Development of Thermal Interface Materials and Impact of Application Surface

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Honeywell Electronic Materials
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MEPTEC: The Heat is On
San Jose, CA
Outline

• Who is HEM

• Motivation & definitions

• Heat spreader surface finish

• TIM2 results & characterization

• TIM1 results & characterization

• Summary
Honeywell Electronic Materials (HEM)

Headquarters: Chandler, AZ

Locations: 10 in the U.S., Canada, China, Japan, Korea, Philippines, Singapore, Taiwan, Thailand, France, Germany

Employees: 1,100

Competitive Advantages
- 40+ Years of Industry Experience and Relationships
- Core Competencies:
  - Chemistry, Organic and Inorganic
  - Metallurgy
  - Packaging Material Science
  - Process Integration Capability and OEM Alliances
  - Acids, Solvents, Etchants and Cleaning Chemistries
  - Direct Global Distribution

38% Aerospace | 31% Automation & Control | 17% Transportation & Power Systems | 14% Specialty Materials
## HEM Segments and Products

<table>
<thead>
<tr>
<th>Segment</th>
<th>Products</th>
</tr>
</thead>
</table>
| Dielectrics      | • Spin-on glass (SOG)  
                  | • Bottom anti-reflective coating (BARC)  
                  | • Spin-on low-k  
                  | • Low-k enablers |
| Electronic       | • Straights etchants  
                  | Chemicals        | • High-purity solvents  
                  | • Selective etchants |
| Packaging        | • Thermal spreaders  
                  | Materials       | • Thermal Interface Materials  
                  | • Evaporative materials, preforms, & wire  
                  | • Sapphire Wafers |
| Metals           | • Al, Ti, Cu, Ta targets  
                  |                | • Thermocouples  
                  | • Coils |

*Image of products*
The Thermal Challenge

• Keep the die below 90°C
  - Heat output of >150 W
  - Hot spot >300 W/cm²
  - Heat removed via conduction
    TIM1 → Spreader → TIM2 → Heat Sink

• TIM1
  - Void free to prevent new hot spots
  - Stable to handle high temperature & thermal cycles

• Heat Spreader
  - Flat to achieve low BLT
  - Surface finish for markability

• TIM2
  - Accommodate non-uniform bond line to the heat sink

Heat Transfer Modes
- Conduction - Convection - Radiation

1.5 GHz Itanium Thermal Map
130W / 3.74 cm²
35 W/cm²

Designed Hot Spot
Heat Sink

TIM2

Spreader

TIM1

Die

\[ _{jc} = \frac{(T_{\text{junction}} - T_{\text{case}})}{\text{Die power}} \]

\[ _{cs} = \frac{(T_{\text{case}} - T_{\text{sink}})}{\text{Die power}} \]

\[ _{ca} = \frac{(T_{\text{case}} - T_{\text{ambient}})}{\text{Die power}} \]
TIM Fundamentals

- Dry, smooth surfaces
  - Only 1 - 2% solid contact area
  - 98 - 99% low conductivity gas

- With thermal interface material
  - Near zero solid contact area
  - 70 - 95% TIM contact area
    - Much higher conductivity than gas

**TIM effectively improves heat transfer performance**
Thermal Contact Resistance

Assume same material contact \((E_1, k_1)\) with TIM and \(E_{TIM} \ll E_1\)

\[
R_{c(TIM \ll 1)} = \frac{1}{1.55} \left( \frac{\sigma}{\tan \theta} \right) \cdot \left( \frac{E_{TIM} \tan \theta}{\sqrt{2P\left(1 - \nu_{TIM}^2\right)}} \right)^{0.94} \frac{1}{2} \left( \frac{1}{k_1} + \frac{1}{k_{TIM}} \right)
\]

- : rms surface roughness
\(\tan -\) : average slope of surface asperity
\(E_1, E_{TIM}\) : elastic modulus of contact pair and TIM
\(k_1, k_{TIM}\) : thermal conductivity of contact pair and TIM
\(P\) : contact pressure
\(-\) : Poisson’s ratio for compression, \(\frac{\_xx}{\left(\_xx - \_yy\right)}\)

Contact resistance is critical for heat transfer at the interface of two different materials

Thermal Impedance (Z) Measurement

Thermal Impedance (Z) is defined as the ratio of temperature difference (ΔT) to heat flux (Q).

\[ Z = \frac{\Delta T}{Q} \]

Heat flux (Q) can be calculated as follows:

\[ Q = k_{Cu} \times \text{Slope} / \text{Area} \]

where:
- \( k_{Cu} \) is the thermal conductivity of copper
- \( \text{Slope} \) is the slope in the graph
- \( \text{Area} \) is the area of the interface

Based upon ASTM Standard D5470
Everyone implements differently

Standard test for thermal pastes includes
conductivity and contact resistance

BLT

Slope

Temperature

ΔT

Q = \( k_{Cu} \times \text{Slope} / \text{Area} \)

Z = \( \Delta T / Q \)
Flatness and Roughness Definitions

- **Flatness** = distance between highest and lowest point parallel to the average line or plane
- **Rq** = root mean square roughness = standard deviation of heights
- **Ra** = average roughness = distance between average positive and average negative height

Ref: Jukka Rantala, Electronic Cooling, May 2004

Laser profilometry used to measure surface roughness
**Heat Spreader: Selected Options**

<table>
<thead>
<tr>
<th>One Piece</th>
<th>Two Piece</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="One Piece Image" /></td>
<td><img src="image2" alt="Two Piece Image" /></td>
</tr>
</tbody>
</table>

**Growing trend for thermal management outside of CPU needs**
Coined Heat Spreader

Close-up of profile (micrometer)

$\text{Cavity side}$

$100 \text{ pts/mm & 1 mm/s}$

$\text{Ra} = 0.36 \, \mu\text{m}$

$25 \, \mu\text{m}$

$8 \, \mu\text{m flatness}$
Coined & Deburred Heat Spreader

Ra = 0.53 µm

Cavity side
100 pts/mm & 1 mm/s

8 µm flatness

25 µm
Effect of Ni Plating on Heat Spreader

Plating smoothes out the irregularities

5 µm

Coined
$R_a = 0.36 \mu m$

Coined &
Deburred
$R_a = 0.54 \mu m$

Bare Cu

Ni Plated
TIM2 Materials and Testing

MATERIALS

• PCM45F
  - Pad format
  - <0.25 °C-cm²/W at 0.002” BLT

• PCM45SP
  - Screen printable format
  - <0.25 °C-cm²/W at 0.002” BLT

TESTING

• Test effects
  - Pressure
  - Block surface profile
  - Shim to control minimum BLT
TI is much lower with the domed blocks
Profile Impact on Shimmed TI Measurement

Block profile has less impact when min BLT is controlled
Cupped blocks result in a fairly thick sample. This explains the higher TI seen previously.
Profile of Ground and Plated Blocks

Surface grinding dramatically reduces cupping
Some cupping due to dog-boning during plating
Flat Block Profile Impact on TI

Flat blocks result in TI between cupped and domed blocks

Tested without the standard 0.002” shim
Flattening the chiller block dramatically reduces the thermal resistance.
TIM2 Application Surface Summary

• Surface profile impacts measured TI
  - Cupped blocks give higher value than reality
  - Domed blocks give lower value than reality

• Test pressure impacts measured TI
  - Higher pressure causes more squeeze out – thinner BLT

• Shims give the most realistic test results
  - BLT in practice is 0.001 – 0.003” due to spreader and heat sink flatness
  - Minimizes the effect of block surface profile

• Surface metal finish impacts results
  - Customer feedback
  - Al, Cu, Ni plating change the thermal resistance values
TIM1 Materials and Testing

HEM MATERIALS

• Solder
  - Preforms and wire format
  - As low as 0.025 °C-cm²/W thermal impedance

DEVELOPMENTAL MATERIALS

• TM200
  - Dispensable filled curable polymer
  - <0.15 °C-cm²/W thermal impedance

• Grease
  - Printable filled polymer
  - <0.1 °C-cm²/W thermal impedance

• PSH
  - Dispensable polymer-solder-hybrid
  - <0.075 °C-cm²/W thermal impedance

TESTING

Test effects

• Surface roughness
• Surface chemistry
What is PSH?

PSH = Polymer Solder Hybrid = smart materials
- High conductivity filler
- Low melting solder alloy
- Low modulus polymer matrix

Heat Conduction through a continuous network & lower contact resistance
Benefits of solder conductivity without the compliance issues
Machine Ground TI Block & Spreader

Machine Ground TI Block
Ni Plated 200X

Coined Spreader
Ni Plated 200X

TI blocks need to match spreader surface finish
to obtain the most useful data
Metalized Si wafer & fly cut blocks

Fly cut is similar to the etched and plated wafer
Surface condition impacts performance

Surface treatment has a large impact in TI value

Conductive phase was 80% solder & 20% Filler B
Example formulation

Surface treatment has a large impact in TI value
PSH on Ni & Au Plated Spreaders

PSH interacts quite strongly with Au plated spreader.

Ni Plated Spreader

Au Plated Spreader

PSH interacts quite strongly with Au plated spreader.
Impact of Spreader Surface Plating

Au plating of the spreader gives better performance
Effect of Ni Surface Aging

Ni surface was lapped with 6 µm diamond

Ni + Au plated block except as noted

Exposure to Air Increases the Thermal Impedance
Competitive Benchmarking

PSH is significantly better than competitive pastes

Thermal Conductivity (W/m-K)

<table>
<thead>
<tr>
<th>Product</th>
<th>Reported $^\dagger$</th>
<th>Measured*</th>
</tr>
</thead>
<tbody>
<tr>
<td>HON Devel PSH</td>
<td>6.3</td>
<td></td>
</tr>
<tr>
<td>Competitor A</td>
<td>11</td>
<td>5.5</td>
</tr>
<tr>
<td>Competitor B</td>
<td>60</td>
<td>7.8</td>
</tr>
<tr>
<td>Indium</td>
<td>84</td>
<td></td>
</tr>
</tbody>
</table>

$^\dagger$ Laser flash of bulk sample

*K = 1/slope from TI measurement vs. BLT
TIM1 Application Surface Summary

• Surface roughness is important
  - Fine, deformable particles lock into the crevices

• Surface chemistry is important
  - TIM1s are often designed to react at the interface
    - Lower contact resistance due to bonding
    - Less pump out due to bonding
  - Surface chemistry interaction specially strong for PSH type TIMs
Conclusions

• The performance of TIMs depends upon
  - Surface flatness
  - Surface roughness
  - Surface chemistry

• Lab testing conditions for designing TIMs must mimic the application to obtain useful information
  - TIM2 materials should be tested at application BLT
    - Due to both component flatness and TIM squeeze out in use
  - TIM1 materials should be tested using representative surface roughness and chemistry
    - They often rely on significant mechanical and chemical interactions to obtain their high thermal performance

Honeywell has TIM1, TIM2, and spreaders along with the testing capabilities to fulfill these requirements.