How Interfacial Structure Can Play a Key Role in Package Reliability

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Talk Outline

• Interface formation and trade-offs for electronic packaging applications
  – Key interfacial properties
  – Reliability and failure modes
  – Properties and impact of Intermetallic Compounds (IMC)
• AuSn Die Attach
• AuSn Lead Attach
• SnAgCu Solder
• IMC Formation Dynamics
• Considerations to minimize the impact of IMC on reliability
Interface formation and trade-offs for electronic packaging applications
Interfacial Requirements: Electronic Packaging Applications

• Metal/Ceramic, Metal/Organic, Metal/Metal Adhesion
• Mechanical Stability of Interface
  – Temperature cycle (CTE stress)
  – Mechanical shock and/or vibration
  – Lead peel or die sheer
• Thermal conductivity through the interfacial structure
• Chemical stability in device working environment
Interfacial Failure Modes

Single mode failure along the metal/ceramic interface, potential for reliability issues
Causes for Single Mode Interfacial Failure

- Poor adhesion of metal to ceramic/plastic substrates
  - Contamination
  - Inappropriate material choices
- Presence of a brittle, continuous phase at the interface between the metal and ceramic/plastic
Effect of Interfacial Mechanical Properties on Adhesion and Failure Mode- Thin Films on AlN Ceramic

Harris et. al

Lead soldered to thin film layer, peel results

![Graph showing peel strength vs. atomic % aluminum (x)](image)

- Peeling strength results for Ni$_{1-x}$Al$_x$ on AlN
- Solder failure and ceramic/metal failure modes
- Peel strength values:
  - 0 to 12
  - Values at specific atomic % aluminum (x)

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What are IMCs?

- Ordered alloy phases
- Two or more metal components
- Narrow compositional range (lines on a phase diagram)
- Different atomic species occupy specific sites on the crystal lattice
# Properties of IMCs

<table>
<thead>
<tr>
<th>Property</th>
<th>Cu₆Sn₅</th>
<th>Cu₃Sn</th>
<th>Ni₃Sn₄</th>
<th>Cu</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vickers Hardness (Kg/mm²)</td>
<td>378 (+/- 55)</td>
<td>343 (+/- 47)</td>
<td>365 (+/-7)</td>
<td>50</td>
</tr>
<tr>
<td>Mechanical Character</td>
<td>Brittle</td>
<td>Brittle</td>
<td>Brittle</td>
<td>Ductile</td>
</tr>
<tr>
<td>Poisson Ratio</td>
<td>0.309</td>
<td>0.299</td>
<td>0.330</td>
<td>.34</td>
</tr>
<tr>
<td>Thermal Expansion (ppm/c)</td>
<td>16.3</td>
<td>19.0</td>
<td>13.7</td>
<td>16</td>
</tr>
<tr>
<td>Thermal Conductivity (W/m-K)</td>
<td>34.1</td>
<td>70.4</td>
<td>19.6</td>
<td>385</td>
</tr>
<tr>
<td>Resistivity (micro-ohm-cm)</td>
<td>17.5</td>
<td>8.93</td>
<td>28.5</td>
<td>1.7</td>
</tr>
<tr>
<td>Density (g/cc)</td>
<td>8.3</td>
<td>8.9</td>
<td>8.65</td>
<td>8.9</td>
</tr>
</tbody>
</table>

Difficult to form experimental samples of bulk IMC single phase material with small grain size- See Fields and Low

*From Fields and Low, NIST Metallurgical Division*
Properties of IMC - Summary

- Mechanically Brittle
- Low Thermal Conductivity (Compared to the constituent elements)
- Low Electrical Conductivity (Compared to the constituent elements)
Why do IMC’s Form at Electronic Packaging Interfaces?

<table>
<thead>
<tr>
<th>Layer</th>
<th>Typical Layer Compositions</th>
<th>Possible IMC Compositions forming between layers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bonding (to ceramic or UBM)</td>
<td>Ti, W, Cr</td>
<td>Ti2Ni, TiNi3, Ti2Pd, Ti2Pd3, TiPd5, Ti2Cu, Ti3Cu4, Ti2Cu3, TiCu4</td>
</tr>
<tr>
<td>Diffusion barrier, wetting layer</td>
<td>Ni, Pd, Cu</td>
<td></td>
</tr>
<tr>
<td>Solder or die attach</td>
<td>AuSn, AuSi, Ag-Sn-Cu</td>
<td>Ni3Sn, Ni3Sn2, Ni3Sn4, NiSi, NiSi2, Pd5Si, Pd9Si2, Pd3Si, Pd2Si, PdSi, Pd3Sn, Pd2Sn, PdSn, PdSn2, PdSn3, PdSn4</td>
</tr>
</tbody>
</table>
Summary of Discussion

• The presence of *continuous brittle layers* at an interface leads to single mode interfacial failure and reduced reliability of the interface
• IMCs are stochiometric metal compounds with narrow compositional ranges
• IMCs are mechanically brittle
• Groups of elements that are necessary to form effective interfacial structures (adhesion layers, bonding/diffusion layers, solders) also form IMCs
Case Studies

1. AuSi Die Attach
2. AuSn Die Attach
3. Sn-Ag-Cu Solder
AuSi Eutectic Die Attach

- Silicon device with Au/Si backside metal
- Metallized ceramic or metal package with Au plated layer
- Die attach at 420°C
- Eutectic is a mixture of Au and Si
- TC = 120 W/m-K
- Used in Power RF
AuSi Eutectic Die Attach: Metal Stack Up

- Silicon Die
- Au/AuSi Backside
- Au Plated Layer
- Ni Plated Layer
- Metallized ceramic

NiSi
- AuSi Eutectic
- Ni Plated Layer
- Metallized ceramic

430°C die attach process
Reaction of the Ni plated layer with silicon (from the AuSi eutectic) at the die bond temperature (420°C) resulted in the formation of a NiSi IMC along the interface. Single mode interfacial failure from environmental or mechanical stress results.
Doping Ni with Co Frustrates IMC Formation during AuSi Die Attach

Silicon Die

Au-Si eutectic

Discontinuous “blocks” of NiSi vs. a continuous layer

NiCo Plated Layer

Die shear results in fracture of the silicon die
AuSn Lead Attach- Case Study
AuSn Lead Attach

- Widely used for lead and die attach for high power silicon and GaAs
- AuSn preform reacts at 300°C
- TC = 57 W/m-K
- Eutectic is a mixture of Au$_5$Sn and AuSn
AuSn Lead Attach: Metal Stack Up

Copper Lead Frame

Nickel Plated Layer

Gold Plated Layer

AuSn Layer

Metallized Ceramic

>300°C Nitrogen/Hydrogen
AuSn Lead Attach: Temperature Shock Results

- Temperature Shock
- Brittle fracture along the interface
- Single mode failure mechanism

(Cu_{0.5}Ni_{0.5})Sn_{4} * Ternary IMC

* This AuNiSn IMC was first identified by E. Cotts
AuSn Lead Attach: \( (\text{Au}_{0.5}\text{Ni}_{0.5})\text{Sn}_4 \) IMC Induced Brittle Fracture

Copper Lead

Ni Plated Layer

AuNiSn IMC

AuNiSn on both sides of the failure surface
ID of the \((Au_{0.5}Ni_{0.5})Sn_4\) IMC
1. Shear test on a solder ball before and after an annealing cycle

![Diagram of solder ball and pad interface]

2. Measured the load-displacement curve.

Zribi et al., IEEE Electronic Components and Technology Conference, 1999

**Graphs:**
- **Anneal time = 0**
- **150 hrs at 150°C**

- **Isolated Ni₃Sn₄ at Ball/Pad Interface**
- **Failure in the solder ball**

- **Continuous layer of (Au₀.₅Ni₀.₅)Sn₄ at the Ball/Pad Interface. Brittle failure along the interface**
Mechanical Properties of (Au$_{0.5}$Ni$_{0.5}$)Sn$_4$

- Ternary substitutional IMC (Au substitutes for Ni on the Ni site) – more brittle than the binary NiSn
- Au (atomic radius 2.88Å) for Ni (1.49 Å) creates a stress in the layer which decreases ductility and conductivity

Lattice Strain = B(Xtl Structure) [((r$_{\text{solvent}}$ - r$_{\text{solute}}$)/ r$_{\text{solvent}}$)$^2$]
(Au0.5Ni0.5)Sn4 IMC morphology is controlled by interfacial kinetics (diffusion of reacting species)

- Continuity of layer and layer thickness
  - Increase with increased reflow temperature
  - Increase with increased reflow time

- Reflow Process Window Must be Established
  - High enough temperature to form joint/fillet structure
  - Short enough time to minimize IMC formation

- Doping Plated Nickel with Co slows the formation of IMCs
AuSn Lead Attach: Minimizing IMC Impact

Lowered reflow temperature (300°C) doping plated nickel with cobalt eliminated IMC formation.
Sn-Ag-Cu Solder Ball Attach
Ag-Cu-Sn Solder Ball Stack Up

SAC 305 Solder

Au

Ni

Copper Pad
Brittle Failure at Ball/Pad Interface After Shear
Ni-Cu-Sn IMC @ Back of Detached Ball
Ni-Sn IMC on Pad
Sn-Ag-Cu Solder Ball Failure

SAC 305 Solder

Ni-Cu-Sn IMC

Ni$_3$Sn$_4$ IMC
Sn-Ag-Cu Solder Ball Failure

Diffusion voids at interface

Ni-Cu-Sn ternary

Interface of Failure

Ni$_3$Sn$_4$

Nickel Plate

<table>
<thead>
<tr>
<th>Acc.V</th>
<th>Spot</th>
<th>Magn</th>
<th>Det</th>
<th>WD</th>
<th>Exp</th>
<th>Sample 1: Ball detached</th>
</tr>
</thead>
<tbody>
<tr>
<td>15.0 kV</td>
<td>3.0</td>
<td>8000x</td>
<td>BSE</td>
<td>10.0</td>
<td>0</td>
<td>2 μm</td>
</tr>
</tbody>
</table>
Sn-Ag-Cu Solder Ball Failure

• SAC 305 Ball/Pad Interface Fails by Brittle Fracture along the interface
• Two layers of IMCs are observed: Ni$_3$Sn$_4$ and Ni-Cu-Sn (most likely (Ni$_x$Cu$_{1-x}$)$_3$Sn$_4$)
• Fracture surface is between these two IMC layers
• Strategy for improving reliability: prevent/minimize the formation of the Ni-Cu-Sn phase
  – Alter metallization scheme
  – Minimize solder re-flow time
IMC Formation Dynamics - Example
(Work from CMC and from E. Cotts, SUNY Binghamton)
System for Analysis

Solder Ball (PbSn)

Plated Au

Plated Nickel

Copper
Stage 1: After Reflow (210°C)

Au layer is digested by the molten PbSn solder

- Solubility of Ni in PbSn at 210°C is very low: 10⁻⁵%
- Solubility of Au in PbSn at 210°C is 3-4%
- Ni layer adjacent to AuPbSn forms Ni₃Sn₄ IMC

Cotts et al.
Structure after Reflow

SEM Analysis (CMC)

Ni$_3$Sn$_4$ Ni Plate AuSn$_4$

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Stage 2: Aging at 150C

Au diffuses from the PbSn back to the interface- solid state diffusion

- With thermal aging, Au diffuses BACK TO THE INTERFACE
- Reacts with Ni$_3$Sn$_4$ to form (Au$_{0.5}$Ni$_{0.5}$)Sn$_4$ Ternary IMC
Aging at 150C (Cotts Results)

$(\text{Au}_{0.5}\text{Ni}_{0.5})\text{Sn}_4$

**Figure 8:** Optical micrograph (1000X). Ni-Sn intermetallic growth at the interface solder-Ni.

**Figure 12:** SEM backscattered electrons image of the showing the $(\text{Au}_{0.5}\text{Ni}_{0.5})\text{Sn}_4$ phase at the interface. ZAF analysis at two different spots are included.

<table>
<thead>
<tr>
<th>Element</th>
<th>Group 1</th>
<th>Group 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Au</td>
<td>8.6387</td>
<td>8.6722</td>
</tr>
<tr>
<td>Sn</td>
<td>83.3010</td>
<td>81.0496</td>
</tr>
<tr>
<td>Ni</td>
<td>11.1603</td>
<td>10.2796</td>
</tr>
<tr>
<td>Total</td>
<td>100.0000</td>
<td>100.0000</td>
</tr>
</tbody>
</table>
Summary of AuNiSn IMC Formation Steps

- Au layer dissolves rapidly in the solder during reflow
- A NiSn IMC forms at the solder pad interface during reflow once the Au layer is gone
- Au diffuses from the solder ball bulk back to the interface over time (accelerated by annealing at 150C)
- Au reacts with the NiSn IMC to form a ternary AuNiSn IMC
- Note that this occurs via a solid state diffusion mechanism
Groups of elements that are necessary to form effective interfacial structures in electronic packaging applications (adhesion layers, bonding/diffusion layers, solders) also form IMCs.

IMCs are mechanically brittle and can influence package metallization reliability, especially when they form a thick, continuous layer.

Ternary IMCs are more problematic than binary (typically) due to increased lattice stress.

IMC reliability issues seen for AuSi, AuSn, SAC, PbSn Systems with ceramic or organic package metallization.

Steps to minimize the extent and thickness of IMCs are key to improved package reliability.
Key Steps to Minimize the Reliability Impact of IMC Formation

- **Microstructural Characterization**: Characterize all interfaces after each processing stage to identify potential IMC issues. Special concern for ternary IMCs.
- **Failure Mechanism**: Special attention to situations with interfacial failure (even with high shear values)
- **Slow IMC Formation through Alloying**: For example, doping plated nickel with cobalt to reduce reactivity
- **Minimize Diffusion Effects**: Minimize reflow temperature and time, limit thermal exposure after reflow (know what thermal budget your system can tolerate)
- **Minimize Concentration of IMC Constituents**: For example, minimizing the Au layer thickness to reduce Au-Ni-Sn IMC Formation
- **Consider the potential effects of solid state diffusion**: Note that detrimental IMCs can form after the metal interface is formed. Consider this in FMEA and in long term testing.