Agenda

• iNEMI Overview – Grace O’Malley, iNEMI

• Part 1: Impact of Low CTE Molding Compounds on Solder Joint Reliability – Geert Willems, imec

• Part 2: Early Fatigue Failures in Copper Wire Bonds Inside Packages with Low CTE – Bart Vandeveldende, imec

• Potential Next Steps

• Contact Details
About iNEMI


5 Key Deliverables:
- Technology Roadmaps
- Collaborative Deployment Projects
- Research Priorities Documents
- Proactive Forums
- Position Papers

3 Major Focus Areas:
- Miniaturization
- Environment
- Medical Electronics

International Electronics Manufacturing Initiative (iNEMI) is an industry-led consortium of around 107 global manufacturers, suppliers, industry associations, government agencies and universities. A Non Profit Fully Funded by Member Dues; All Funding is Returned to the Members in High Value Programs and Services; In Operation Since 1994.

Visit us at www.inemi.org
International Membership Across The Total Supply Chain

<table>
<thead>
<tr>
<th>The International Membership</th>
<th>Incorporated Location; Number of Members</th>
</tr>
</thead>
<tbody>
<tr>
<td>INEMI Member Business Type</td>
<td>North America</td>
</tr>
<tr>
<td>OEM</td>
<td>14</td>
</tr>
<tr>
<td>ODM/EMS (inc. pkg. &amp; test services)</td>
<td>5</td>
</tr>
<tr>
<td>Suppliers (materials, software, services)</td>
<td>9</td>
</tr>
<tr>
<td>Equipment</td>
<td>8</td>
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<tr>
<td>Universities &amp; Research Institutes</td>
<td>8</td>
</tr>
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<td>Organizations</td>
<td>11</td>
</tr>
<tr>
<td>Totals</td>
<td>55</td>
</tr>
</tbody>
</table>

✓ Total Global Supply Chain Integration
✓ 70% Growth in past 3 years
PART I:
IMPACT OF LOW CTE MOLDING COMPOUNDS
ON SOLDER JOINT RELIABILITY

GEERT WILLEMS
BART VANDEVELDE, STEVEN THIJS
IMEC – CENTER FOR ELECTRONICS DESIGN & MANUFACTURING
1. Towards “Green”, low CTE molding compounds

2. The impact of low CTE molding compounds
   1. Solder joint fatigue
   2. What lifetime is required?
   3. What does literature tell us?
   4. Failure experience

3. FE study of TSOP, QFN and BGA with GMC

4. Recent experimental results

5. Impact on Assembly

6. Conclusions
1. MOLDING COMPOUNDS

Plastic molding compounds are used to encapsulate the IC/leadframe or IC/substrate assembly in plastic IC packaging:

Leaded packages: SOIC, QFP, TSOP,...

Leadless packages: QFN, MLF, LPP,...

Area array packages: PBGA
Molding compound requirements:
Compatibility with silicon die & first level interconnect (wire bond, flip chip, die attach)
Thermal, mechanical, moisture robustness
Leadframe – substrate matching (warpage)
Electrical properties
Thermal conductivity
Flame retardant
Manufacturability
Cost
...
1. LOW CTE MOLDING COMPOUND

Driven by:

- Need for reduced moisture sensitivity (lead-free)
- “Going Green” trend: Halogen-free plastics
- Die stress: new IC-dielectrics
- Cost

→ Electronic component manufacturers introduced highly SiO$_2$ filled (85%) “Green mold compounds”

Example

Customer Notification
Mold Compound Change

Dear Valued Customer:

This notification is for the purpose of informing you of that our Assembly supplier is converting all mold compounds to green material sets.

Purpose
Due to their worldwide GREEN policy, transfer all devices which use non-green molding compounds to green molding compounds.

February 10, 2010

80% vol

10 μm
1. LOW CTE MOLDING COMPOUNDS

The change-over took place between 2005-2010
(from a leading semiconductor supplier)

High penetration level of highly filled GMC
All plastic components: SOIC, TSOP, QFN, BGA,...
Customer notification is MISLEADING!
2\textsuperscript{nd} level interconnect reliability has not been considered!?

\textbf{Customer Impact}

No customer impact is anticipated with this change; there is no change to form, fit, or function.
2. LOW CTE MOLD COMPOUNDS
THE IMPACT

High SiO$_2$ filling creates molding compound with very low thermal expansion: CTE=6-10 ppm.
For reference: CTE Al$_2$O$_3$ = 6.7 ppm (ex. CBGA)

In the past it matched the PCB CTE of 15-18 ppm

This creates a nearly tenfold increase in thermal mismatch between component and PCB.

Depending on component and PCB details:
A major increase of thermo-mechanical strain of solder joints and component leads (TSOP).

A major threat to solder joint and interconnect reliability
2. IMPACT OF LOW CTE MOLDING COMPOUNDS

1. Better CTE match with silicon $\rightarrow$ lower stress in Si die 😊

2. Higher CTE mismatch with BT laminate $\rightarrow$ more warpage of the package with temperature changes 😞

3. Higher CTE mismatch with PCB $\rightarrow$ higher loading of the 2$^{nd}$ level solder connections 😞
2.1. SOLDER JOINT FATIGUE

Thermally induced stress-strain

Joint strain \( \gamma \sim \frac{\Delta L}{S} \sim L(CTE_{c} - CTE_{b})\Delta T/2S \)

Thermo-mechanical strain increases with:

- increasing thermal mismatch (ceramic, bare silicon, **GREEN MOLD COMPOUND** \( \approx \) ceramic)
- increasing component size (**large BGAs**, **large dies**)
- decreasing stand-off (**small ball sizes**, **leadless packages**)!
- increasing thermal cycling (**outdoor**, **high power dissipation**)
Example: 10x10 mm² CSP soldered on FR4 PCB after 500 temperature cycles (0 to 100°C)

- Micro-crack initiation
- Crack propagation
- Fracture

SILICON: 2.6 ppm/°C

PCB: 17 ppm/°C

Corner: 500 μm
2.1 SOLDER JOINT FATIGUE
GMC VS. CERAMIC

CTE GMC (6-10 ppm) comparable to ceramic (Al₂O₃=6.7 ppm) CTE
But elasticity of GMC (E-modulus) is an order of magnitude smaller than that of ceramics → ten times more flexible.

Consequences
Package flexibility becomes a dominating factor in the solder joint reliability.
The simple Engelmaier approach to solder joint reliability of IPC-D-279, cannot be applied to plastic packages.
### 2.2. WHAT IS REQUIRED?

**SOME FIGURES FOR REFERENCE (IPC-9701)**

<table>
<thead>
<tr>
<th>Product Category (Typical Application)</th>
<th>Temperature, °C / °F(1)</th>
<th>Worst-Case Use Environment</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Storage Operation</td>
<td>Tmin(2) °C / °F</td>
</tr>
<tr>
<td>Consumer</td>
<td>-40/85 0/55</td>
<td>0/32 60/140</td>
</tr>
<tr>
<td>Computers and Peripherals</td>
<td>-40/85 0/55</td>
<td>0/32 60/140</td>
</tr>
<tr>
<td>Telecom</td>
<td>-40/85 -40/85</td>
<td>-40/40 85/185</td>
</tr>
<tr>
<td>Commercial Aircraft</td>
<td>-40/85 -40/85</td>
<td>-55/-67 95/203</td>
</tr>
<tr>
<td>Industrial and Automotive - Passenger Compartment</td>
<td>-55/150 -40/85</td>
<td>-55/-67 95/203</td>
</tr>
<tr>
<td>Military (ground and shipboard)</td>
<td>-40/85 -40/85</td>
<td>-55/-67 95/203</td>
</tr>
<tr>
<td>Space (geo)</td>
<td>-40/85 -40/85</td>
<td>-55/-67 95/203</td>
</tr>
<tr>
<td>Military Aircraft (a, b, c, d, e)</td>
<td>-55/125 -40/85</td>
<td>-55/-67 125/257</td>
</tr>
<tr>
<td>Maintenance (under hood)</td>
<td>-55/150 -40/125</td>
<td>-55/-67 125/257</td>
</tr>
</tbody>
</table>

& = in addition

1. All categories may be exposed to a process temperature range of 18°C to 260°C [64.4°F to 500°F].
2. Tmin and Tmax are the operational (test) minimum and maximum temperatures, respectively, and do not determine the maximum ΔT.
3. ΔT represents the maximum temperature swing, but does not include power dissipation effects; for power dissipation calculate ΔT; power dissipation can make pure temperature cycling accelerated testing significantly inaccurate. It should be noted that the temperature range, ΔT, is not the difference between Tmin and Tmax; ΔT is typically significantly less.
4. The dwell time, tD, is the time available for the creep of the solder joints during each temperature half-cycle.
2.2. WHAT IS REQUIRED?  
SOME FIGURES FOR REFERENCE (IPC-9701)

Computer and peripherals: $\Delta T=20K$, 4cpd, 5y, 0.1%
- N63% (0-100°C) $\rightarrow$ 1250 cycles/5y

Telecom: $\Delta T=35K$, 1cpd, 7-20y, 0.01%
- N63% (0-100°C) $\rightarrow$ $>$2000 cycles/7y...6000 cycles/20y

Industrial/automotive:
$\Delta T=20K(50%)/40K(27%)/60K(16%)/80K(6%)$, 365cpy, 10-15y, 0.1%
- N63% (0-100°C) $\rightarrow$ $>$3000 cycles/10y...4500 cycles/15y

Commercial aircraft: $\Delta T=20K$, 1cpd, 20y, 0.001%
- N63% (0-100°C) $\rightarrow$ 3500 cycles/20y

Military: $\Delta T=40K(27%)/60K(73%)$, 365cpy, 10-20y, 0.1%
- N63% (0-100°C) $\rightarrow$ 5500 cycles/10y...11000 cycles/20y

10 year lifetime requires
N63% (0-100°C) $>$ 3000 cycles (N63%-(-40-125°C)>1500 cycles)

Notes:
- Weibull slope=6
- No power cycling
- Tmax= max. operation
2.3. LITERATURE: QFN SIMULATION

- All simulations confirm reduction in lifetime with factor 1 to 4.
- Higher CTE and lower E is recommended: opposite to GMC

![Graph showing Fatigue Life vs. MC CTE](image)

T.Y. Tee et al. 2003

QFN8x8:
-40/150C
PCB: 1.6mm
2.3. LITERATURE: QFN SIMULATION

**TABLE V**

<table>
<thead>
<tr>
<th></th>
<th>Control</th>
<th>Run 1</th>
<th>Run 2</th>
<th>Run 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>CTE of Molding Compound (ppm/°C) (EMC 1)</td>
<td>8</td>
<td>13</td>
<td>8</td>
<td>13</td>
</tr>
<tr>
<td>CTE of Leadframe (ppm/°C) (Alloy-42)</td>
<td>6.4</td>
<td>6.4</td>
<td>16.7</td>
<td>22</td>
</tr>
<tr>
<td>Equivalent Creep Strain Range ($\Delta \varepsilon_{crp}$)</td>
<td>0.0300</td>
<td>0.0167</td>
<td>0.0106</td>
<td>0.00538</td>
</tr>
<tr>
<td>Fatigue Life based on $\Delta \varepsilon_{crp}$</td>
<td>468</td>
<td>1623</td>
<td>4259</td>
<td>17962</td>
</tr>
<tr>
<td>$\Delta W$ (MPa)</td>
<td>0.397</td>
<td>0.182</td>
<td>0.0836</td>
<td>0.0428</td>
</tr>
<tr>
<td>Fatigue Life based on $\Delta W$</td>
<td>529</td>
<td>1028</td>
<td>1997</td>
<td>3536</td>
</tr>
</tbody>
</table>

X. Zhang et al., 2002

Fig. 2: Schematic diagram of the cross section of a 26-pin BLP package.

2) The EMC 2 which has a high CTE content (13 ppm/°C) offers at least 1.9 fold improvement in fatigue life over the EMC 1 which has a lower CTE content (8 ppm/°C).

**TABLE VI**

<table>
<thead>
<tr>
<th>LB Land Size (mm x mm)</th>
<th>Thickness of PCB (mm)</th>
<th>Temperature Profile</th>
<th>$\Delta \varepsilon_{crp}$ (MPa)</th>
<th>N ($\Delta \varepsilon_{crp}$)</th>
<th>$\Delta W$ (MPa)</th>
<th>N ($\Delta W$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.2 x 0.6</td>
<td>0.4</td>
<td>Condition 1</td>
<td>0.021754</td>
<td>926</td>
<td>0.2539</td>
<td>774</td>
</tr>
<tr>
<td>1.2 x 0.6</td>
<td>0.4</td>
<td>Condition 2</td>
<td>0.023635</td>
<td>774</td>
<td>0.1795</td>
<td>1041</td>
</tr>
<tr>
<td>1.2 x 0.6</td>
<td>1.2</td>
<td>Condition 1</td>
<td>0.028939</td>
<td>504</td>
<td>0.0975</td>
<td>528</td>
</tr>
<tr>
<td>1.2 x 0.6</td>
<td>1.2</td>
<td>Condition 2</td>
<td>0.033911</td>
<td>360</td>
<td>0.2811</td>
<td>710</td>
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<tr>
<td>1.2 x 0.45</td>
<td>0.4</td>
<td>Condition 1</td>
<td>0.02475</td>
<td>707</td>
<td>0.311</td>
<td>651</td>
</tr>
<tr>
<td>1.2 x 0.45</td>
<td>0.4</td>
<td>Condition 2</td>
<td>0.02352</td>
<td>786</td>
<td>0.1765</td>
<td>1056</td>
</tr>
</tbody>
</table>
### 2.3. LITERATURE: BGA SIMULATION

T.Y. Tee et al. 2006

**BGA: -40/125°C**

#### Table III: Summary of C²BGA Parametric Studies

<table>
<thead>
<tr>
<th>Cases</th>
<th>Design Variations</th>
<th>Life (cycles)</th>
<th>% Diff</th>
<th>Warpage (µm)</th>
<th>% Diff</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>Control (see Table 2)</td>
<td>2238</td>
<td>-</td>
<td>27</td>
<td>-</td>
</tr>
<tr>
<td>C1</td>
<td>Die size=3x3mm</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C2</td>
<td>MC thickness=0.6mm, Die thickness=0.225mm</td>
<td>2238</td>
<td>0.00</td>
<td>26.7</td>
<td>-1.1</td>
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<tr>
<td>C3</td>
<td>Substrate thickness=0.22mm</td>
<td>2456</td>
<td>9.74</td>
<td>23.2</td>
<td>-14.1</td>
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<tr>
<td>C4</td>
<td>Solder ball diameter=0.4mm, Solder ball height=0.3mm</td>
<td>1916</td>
<td>-14.4</td>
<td>34.5</td>
<td>27.8</td>
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<tr>
<td>C5</td>
<td>Die attach B</td>
<td>1689</td>
<td>-24.5</td>
<td>39.9</td>
<td>47.8</td>
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<tr>
<td>C6</td>
<td>Die attach C</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C7</td>
<td>Mold compound D</td>
<td>2456</td>
<td>9.74</td>
<td>23.2</td>
<td>-14.1</td>
</tr>
<tr>
<td>C8</td>
<td>Mold compound C</td>
<td>1916</td>
<td>-14.4</td>
<td>34.5</td>
<td>27.8</td>
</tr>
<tr>
<td>C9</td>
<td>Mold compound B</td>
<td>1689</td>
<td>-24.5</td>
<td>39.9</td>
<td>47.8</td>
</tr>
<tr>
<td>C10</td>
<td>Slug attach B</td>
<td>2239</td>
<td>0.04</td>
<td>27</td>
<td>0.0</td>
</tr>
</tbody>
</table>

**G. Effect of Mold Compound Material**

The fatigue life ranking based on the four mold compound materials is:

MC-D > MC-A > MC-C > MC-B,

Mold compound with higher CTE (main effect) and lower modulus is preferred. The thermal cycling temperature range

**Lifetime**

**Warpage**
2.3. LITERATURE: EXPERIMENTAL QFN

BOARD LEVEL ASSEMBLY AND RELIABILITY CONSIDERATIONS FOR QFN TYPE PACKAGES

Ahmer Syed and WonJoon Kang
Amkor Technology, Inc.
1900 S. Price Road
Chandler, Arizona

QFN7x7:
-55/125C
PCB: 1.6mm

T.Y. Tee et al.
2003

QFN:
-40/125C
PCB: 1.6mm

Table 1. Mold Compound Material properties (supplier data) and BLR Result Summary

<table>
<thead>
<tr>
<th>Mold Compound</th>
<th>alpha 1 (ppm/°C)</th>
<th>alpha 2 (ppm/°C)</th>
<th>Tg (°C)</th>
<th>Modulus (kg/mm²)</th>
<th>Cycles Completed</th>
<th># of Failures</th>
<th>1st Failure</th>
<th>Mean Life</th>
</tr>
</thead>
<tbody>
<tr>
<td>EMC1</td>
<td>7</td>
<td>25</td>
<td>125</td>
<td>2650</td>
<td>1846</td>
<td>29</td>
<td>649</td>
<td>978</td>
</tr>
<tr>
<td>EMC2</td>
<td>7</td>
<td>33</td>
<td>120</td>
<td>2710</td>
<td>4100</td>
<td>29</td>
<td>2166</td>
<td>3150</td>
</tr>
<tr>
<td>EMC3</td>
<td>8</td>
<td>35</td>
<td>130</td>
<td>2650</td>
<td>5012</td>
<td>22</td>
<td>1219</td>
<td>2384</td>
</tr>
<tr>
<td>EMC4</td>
<td>9</td>
<td>35</td>
<td>150</td>
<td>2800</td>
<td>5012</td>
<td>22</td>
<td>2700</td>
<td>3622</td>
</tr>
<tr>
<td>EMC5</td>
<td>10</td>
<td>42</td>
<td>135</td>
<td>2400</td>
<td>5657</td>
<td>12</td>
<td>3747</td>
<td>5320</td>
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<td>EMC6</td>
<td>11</td>
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<td>2400</td>
<td>5012</td>
<td>12</td>
<td>3578</td>
<td>4708</td>
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<tr>
<td>EMC7</td>
<td>12</td>
<td>49</td>
<td>130</td>
<td>1900</td>
<td>5012</td>
<td>3</td>
<td>4218</td>
<td>NA</td>
</tr>
<tr>
<td>EMC8</td>
<td>14</td>
<td>43</td>
<td>185</td>
<td>1800</td>
<td>5657</td>
<td>24</td>
<td>3684</td>
<td>5090</td>
</tr>
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</table>

Comprehensive board-level solder joint reliability modeling and testing of QFN and PowerQFN packages

Tong Yan Tee a,*, Hun Shen Ng a, Daniel Yap a, Zhaowei Zhong b

Thermal cycling test results

<table>
<thead>
<tr>
<th>Case</th>
<th>Package</th>
<th>Dominant effect</th>
<th>β (slope)</th>
<th>η (cycles)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>QFN-4×4</td>
<td>Mold compound</td>
<td>3.92</td>
<td>3131</td>
</tr>
<tr>
<td>2</td>
<td>QFN-4×4</td>
<td>CTE = 10 ppm/°C</td>
<td>7.57</td>
<td>4894</td>
</tr>
<tr>
<td>3</td>
<td>QFN-4×4</td>
<td>Die thickness = 0.24 mm</td>
<td>5.40</td>
<td>4646</td>
</tr>
<tr>
<td>4</td>
<td>QFN-4×4</td>
<td>Die thickness = 0.36 mm</td>
<td>1.66</td>
<td>2743</td>
</tr>
<tr>
<td>5</td>
<td>QFN-8×8</td>
<td>75% center pad soldering</td>
<td>4.94</td>
<td>1242</td>
</tr>
<tr>
<td>6</td>
<td>QFN-8×8</td>
<td>91% center pad soldering</td>
<td>4.85</td>
<td>1426</td>
</tr>
<tr>
<td>7</td>
<td>QFN-8×8</td>
<td>Without solder fillet</td>
<td>8.09</td>
<td>631</td>
</tr>
<tr>
<td>8</td>
<td>QFN-8×8</td>
<td>With solder fillet</td>
<td>5.85</td>
<td>871</td>
</tr>
</tbody>
</table>
2.3. LITERATURE: EXPERIMENTAL BGA

![Image of a BGA component]

**Figure 9.** Fatigue life decreases higher filler content mold compound (0.85mm thick test board, −40°C to 125°C, 1 cycle/hr).

**SOLDER JOINT FATIGUE LIFE OF FINE PITCH BGAs - IMPACT OF DESIGN AND MATERIAL CHOICES**

Robert Darveau, Jim Heckman, Ahmer Syed, and Andrew Mawer (1999)

**Effect of Mold Compound Filler Content**

Shown in Figure 9 are several data sets comparing low and high filler content mold compounds. It is seen that the higher filler content mold compound can cut the fatigue life in half. The effect was less severe for packages with smaller relative die size or a larger ball count.
2.3 A VIEW FROM THE CERAMIC PACKAGING WORLD

Ceramic Packages for Large Scale Integration (LSI) Devices

Kyocera provides both ceramic and organic packages for Large Scale Integration (LSI) devices. In addition to alumina (Al2O3) ceramics, we produce aluminum nitride (AlN) with high thermal conductivity (150W/mK), as well as Low Temperature Co-Fired Ceramic (LTCC) packages with high (12.3 ppm/K) and low (3.4 ppm/K) coefficients of thermal expansion.

Flip Chip HITCE LTCC BGA Package

Organic Packages (KYOCERA SLC Technologies)

High Second Level Reliability

Kyocera’s HITCE LTCC material offers a coefficient of thermal expansion (CTE) close to that of printed boards, providing high reliability in board assembly.

- CTE: 12.3 ppm/K (R.T. to 400°C)
- Young’s Modulus of Elasticity: 74GPa

Second Level Reliability Test Samples
Ceramic Package
Configuration: BGA (1.27mm pitch)
Materials: Alumina (Al2O3), HITCE LTCC
Outer Dimension: 33mm x 33mm
Thickness: 1.2mm and 1.8mm
Motherboard
Material: FR-4 (CTE: 15ppm/K)
Outer Dimension: 65mm x 65mm
Thickness: 1.6mm

Reference Data

<table>
<thead>
<tr>
<th>Temperature Cycles (-40°C to +125°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al2O3</td>
</tr>
<tr>
<td>HITCE</td>
</tr>
<tr>
<td>7 ppm</td>
</tr>
<tr>
<td>12 ppm</td>
</tr>
</tbody>
</table>
2.4. FAILURE RESULTS (I)

Two reoccurring issues have been identified.

<table>
<thead>
<tr>
<th>Product</th>
<th>Time to FAILURE (hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A</td>
</tr>
<tr>
<td>BGA solder crack</td>
<td>2789 (=349c)</td>
</tr>
<tr>
<td>TSOP solder crack</td>
<td>4364 (=546c)</td>
</tr>
</tbody>
</table>
2.4. FAILURE RESULTS (2)

Solder joint failure: BGA and TSOP II

Lead failure!
TSOP I – Cu leadframe
3. FE STUDIES


- **TSOP**
  - SnPb

- **QFN**
  - SAC (0.5 mm pitch)

- **PBGA**
  - 1.27 mm pitch

- **FBGA**
  - 0.8 mm pitch

- **C2BGA**
  - 0.5 mm pitch
3. TSOP I WITH GMC

Plastic deformation in Cu leads
3. TSOP II WITH GMC

- $T_{\text{min}}$
- $T_{\text{max}}$

Creep strain (-)
3. TSOP PACKAGES – COPPER LEADFRAME

![Graph showing plastic strain per cycle vs. CTE overmould for SnPb Solder joint and Cu lead.]

- **SnPb Solder joint**
- **Cu lead**

**Graph Details:**
- **X-axis:** CTE overmould (ppm/°C)
- **Y-axis:** Plastic strain per cycle (%)
3. TSOP PACKAGES – ALLOY42 LEADFRAME

Plastic strain per cycle (%) vs CTE overmould (ppm/°C)

- TSOPII
- TSOPI

SnPb Solder joint

Alloy42 lead
3. QFN 7MM X 7MM

Literature data shows 81% reduction

Table 1. Mold Compound Material properties (supplier data) and BLR Result Summary

<table>
<thead>
<tr>
<th>Mold Compound</th>
<th>alpha 1 (ppm/°C)</th>
<th>alpha 2 (ppm/°C)</th>
<th>Tg (°C)</th>
<th>Modulus (kg/mm²)</th>
<th>Cycles Completed</th>
<th># of Failures</th>
<th>1st Failure</th>
<th>Mean Life</th>
</tr>
</thead>
<tbody>
<tr>
<td>EMC1</td>
<td>7</td>
<td>25</td>
<td>125</td>
<td>2650</td>
<td>1648</td>
<td>29</td>
<td>840</td>
<td>978</td>
</tr>
<tr>
<td>EMC2</td>
<td>7</td>
<td>33</td>
<td>120</td>
<td>2710</td>
<td>4100</td>
<td>29</td>
<td>2190</td>
<td>3150</td>
</tr>
<tr>
<td>EMC3</td>
<td>8</td>
<td>35</td>
<td>130</td>
<td>2650</td>
<td>5012</td>
<td>22</td>
<td>1219</td>
<td>2384</td>
</tr>
<tr>
<td>EMC4</td>
<td>9</td>
<td>35</td>
<td>150</td>
<td>2800</td>
<td>5012</td>
<td>22</td>
<td>2700</td>
<td>3822</td>
</tr>
<tr>
<td>EMC5</td>
<td>10</td>
<td>42</td>
<td>135</td>
<td>2400</td>
<td>5657</td>
<td>12</td>
<td>3747</td>
<td>5320</td>
</tr>
<tr>
<td>EMC6</td>
<td>11</td>
<td>45</td>
<td>135</td>
<td>2400</td>
<td>5657</td>
<td>12</td>
<td>3578</td>
<td>4708</td>
</tr>
<tr>
<td>EMC7</td>
<td>12</td>
<td>48</td>
<td>150</td>
<td>5600</td>
<td>5657</td>
<td>12</td>
<td>2700</td>
<td>3822</td>
</tr>
<tr>
<td>EMC8</td>
<td>14</td>
<td>43</td>
<td>155</td>
<td>1830</td>
<td>5657</td>
<td>24</td>
<td>3916</td>
<td>4708</td>
</tr>
</tbody>
</table>

CTE overmould (ppm/°C)

Temperature cycles: -40 to 125°C; 2.4 mm PCB

85% reduction!
3. PBGA (~ 27x27 FULL AREA ARRAY)

pitch = 1.27 mm

pitch = 0.8 mm

pitch = 0.5 mm

75% reduction!  80% reduction!  85% reduction!

0 to 100°C cycling; 2.4 mm PCB thickness
3. PBGA: IMPACT OF BOARD THICKNESS

PBGA 27x27 area array
1.27mm pitch

MTTF (cycles)

<table>
<thead>
<tr>
<th>CTE (ppm/°C)</th>
<th>0.8 mm</th>
<th>1.6 mm</th>
<th>2.4 mm</th>
<th>No PCB flexing</th>
</tr>
</thead>
<tbody>
<tr>
<td>GMC 5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GMC 10</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GMC 15</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GMC 20</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

SAC Solder

0 to 100°C cycling
3.0.5MM PARTIALLY POPULATED PBGA

FR4 board: 2.1 mm, CTE=17.6 ppm/K

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ball size</td>
<td>0.3 mm</td>
</tr>
<tr>
<td>Ball pitch</td>
<td>0.5 mm</td>
</tr>
<tr>
<td>Size</td>
<td>13x13 mm²</td>
</tr>
<tr>
<td>Array size</td>
<td>24x24 (4 rows – 320 balls)</td>
</tr>
<tr>
<td>Overmould CTE</td>
<td>8 ppm/°C</td>
</tr>
</tbody>
</table>

Ramp-time: 15 min
Dwell-time: 45 min
3.0.5MM PARTIALLY POPULATED PBGA

Impact GMC

- 2x increase
- -1.3x

MTTF [x1000 cycles]

Overmould CTE [ppm/°C]

MTTF [x1000 cycles]

Board thickness [mm]

Cumulative Distribution Function

Cycles to failure

- SAC
- Non-Green MC
- SAC
- SAC

Divided by 4!

60°C cycle
3. SNPB VERSUS SAC SOLDER

Why is SnPb version worse than SAC?

1. Under low stress conditions, lifetime of SAC is higher than that of SnPb.

2. Strain itself depends on the solder alloy. SAC is stronger than SnPb. Therefore SAC solder joints of flexible components on flexible PCBs will deform less than SnPb solder joints under the same conditions of thermal cycling.
3.0.5MM PBGA: SAC SOLDER BALLS

Stronger connections: more bending of both board and package. Less strain/deformation of solder balls.

<table>
<thead>
<tr>
<th>Materials</th>
<th>Yield Strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAC</td>
<td>25°C: 31.8</td>
</tr>
<tr>
<td></td>
<td>75°C: 21</td>
</tr>
<tr>
<td></td>
<td>125°C: 13.6</td>
</tr>
<tr>
<td>SnPb</td>
<td>0°C: 21.1</td>
</tr>
<tr>
<td></td>
<td>50°C: 13.8</td>
</tr>
<tr>
<td></td>
<td>100°C: 6.1</td>
</tr>
</tbody>
</table>

0.33%
3. 0.5MM PBGA: SNPB SOLDER BALLS

Weaker connections: limited board bending because solder balls plastically deform (more solder joint deformation)
Why is SnPb version worse than SAC?

1. Under low stress conditions, lifetime of SAC is higher than that of SnPb.

2. Strain itself depends on the solder alloy. SAC is stronger than SnPb. Therefore SAC solder joints of flexible components on flexible PCBs will deform less than SnPb solder joints under the same conditions of thermal cycling.
No PCB bending yields even more strain

SnPb – 3.28%
No bending

SnPb – 1.37%
bending

Divided by 6

212 cycles

1231 cycles
3.0.5MM PBGA: NO PCB BENDING

Board bending allowed

- No board bending allowed
- PCB stiffeners on backside
- Components on backside
- BGA back-to-back mounting
- PCB mounting on backplate/casing
3. 0.5MM VS. 0.8MM PITCH PBGA

Partly populated area array
0.5mm pitch
Ball size 0.3mm

Fully populated area array
0.8mm pitch
Ball size 0.5mm
3.0.5MM VS. 0.8MM PITCH PBGA

Changing package type can improve lifetime up to 4x

MTTF [x1000]

- **SnPb** - No board bending
- **SAC** - Board bending allowed

<table>
<thead>
<tr>
<th>Package Type</th>
<th>0.5mm pitch</th>
<th>0.8mm pitch</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 perimeter rows</td>
<td>613</td>
<td>1970</td>
</tr>
<tr>
<td>Dummy balls</td>
<td>7470</td>
<td>28000</td>
</tr>
<tr>
<td>MTTF [x1000]</td>
<td>900</td>
<td></td>
</tr>
</tbody>
</table>
4. RECENT EXPERIMENTAL RESULTS
GREEN MOLD COMPOUND TEST VEHICLE BGA228

Small pitch BGA:
- 0.5 mm pitch, 12 mm x 12 mm, 228 pins.
- 4 types:
  - Pb en Pb-free versions (SAC305, SAC105).
  - Old (non-green) components: SnPb.
- 36 components on each board, all placed on the same side.
PCB: 2.4mm – 8-layer Cu
Temperature cycling:
- 0°C- 100°C.
- 10°C/min ramp rate
- 20 minutes soak time.
- Cycle time = 1 h.

4. RECENT EXPERIMENTAL RESULTS
GREEN MOLD COMPOUND TEST VEHICLE BGA228
4. RECENT EXPERIMENTAL RESULTS
GREEN MOLD COMPOUND TEST VEHICLE BGA228

RESULTS

Temperature cycling:
• 0°C - 100°C.
• 10°C/min ramp rate.
• 20 minutes soak time.
• Cycle time = 1 h.

GMC
1200-1500

Non GMC
>3000

| GMC | 1272 6.202 63.72 36/0 |
| GMC | 1534 9.829 16.94 35/0 |
| GMC | 1175 5.136 3.99 35/0  |
| GMC | 1302 3.215 79.6 34/0  |
| GMC | 3089 7.849 78.36 36/15|

Temperature cycles to failure ([0-100°C])
5. IMPACT ON ASSEMBLY: HEAD-IN-PILLOW

What:

Head-in-Pillow BGA Defects
Karl Seelig
AIM
Cranston, Rhode Island, USA

Head-in-pillow (HiP), also known as ball-and-socket, is a solder joint defect where the solder paste deposit wets the pad, but does not fully wet the ball. This results in a solder joint with enough of a connection to have electrical integrity, but lacking sufficient mechanical strength. Due to the lack of solder joint strength, these components may fail with very little mechanical or thermal stress. This potentially costly defect is not usually detected in functional testing, and only shows up as a failure in the field after the assembly has been exposed to some physical or thermal stress.

Head-in-pillow defects have become more prevalent since BGA components have been converted to lead-free alloys. The defect can possibly be attributed to chain reaction of

Associated to lead-free soldering?

But:

▸ Seems to become more and more prevalent 1-2 years after 1/7/2006
▸ Occurs also with SnPb soldering.
▸ HiP unheard of in SnPb soldering prior to 2008?!

References:
9. IEC 601191-6-19 (draft), “Measurement methods of package warpage at elevated temperature and the maximum permissible warpage"
Major root cause of Head-in-Pillow is component warpage.
More warpage when temperature is higher → lead-free
But:
▸ Is also reported for SnPb soldering of BGA
▸ Became an issue after the introduction of lead-free soldering.
Lower mold compound CTE will increase/alter the warpage behaviour of PBGA.
Look at the GMC introduction
Conclusion seems to be:
GMC most likely root cause of “HiP-epidemic”.
6. CONCLUSIONS

Green molding compounds with CTE in the range 6-10ppm increase the thermal mismatch between “plastic” packages and the PCB upto tenfold (1 → 10ppm).

This creates major issues:

- Reduction in lifetime (1/1...1/4...) below acceptable level due to solder joint failure of “plastic” packages especially TSOP, BGA, QFN
- Reduction in lifetime below acceptable level due to Cu lead failure of TSOP type 1 components.
- Assembly: Yield reduction due to Head-in-Pillow of BGA solder joints.
- Increased risk of “Early Failure” due to electrically undetected HiP BGA solder joints.
- Very limited (and costly) workarounds: underfill (?)
6. CONCLUSIONS

GMC are a far greater threat to reliability than the transition to lead-free solder ever was:

▸ Reduction of lifetime: factor 1 to 10 instead of tens of %.
▸ High reliability SnPb soldered products are most affected!
▸ Introduction “below the radar”.

To make reliable electronics on PCB we need plastic packages with mold compounds having a CTE>12ppm.
END of PART I
Thank you

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www.edmp.be
PART 2:
EARLY FATIGUE FAILURES IN COPPER WIRE BONDS INSIDE PACKAGES WITH LOW CTE

BART VANDEVELDE, GEERT WILLEMS
IMEC – CENTER FOR ELECTRONICS DESIGN & MANUFACTURING
TWO MAJOR TRENDS IN IC PACKAGING

Trend 1
Conventional high-CTE mold compounds

2005

Trend 2
Gold wire bonds

2010

Green low-CTE mold compounds

Copper wire bonds
TREND 2: SWITCH FROM AU TO CU WIRE BOND MATERIAL

Drivers:

- Cost
- Increased electrical performance (lower electric resistivity): higher currents are possible
- Higher thermal conductivity: higher capability to pull heat away from the die, leading to better performance at elevated temperatures and greater reliability
- Copper wire can be bonded on die pads plated with thick copper and nickel palladium finish: stable metal joint at high temperatures
TREND 2: SWITCH FROM AU TO CU WIRE BOND MATERIAL

Concerns:

- higher stiffness of copper leads to higher bond forces on the bond pads requiring a stronger design of the bond pad protecting the underlying circuitry

- NEW:
  potential wire bond fatigue in combination with low-CTE overmold compounds
Moving the CTE mismatch from 0 to 10 ppm/°C difference

CTE mismatch of about 10 ppm/°C
EXPERIMENTAL FINDINGS: FAILURE ANALYSIS AFTER QUALIFICATION TESTS

- Wire bond failures have been seen after temperature cycling tests.
- Failures are under 45°, indicating copper wire got vertical stretching and compression (highest shear stress along 45° plane).
- Low number of cycles to failure (< 10000) indicates that repeated plastic deformation occurred in the wire.

This problem was never seen with Au wires nor with Cu wires in combination with conventional mold compounds.
# PROPERTIES FOR OVERMOLD MATERIALS

<table>
<thead>
<tr>
<th>Property</th>
<th>Conventional Mold</th>
<th>Green Mold</th>
<th>Green over Conventional</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young’s modulus</td>
<td>17000 MPa</td>
<td>28000 MPa</td>
<td>65% higher</td>
</tr>
<tr>
<td>CTE</td>
<td>13 ppm/°C</td>
<td>7 ppm/°C</td>
<td>45% lower</td>
</tr>
<tr>
<td>Glass Transition Point</td>
<td>150°C</td>
<td>130°C</td>
<td>15% lower</td>
</tr>
</tbody>
</table>

Data extracted from datasheets of two particular materials
### Properties for Wire Bond Materials

<table>
<thead>
<tr>
<th>Property</th>
<th>Gold wire</th>
<th>Copper wire</th>
<th>Cu over Au</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young’s modulus</td>
<td>79000 MPa</td>
<td>123000 MPa</td>
<td><strong>55% higher</strong></td>
</tr>
<tr>
<td>CTE</td>
<td>14.2 ppm/°C</td>
<td>16.5 ppm/°C</td>
<td><strong>16% higher</strong></td>
</tr>
<tr>
<td>Yield stress</td>
<td>~ 200 MPa</td>
<td>~ 160 MPa</td>
<td><strong>20% lower</strong></td>
</tr>
<tr>
<td>Electrical Resistivity</td>
<td>2.2 10^-8 Ω m</td>
<td>1.7 10^-8 Ω m</td>
<td><strong>23% lower</strong></td>
</tr>
</tbody>
</table>

*Reference: Heraeus website*
SIMULATING THE MATERIAL CHANGE IMPACT USING A FINITE ELEMENT MODEL

3D slice model

Applied load: cycling between -40°C and +150°C
RESULTS

<table>
<thead>
<tr>
<th></th>
<th>Conventional (high CTE) overmold</th>
<th>Green (low CTE) overmold</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>13 ppm/°C</td>
<td>7 ppm/°C</td>
</tr>
<tr>
<td>Au wire</td>
<td>No plastic deformation</td>
<td>No plastic deformation</td>
</tr>
<tr>
<td>(14.2 ppm/°C)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cu wire</td>
<td>No plastic deformation</td>
<td></td>
</tr>
<tr>
<td>(16.5 ppm/°C)</td>
<td></td>
<td>$\Delta \varepsilon_{pl} = 0.37%$</td>
</tr>
</tbody>
</table>

- Only plastic deformation seen for the combination GMC & Cu wire
- Good agreement between maximum strain point in FEM and the failure mode seen in SEM
## PREDICTION OF LIFE TIME?

<table>
<thead>
<tr>
<th></th>
<th>Conventional (high CTE) overmold</th>
<th>Green (low CTE) overmold</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>13 ppm/°C</td>
<td>7 ppm/°C</td>
</tr>
<tr>
<td><strong>Au wire</strong></td>
<td>No plastic deformation</td>
<td>No plastic deformation</td>
</tr>
<tr>
<td>(14.2 ppm/°C)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Cu wire</strong></td>
<td>No plastic deformation</td>
<td>Δε_{pl} = 0.37%</td>
</tr>
<tr>
<td>(16.5 ppm/°C)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

High cycle fatigue (> 10000 cycles)

Prediction based on fatigue model for PTH: 0.37%

→ ~ 1500 cycles to failure

*Same order of magnitude as seen in experiments*
FEM BASED PARAMETER STUDY: WHAT IS THE MINIMUM OVERMOLD CTE REQUIRED TO AVOID WIRE BOND FAILURE?

Parameter study: overmold CTE from 7 to 16 ppm/°C

<table>
<thead>
<tr>
<th>Overmold</th>
<th>CTE (ppm/°C)</th>
<th>E-modulus (MPa)</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>OM1</td>
<td>7</td>
<td>30000</td>
<td>Green MC</td>
</tr>
<tr>
<td>OM2</td>
<td>8</td>
<td>26500</td>
<td></td>
</tr>
<tr>
<td>OM3</td>
<td>10</td>
<td>24000</td>
<td></td>
</tr>
<tr>
<td>OM4</td>
<td>12</td>
<td>21000</td>
<td></td>
</tr>
<tr>
<td>OM5</td>
<td>14</td>
<td>18500</td>
<td></td>
</tr>
<tr>
<td>OM6</td>
<td>16</td>
<td>15000</td>
<td>Conventional MC</td>
</tr>
</tbody>
</table>

Green MC: low CTE, high E-modulus
RESULTS OF FEM BASED PARAMETER STUDY

- Below 12 ppm/°C, plastic deformation is seen in copper wire, not in Au wire
- The plastic deformation is linear to the CTE difference with Cu, indicating that CTE-difference is the driving force.
- For 16 ppm/°C overmold, the CTE mismatch above glass transition point causes higher stress

![Graph showing Delta plastic deformation per temperature cycle (%) versus Overmold CTE (ppm/°C). The graph compares Au wire and Cu wire.]
TRANSLATING THE PLASTIC STRAIN INTO LIFE TIME PREDICTION

Delta plastic deformation per temperature cycle (%)

Overmold CTE (ppm/°C)

MTTF (cycles)

Overmold CTE (ppm/°C)
### Minimum CTE of Overmold

<table>
<thead>
<tr>
<th>Minimum life time</th>
<th>Minimum CTE</th>
</tr>
</thead>
<tbody>
<tr>
<td>N &gt; 10000 cycles</td>
<td>CTE &gt; 10 ppm/°C</td>
</tr>
<tr>
<td>N &gt; 5000 cycles</td>
<td>CTE &gt; 9 ppm/°C</td>
</tr>
<tr>
<td>N &gt; 2500 cycles</td>
<td>CTE &gt; 8 ppm/°C</td>
</tr>
</tbody>
</table>

**Important remark:**
These results also depend on wire bond shape, wire coating and package construction.
CONCLUSIONS

Large CTE mismatch between Cu wire and low-CTE overmold leads to mechanical fatigue in Cu wire

Could the combination of low-CTE overmolds be a showstopper for copper wire bonds?

▸ Yes for extreme conditions and long life time requirements

Guidelines to avoid this failure:

▸ Select a molding compound with a bit higher CTE than 7 ppm/°C which reduces the CTE mismatch avoiding plastic deformation in the wire (minimum CTE depends on TC conditions, life time, package design)

▸ Improved shape of the wire can also help to minimise the stress impact
IMEC’S INTEREST

- Experimental work confirming the solder joint and copper wire bond reliability predictions.
- Experimentally determined life time numbers with sufficient details on geometry and used materials to support predictability of FEM and ongoing analytical modeling work.
- Reliable electronics needs mold compounds with a CTE>12ppm. A requirement that must come from telecom, automotive, avionics, industrial equipment and other high reliability product OEM. Imec can and is willing to provide scientific support.
Thank you!
Questions?

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www.edmp.be
Summary

Is this an opportunity for collaboration?

• iNEMI initiative survey in Q4 confirmed industry interest in the area of GMC and copper wire bonding

• Imec has interest in pursuing experimental work to confirm solderjoint and/or copper wire bonding reliability.

• iNEMI already has ongoing project on copper wire bonding reliability:
  http://www.inemi.org/project-page/copper-wire-bonding-reliability
The iNEMI Project Process - 5 Steps

1. SELECTION ✔️
2. DEFINITION ✔️ Open for Industry input
3. PLANNING
   iNEMI Technical Committee (TC) Approval Required for Execution
4. EXECUTION / REVIEW
5. CLOSURE Limited to Committed Members

Goal is to submit Statement of Work (SOW) To Technical Committee (TC) in June
Summary

Next steps

• iNEMI to contact webinar attendees and others to confirm interest (Feb )

• Form initiative teams in March – iNEMI membership not necessary for initiative phase

• Develop Statement Of Work (SOW) by June 30

• Call for participation in Project (July & August)

• Project start in September

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