Rapid Assessment of Power Module Reliability using Transient Thermal Analysis

Professor Mark Johnson

Pearl Agyakwa, Martin Corfield, Jingru Dai, Amir Eleffendi, Paul Evans, Jianfeng Li, Yun Wang, Li Yang
- Introduction to reliability
- Rapid assessment of degradation
- Transient thermal analysis
- Correlation with non-destructive characterisation
- Conclusions
Reliability

- **Region I infant mortality:**
  - Failure due to manufacturing faults etc.
  - No meaningful lifetime prediction

- **Region II constant failure rate:**
  - Mean Time Between Failure (MTBF) = total service time/number of failures
  - No meaningful lifetime prediction

- **Region III progressive wear-out**
  - Depends on in-service use
  - Mean Time To Failure (MTTF)

**Lifetime prediction possible**
Physics-of-Failure (PoF)

- Combined modelling and accelerated life testing
- Identify root cause (physics) of life-limiting degradation and failure mechanisms
- Develop predictive models for key degradation mechanisms
- Apply validated models to
  - Assess design options
  - Design improved accelerated tests
  - Prognostics and health management
Experimental Approach

1. Accelerated life tests through passive & power cycling, vibration, humidity etc.
2. Parallel studies of diffusion phenomena
3. Fine-scale microstructural characterisation
4. Formulation of empirical relationships & validation

Observations

- Failure mechanisms and models need to be valid for both accelerated test and in-service conditions
- Acceleration of desired mechanism may be masked by other failure mechanisms
- Destructive characterisation (e.g. shear test/cross-sectioning) prevents same sample analysis and cannot be done in real time
- Many samples required to build accurate picture of spread and uncertainty
<table>
<thead>
<tr>
<th>Interconnect type</th>
<th>Wear-out mechanism</th>
<th>Damage processes</th>
<th>Indicators</th>
</tr>
</thead>
<tbody>
<tr>
<td>SnAg/SAC solder</td>
<td>Cracking &amp; delamination</td>
<td>Creep &amp; TMF IMC growth/thickening alter bulk mechanical properties; Large IMCs help cracks to propagate; Creep voids speed up TMF</td>
<td>Increased $R_{th}$ Crack propagation observed by SAM, X-ray CT Reduced shear strength Microstructural changes</td>
</tr>
<tr>
<td>Wire bonds Al-Al</td>
<td>Wire-bond lift-off, loop cracks</td>
<td>Thermomechanical stresses due to CTE mismatch leading to cracking at interface, heel and loop, residual surface oxide, IMC growth, creep, electromigration</td>
<td>Increased $V_f$ Crack propagation observed by SAM, X-ray CT Reduced shear strength Microstructural changes</td>
</tr>
</tbody>
</table>
● Power cycling e.g. using Mentor Graphics Power Tester 1500A
  • Constant current and constant (peak) temperature control strategies
  • In-situ voltage and temperature measurement
  • In-situ transient thermal analysis
● Non-destructive characterisation
  • Periodic assessment using X-ray computed tomography or Scanning Acoustic Microscopy
  • Provides validation of and correlation with Rth, Von measurement
● Post-test microstructural evaluation
Thermal resistance of interface between module and tester cold-plate modified to alter relative temperature swing in different layers

- Higher interface thermal resistance emphasises swing close to base-plate
- Lower interface thermal resistance emphasises swing close to die

Control strategy alters behaviour under degradation

- Junction temperature control leads to reduced heating power as degradation progresses (increased $R_{th}$, $V_{on}$)
- Current control leads to increased temperature swing (increased $R_{th}$) and/or heating power (increased $V_{on}$)
- Module mounted on water-cooled heatsink with a 25 μm Kapton film to achieve ΔT≈70°C at the substrate (measured by integrated NTC)
- Current and junction temperature control strategies
- Transient thermal impedance measured every 1000 cycles
- Power cycling test was interrupted regularly and modules were removed for Scanning Acoustic Microscopy (SAM)
Comparison of Control Methods

**Max Tj**

- Constant $\Delta T$
- Constant current

**Vce**

- Failure mode
- Solder fatigue
- Wire bond lift-off + solder fatigue

Graphs showing the relationship between number of cycles and temperature.
Constant Current Control

- After 12,500 cycles, wire bond foot imprints in the two IGBTs on the middle substrate became less distinct indicating the start of wire bond lift-off.
- After 21,000 cycles significant degradation of the solder layer between substrate and base-plate.
Constant Tj Control

- Increased delaminated area with increased number of power cycles
- Delamination initiates at edge of substrate and propagates towards the centre
Cumulative structure function

- Plot of cumulative thermal capacitance vs. cumulative thermal resistance

0-6,000 cycles: no obvious changes observed below $R_{th}=0.06$ (K/W) indicating no significant extent of degradation in the heat flow path from chip to the baseplate
Cumulative Structure Function

7000-17000 cycles

- Signs of degradation in the heat flow path with a maximum $R_{th}$ variation of 47.8%
- Changes indicative of increasing thermal resistance: curves shifted to the right as the test proceeded
- Junction-to-case thermal resistance $R_{thjc}$ can be measured from the structure function between the case layer and the Kapton film layer.
- Correlated with attached area from SAM images.
- Increase in $R_{thjc}$ is presumed to be related to solder fatigue.
- Plot of $K$ vs. cumulative $R_{th}$: $K_\Sigma = \frac{dC_\Sigma}{dR_\Sigma} = \lambda cA^2$
- Each peak represents a specific material in the thermal stack
- Value of $K$ is proportional to the squared cross-sectional area
- No sign of degradation in module thermal path before 6000 cycles
- From 7000-15000 cycles amplitudes of some peaks decline and shift.
- The decreased amplitude in Peak 2 and Peak 3 indicates a reduced effective thermal cross-sectional area within the substrate solder and base-plate.
- Horizontal shift of Peak 3 reveals an increase in the thermal impedance of the solder layer.
The $K$-value determined from transient thermal impedance measurements agrees well with the attached area, as determined by scanning acoustic microscopy.

Differential structure function and $K$-value can be used to quantify the level of degradation in different layers of the thermal path.
Confirmation of Degradation Mechanism

- Metallurgical cross-sectioning confirmed that cracking took place at the substrate-base-plate interface
- Cracks occurred in the substrate-to-baseplate solder layer from the edge, emanating at the interface between the solder and the bottom Cu DBC layer
- DBC itself survived without any delamination
- No obvious voids or edge cracks were observed in the die attach layer
Conclusions

● Reliability studies essential to many power electronic components and systems

● Detailed understanding of wear-out mechanisms needed to:
   Develop models for design and prognosis
   Understand impact of manufacturing processes & materials
   Quantify variability

● Rapid assessment of degradation under thermal cycling enabled by power cycling coupled with on-line measurement of key degradation indicators

● Selection of dominant degradation mechanism:
   Modification of base-plate to cold-plate thermal resistance
   Change of control strategy

● Transient thermal impedance analysis provides a means for rapid quantitative assessment of thermal path degradation
   Correlated with detailed characterisation using non-destructive techniques e.g. SAM X-ray CT