140°C and 2.25 to 3.8 x 10^4 A/cm^2

V-groove solder lines

**Electrodes:** Cu wires or Ni wires
**Solder:** Eutectic SnPb, eutectic SnAgCu and eutectic SnAg
**Test condition:**
- Eutectic SnPb: 150°C and 2.8 x 10^4 A/cm^2, or RT and 5.7 x 10^4 A/cm^2
- Eutectic SnAgCu: 120°C to 180°C and 3.2 to 4 x 10^4 A/cm^2
- Eutectic SnAg: 150°C and 3.0 x 10^4 A/cm^2
Sample Structure of Flip Chip Solder Joint

(a) Side View

(b) Top View

Si Chip

Al interconnect
Al/Ni(V)/Cu UBM

Au/Ni(V) bond-pad

FR4

Underfill

2nd cross section

1st cross section

Fig. Schematic diagram of the electromigration test sample
Sequence of the void propagation in e-SnPb solder joint at 125 °C, and $2.25 \times 10^4$ A/cm$^2$.
Failure Mode in Eutectic SnAgCu Solder Joints

(a) 0 hr

(b) 14 hrs

(c)

\[ J = 3.0 \times 10^4 \text{ A/cm}^2 \]
\[ T = 140 \text{ °C} \]
Effect of Solder Composition

3.8x10^4 A/cm^2 at 120°C.

(a) A eutectic SnPb solder joint after 40 hours,
(b) A eutectic SnAgCu solder joint after 200 hours.

EM in eutectic SnPb > eutectic SnAgCu

<table>
<thead>
<tr>
<th></th>
<th>e-SnPb</th>
<th>e-SnAgCu</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sn (wt %)</td>
<td>63%</td>
<td>97%</td>
</tr>
</tbody>
</table>

3.8x10^4 A/cm^2 at 120°C.
(a) A eutectic SnPb solder joint after 40 hours,
(b) A eutectic SnAgCu solder joint after 200 hours.
EM-driven IMC Formation in Eutectic SnPb Solder Bump

I = 1.27A, T = 100°C,

From professor R.Kao
in National Central Univ. in Taiwan
EM in Composite Pb-Containing Solder Joints

(a) Before current stressing
(b) After 3 hr
(c) After 12 hr
(d) After 20 hr

J=2.58×10^4 A/cm^2
Temp. of Si
Backside : 155°C
From KAIST
Three kind of UBM for high-Pb

1. IBM: Cr/Cr-Cu(phased in)/Cu
2. Delco: Al/Ni(V)/Cu
3. KAIST: Al/TiW/Cu (thick Cu, 5 \( \mu \)m)
Substrate side

37Pb63Sn

Solder Mask

Cu or Ni

Substrate
Electromigration Test Sample

Interconnect

Chip

UBM

97Pb/Sn

electron flow, \( e^- \)

37Pb/Sn

Solder resistor

Substrate

Cu

Substrate side Pad

underfill
Simulation

Cross sectional Structure

Current density distribution (A/cm²)
The magnified cross-sectioned SEM images of cathode side in the downward electron bump

From KAIST
Room Temperature Interaction in Bimetallic Thin Film Couples

King-Ning Tu and Robert Rosenberg
IBM Thomas J. Watson Research Center
Yorktown Heights, New York 10598

Table. Intermetallic compounds formed at room temperature

<table>
<thead>
<tr>
<th></th>
<th>Pb</th>
<th>Sn</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu</td>
<td>-</td>
<td>Cu₆Sn₅</td>
</tr>
<tr>
<td>Ag</td>
<td>-</td>
<td>Ag₃Sn</td>
</tr>
<tr>
<td>Au</td>
<td>AuPb₂</td>
<td>AuSn₄</td>
</tr>
<tr>
<td>Ni</td>
<td>-</td>
<td>Ni₃Sn₄</td>
</tr>
<tr>
<td>Pd</td>
<td>PdPb₂</td>
<td>PdSn₄</td>
</tr>
<tr>
<td>Pt</td>
<td>PtPb₄</td>
<td>PtSn₄</td>
</tr>
</tbody>
</table>

Cu, Ag, Au, Ni, Pd, Pt

……………↓……………………Interstitial Diffusion

Si, Ge, Sn, Pb
Electromigration-Driven Phase Separation

Eutectic SnPb Sample before EM

J = 5.04 \times 10^3 \text{ A/cm}
T = 160^\circ \text{C}
T = 82 \text{ hrs}

From ASE, Taiwan
No chemical potential gradient as a function of composition below the eutectic temperature.
**Sample Preparation**

**Solder:** Eutectic SnPb
Eutectic SnAgCu
Eutectic SnAg

**Electrode:** Cu or Ni wire

**Reflow temperature:** ~ 210-250°C
**Reflow time:** ~1min
• Width of solder line: 
  ~ 100µm
• Length of solder line: 
  ~ 200-800µm
Experiment Setup

- Advantage of V-groove sample:
  - High current density
  - Easy to observe
  - No expected current crowding

Experiment temperature: 120°C, 150°C, 180°C
Current Density: $\sim 10^4$ A/cm²
EM in E-SnPb V-groove Lines

Volume of mass transport

\[ V_{em} = \Omega J_{em} At \]

\[ J_{em} = C \frac{D}{kT} Z^* eE \]

Calculated \( Z^* = 33 \) at high T.
Reported value for bulk Pb is 47.

Calculated \( Z^* = 39 \) at room T.
Reported value for bulk Sn is 18.

2.8 x 10^4 A/cm\(^2\)
150°C
8 days

5.7 x 10^4 A/cm\(^2\)
Room Temp
12 days
Redistribution of Pb and Sn

Redistribution of Pb for EM at 150°C

Redistribution of Sn for EM at RT

Electromigration

\[ J = 2.8 \times 10^4 \text{ amp/cm}^2 \]
\[ T = 150 \, ^\circ\text{C} \]
\[ t = 96 \text{ hrs} \]

\[ J = 4.0 \times 10^4 \text{ amp/cm}^2 \]
\[ T = 150 \, ^\circ\text{C} \]
\[ t = 72 \text{ hrs} \]
Polarity Effect of EM on IMC Thickness

From Dr. Hua Gan, UCLA
EM Effect on Thickness Change of IMC

**Anode (3.2x10^4 A/cm^2, 180°C)**

(a) Solder
Cu₆Sn₅
Cu

0 hr

(b) Solder
Cu₆Sn₅
Cu

10 hr

**Cathode (3.2x10^4 A/cm^2, 180°C)**

(c) Solder
Cu₆Sn₅
Cu

0 hr

(d) Solder
Cu₆Sn₅
Cu

10 hr
EM Effect on Thickness Change of IMC (cont.)

Anode (3.2x10^4 A/cm^2, 180°C)

(a) Solder
Cu₆Sn₅
Cu

(b) Solder
Cu₆Sn₅
Cu₃Sn

Cathode (3.2x10^4 A/cm^2, 180°C)

(c) Solder
Cu₆Sn₅
Cu

(d) Solder
Void
Cu₆Sn₅
Cu₃Sn
EM in Eutectic SnAg Solder Lines with Ni Electrodes

![Image of solder lines with Ni3Sn4 formation and voids]

- Cathode side: Ni → Ni3Sn4 → Void
- Anode side: Ni → Ni3Sn4

Graph showing thickness over time for both anode and cathode sides:

- Anode side: Thickness increases linearly with time
- Cathode side: Thickness increases initially, then decreases

Electrical current density: $J = 3.0 \times 10^4 \text{ A/cm}^2$

Temperature: $T = 150 \degree C$
Summary I

- In the flip chip solder joints, failure is due to the void propagation. Void forms at the cathode near the corner of current entrance into the solder bump.
- There is no chemical potential gradient force against phase separation and fast IMC formation in eutectic alloys.
- Diffusion of Pb and Sn dominates at temperature above 120°C and below 120°C respectively.
- EM enhances IMC formation at anode and inhibits it at cathode.
Summary II

• Flip Chip Solder Joints vs. V-groove Solder Lines:
  1. No current crowding is expected in V-groove solder lines.
  2. It is easy to observe the polarity effect at anodes and cathodes in V-groove solder lines.
  3. It is easy to get the redistribution of species at different depth after EM in V-groove solder lines.

• Eutectic SnPb Solder vs. Eutectic Pb-free Solder:
  1. Failure modes of eutectic SnPb and eutectic SnAgCu flip chip solder joints are the same.
  2. Eutectic Pb-free solders have longer lifetime.

• Cu Electrodes vs. Ni Electrodes:
  1. Both Cu and Ni dissolve into solder due to electrical force and chemical force.
  2. The reactions between Ni electrodes and Pb-free solders are slower compare with Cu electrodes.