Reliability of Power Modules Using Sherlock

DfR Webinar
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DfR Solutions, LLC
Agenda

- Introduction
- Power PCB Applications
- Common Issues
- Lifetime Expectations
- Failure Mechanisms
- Virtual Qualification Approach
- Sherlock Solution
Power Modules Are Used in Several Market Segments

- **Automotive Power Modules**
- **Voltage Power Modules**
- **Switching Power Supply**
- **Solar Power Modules**
- **200W Power Amp**
- **Thermoelectric Modules**
- **IGBT**
What Do They All have in Common?

- High Temperature Environments
- Possible Vibration and Shock Environments
- Temperature and Power Cycling Environments
- Very High Current Flows and Thermal Transfer Requirements
- A variety of materials forming the product
  - Substrate tiles bonded to copper baseplate
Example Life Expectancies

- IGBT – Rail application – 30 years (Each module 100FIT)
- Power Module – Automotive Application – 20 years
  - 10W/cm²
  - DBC Substrate bonded to heatsink
  - Vibration, shock, humidity, salt spray
  - Cost
- Solar Power Inverters-25 years
Semicron Thermal Module

- Vent
- Screw #4-25 1/2" Self tapping Hi-Low type
- Fan Head Phillips
- Screw M6 x 20 DIN 912
- Washer M6.4 DIN 433 Tim
- Cover assembly
- Thermal pad
- Connector
- Driver/controller pcb
- Screw EJOT PTF40x14
- Screw M6 x 25 DIN 7984
- Washer M6.4 DIN 433 Tim
- Pressure plate
- Pressure pad
- Spring contact
- Bridge element
- DC link assembly
- AC link assembly
- DBC assembly
- EMI filter pcb
- Oring
- Metall brushing
- Housing assembly
- Heat sink assembly
Failure Mechanisms

- Thermo-mechanical fatigue induced failures
  - CTE mismatch
  - Temperature swings
- Bond Wire Fatigue
  - Shear Stresses between bond pad and wire
  - Repeated flexure of the wire
  - Lift off (fast temperature cycling effect)
  - Heel Cracking
- Die Attach Fatigue
- Solder Fatigue
  - Voids
- Device Burn Out
- Automotive - degradation of power
  - Solder Fatigue
  - Bond wire failure (lift off due to fast temperature cycling)
- Structural Integrity – ceramic substrate to heat sink in thermal cycling
- IGBTs – solder joint fatigue, wirebond liftoff, substrate fracture, conductor delamination
Bond Wire Fatigue Due to Thermal Effects

Automotive Power Electronics, September 2007
Example of Substrate Delamination

- After 100 cycles of -55 to 200°C – DBC Delamination
- By 1000 cycles there were cracks in AlN substrate and extensive solder joint failures

Failure Modes - Solder and Silicon Cracking

Cracks between DBC Substrate and also between silicon die and bond wire

Mitsubishi, “Power Module Reliability”
Examples of wire bond fatigue cracking and also wire bond lift off
The stress conditions in the chart are for a railroad braking application.

<table>
<thead>
<tr>
<th>Stress condition</th>
<th>Temperature range</th>
<th>Cycles over 30yr life</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overnight shed stop</td>
<td>-40°C to operating temp.</td>
<td>Worst case 10,000</td>
</tr>
<tr>
<td>Station stop</td>
<td>Heat-sink to operating temp.</td>
<td>~3.5E5</td>
</tr>
<tr>
<td>Traction/braking</td>
<td>Experimentally measured at 30°C</td>
<td>~3.4E7</td>
</tr>
<tr>
<td>Power cycling</td>
<td>&lt; 1°C</td>
<td>~7E11</td>
</tr>
</tbody>
</table>
Typically, extensive qualification testing is performed to ascertain the reliability of the power module as shown.

<table>
<thead>
<tr>
<th>Qualification Test</th>
<th>Test Method</th>
<th>Test Conditions</th>
<th>Qualification Standard</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passive Cycling</td>
<td>CENELEC</td>
<td>ΔT case = 80°C, T = 45° to 125°C, Cycle time 6 to 10 mins</td>
<td>20,000 Cycles for MMC base plate, 5000 cycles for copper base plate</td>
</tr>
<tr>
<td>Thermal shock</td>
<td>IEC60068-2-14</td>
<td>-40° to +125°C, 2Hrs at each extreme, Transfer time = 30s</td>
<td>100 Cycles</td>
</tr>
<tr>
<td>Vibration</td>
<td>IEC60068-2-6</td>
<td>F = 55 to 500Hz, Acceleration = 10g</td>
<td>6 hours, 2 hrs in each of 3 mutually axes</td>
</tr>
<tr>
<td>Mechanical Shock</td>
<td>IEC60068-2-27</td>
<td>20g/20msec/half sine</td>
<td>30 shocks, 10 in each of 3 axes</td>
</tr>
<tr>
<td>Low Temp Storage</td>
<td>Dynex</td>
<td>Ta = -40°C</td>
<td>168 hours</td>
</tr>
<tr>
<td>High Temp Storage</td>
<td>Dynex</td>
<td>Ta = 125°C</td>
<td>168 hours</td>
</tr>
<tr>
<td>Humidity</td>
<td>IEC60749-5</td>
<td>Tj = 85°C, RH = 85%, Vce = 80V, Vge = 0V</td>
<td>1000 hours</td>
</tr>
</tbody>
</table>
Copper Wire and Temperature Cycling

- Power module industry believes copper wire is more robust than aluminum
  - Changes being implemented for electric drivetrain

- Part of improvement is believed to be due to reduced temperature variation from improved thermal conductivity
  - Part of improvement could be due to recrystallization
    - Can result in self-healing
  - Part of improvement could be more robust fatigue behavior

Figure 5: Temperature distribution along a 400μm wire of 12mm length. Al dashed curve, Cu solid red curve, current is 19A

D. Siepe, CIPS 2010

N. Tanabe, Journal de Physique IV, 1995
Aluminum vs. Copper – Temperature Cycling

- Copper clearly superior

J. Bielen, EuroSime, 2006

N. Tanabe, Journal de Physique IV, 1995
Thermal Aging of Cu Wire Bonds vs. Gold

Shear strength of Au and Cu ball bonds on Al pads. At lower temperatures (<150°C) they are similar in strength loss.

Points

- Cu is comparable in cost to aluminum but less proven – used on low cost products (not those where the cost of the IC is much greater than the package).
- Cu bonding is slower (5 wires/sec) so that adds process cost if high I/O
- Pd coating helps but adds cost
Major concerns identified by DfR

- Palladium (Pd) coating creates galvanic couple with copper
  - Studies have demonstrated thinning or loss of Pd coating during bonding
  - Uncertain if JEDEC test with acceleration factor based on Peck’s equation (based on aluminum/gold galvanic couple) is still valid

- Push out of aluminum pad
  - Could result in subsurface cracking (metal migration?)
  - Uncertain if existing JEDEC temp cycling test is sufficient to drive crack growth
Die Attach Fatigue

- **Failure mechanisms**
  - CTE mismatch resulting in plastic strain
  - Thermo-mechanical fatigue as a result of temperature cycling
  - Coarsening
Typical Thermal Stress Failures in a Die-Substrate Assembly

**Die-Substrate Assembly**

Crack at the chip’s surface in its mid-portion is due to the normal stresses in the chip.

Crack at the chip’s corner is due to the interfacial stresses.

Crack/delamination at the adherend/adhesive interface (adhesive failure of the bonding material) is due to the interfacial stresses.

Crack in the body of the adhesive (cohesive failure) is due to the interfacial stresses.
Typical Failure Modes in Die-Substrate and Similar Assemblies

- Typical failure modes in die-substrate assemblies are:

  1) adherend (die or substrate) failure: a silicon die can fracture in its midportion or at its corner located at the interface;

  2) cohesive failure of the bonding material (i.e., failure of the die-attach material); and

  3) adhesive failure of the bonding material (i.e., failure at the adherend/adhesive interface).

- An adhesive failure is not expected to occur in a properly fabricated joint. If such a failure takes place, it usually occurs at a very low load level, at the product development stage, and should be regarded as a manufacturing or a quality control failure, rather than a material’s or a structural one.
Die Attach Solder Reliability

Cycling and time-temperature effects on secondary phase morphology and damage accumulation
Sherlock

- User Friendly
- Quick
- Flexible
- Intuitive
- Reliable
- One of a Kind
- State of the Art

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Why Sherlock

- Mil-HBK-217 actuarial in nature
- Physics based algorithms to time consuming
- Need to shorten NPI cycles and reduce costs
- Increased computing power
- Better way to communicate
\( \tau_{HCI} \propto \exp \left[ \frac{b_{HCI}}{V_D} \right] \cdot \exp \left[ \frac{E_{a_{HCI}}}{kT} \right] \)

\( T_f \propto \exp \left( \frac{-0.51 \text{eV}}{kT} \right) \times \exp \left( \sim -0.063\% \text{RH} \right) \)

\( N_f^{-0.6}D_f^{0.75} + 0.9 \frac{S_u}{E} \left[ \frac{\exp(D_f)}{0.36} \right]^{-0.1785 \log^{10^3} N_f} - \Delta \varepsilon = 0 \)

\( \tau_{EM} \propto (J)^{-n} \cdot \exp \left[ \frac{E_{aEM}}{kT} \right] \)

\( \tau_{TDB} \propto \exp \left[ -b_{TDB} \cdot V_G \right] \cdot \exp \left[ \frac{E_{aTDB}}{kT} \right] \)

\( L = L_I \left( \frac{V_r}{V_0} \right) \times 2 \left( \frac{T_f - T_A}{10} \right) \)

\( \frac{t_1}{t_2} = \left( \frac{V_2}{V_1} \right)^n \exp \frac{E_a}{K_B} \left( \frac{1}{T_1} - \frac{1}{T_2} \right) \)

\( \tau_{NBTI} \propto \exp \left[ -b_{NBTI} \cdot V_G \right] \cdot \exp \left[ \frac{E_{aNBTI}}{kT} \right] \)

\( (\alpha_2 - \alpha_1) \cdot \Delta T \cdot L = F \left( \frac{L}{E_1A_1} + \frac{L}{E_2A_2} + \frac{h_s}{A_sG_s} + \frac{h_c}{A_cG_c} + \left( \frac{2-v}{9 \cdot G_b a} \right) \right) \)
Why PoF is Now Important

Electronics: Today and the Future
Electronics: 1960s, 1970s, 1980s

Failure Rate

Time

Wearout!

No wearout!
NPI Cycle Using PoF Modeling
Why DfA? Total Costs are Determined During Design

95% of the O&S Cost Drivers are Based on Decisions Made during Design.

Source: Architectural Design for Reliability, R. Cranwell and R. Hunter, Sandia Labs, 1997
Concurrent Engineering

- **Before Sherlock**
  - Electrical Design, Mechanical Design, and Reliability work separately (silos)

- **After Sherlock**
  - Reliability team inputs design and modeling elements from
  - Design and modeling elements are inputted into Sherlock
The foundation of a reliable product is a robust design
- Provides margin
- Mitigates risk from defects
- Satisfies the customer
What is Sherlock?

How will Sherlock help you?

How is Sherlock unique?

What can Sherlock do?

How can Sherlock solve my design challenges?

How does Sherlock work?

Conclusion
What is Sherlock?

- Physics of Failure Design Reliability Analysis Tool
- Predicts product failure early in design process, quickly and accurately
- Electronics-focused – Used across all industries
How will Sherlock help me?

- Save time, money, resources
- Produce better, more reliable products
- Reduce warranty costs
- Accelerate product development
- Increase profitability
- Enhance customer satisfaction

*Deeper Insight, Earlier in the Design Process*
What Can Sherlock Do?

- 3D FEA
- IC Wearout
- Thermal Cycling
- Shock/Vibe
- PTH Fatigue
- Solder Fatigue
- Hi-Fidelity
- DFMEA
- MTBF
- ICT
How Does Sherlock Work?

Phase 1: Data Input
- Parses standard EDA files (schematic, layout, parts list) automatically
- Uses embedded libraries (part, package, materials, solder, laminate)
- Can build box-level finite element analysis model in minutes

Phase 2: Sherlock Analysis
- Produces holistic analysis critical to develop reliable products
- Easy to assign and create standard structures and conditions
- Assessment options include: Thermal Cycling, Mechanical Shock, Natural Frequency, Harmonic Vibration, Random Vibration, Bending, Integrated Circuit Wearout, Thermal Derating, Failure Rate, Conductive Anodic Filament, High Fidelity PCB Model

Phase 3: Report & Recommend
- Presents results in multiple formats: Tabular / Histogram / Life curve / Overlay
• Easy-to-locate commands
• Industry terminology (parts list, stackup, pick & place, etc.)
Compatible with wide variety of reliability metrics
Handles very complex environments
Import Standard Design Output Files (Gerber/ODB)
Parts List

- Color coding of data origin
- Minimizes data entry through intelligent parsing and embedded package and material libraries
Stackup

- Automatically generates stackup and copper percent (%)
- Library with ~700 laminate materials with 48 different properties
Power Module materials Alumina, and Silicon Nitride in database

Die attach reliability is factored in for solder materials
Wire bonds are assessed using a separate calculator
Automated Mesh Generation

- Identifies optimum mesh density based on board size
- Expert user no longer required; model time reduced by 90%
Features

- Global Part Database
- FEA 3D Model
- Sub-Assembly Analysis
- FEA 3D Viewer
- Result Management
- Component lead modeling
FEA 3D Modeling
ICT and Shock/Vibration Analysis
• Fully 3D elements for the PCB, components and mount points
  • Increase simulation accuracy
  • More reliable meshing algorithm
  • Increased analysis flexibility
    • Sub-assemblies, heat-sinks, chassis analysis
FEA Engine
• Multi-core and 64 bit support
• Faster analysis
Sub-Assembly Analysis

- Attach one or more CCA sub-assemblies to a primary CCA
  - Mezzanine cards supported by standoffs
  - Edge-connected cards
- Sherlock automatically analyzes the main CCA and all CCA sub-assemblies during a single ICT or Shock/Vibration analysis task
- Layer results and component results automatically generated for all circuit cards
High Fidelity PCB

- Newest Feature

- Sherlock can identify and mesh every copper feature within a PCB or substrate

- Provides unrivaled insight into risks due to warpage, thermal issues, mechanical loads, etc.
Vibration/Shock/Bending

- Loading
- Mounting
- Direction
Thermal Cycling Fatigue

- Cumulative Damage Index (CDI)
- Time to failure
- Thermal profile and Flowtherm results
Automated Thermal Derating

- Min / Max temperature assigned to each part (Operating and Storage)
- Sherlock automatically combines operating temperatures with thermal profiles
- Parts that exceed their ratings are flagged
DFMEA

- The only Design Failure Mode Effects Analysis (DFMEA) software dedicated to electronics
Current DFMEA Tools (cont)

- **Sherlock – DFMEA module**
  - Module in Design Reliability Assessment tool
  - Imports data from BOM or ODB++ design files (generated by PADS / Expedition)
    - Later in design cycle than desired
    - Earlier than typically being done today
    - Facilitates integrating Reuse into DFMEA
  - Highest level of automation – Standardized but customizable
  - Common formatting – Can import / export to Excel
  - Generates DFMEA by “Subcircuit” (Reuse Function)
  - SEV / DET based on Standard Practices (Design Standards, etc.)
  - OCC (Occurrence Rating)
    - Based on component Reliability Predictions
      - Delphi Warranty Database
      - Multiple Industry databases
    - Future:
      - Mission profile will drive reliability predictions / OCC
Baseline Component Level DFMEA Generation

Schematic

Parts List
- Circuit Function / SubFunction / Sub-SubFunction
- Reference Designator
- Part Number

Delphi DFMEA Data Source

Failure Rate Class
- Failure Rate
- Failure Modes
- Fail Mode Distribution

Default:
- SEV, OCC, DET
- Failure Cause
- Failure Effects
- Preventions
- Detections

Sherlock Design Assistant

Failure Rate Class
Description, properties

Delphi Component Database (DMS)

Baseline DFMEA Assumes:
- Typical Application
- Not Safety Related

<table>
<thead>
<tr>
<th>Subcircuit Name</th>
<th>Part Number</th>
<th>System Element / Function / Task</th>
<th>Potential Failure Mode</th>
<th>Potential Type or Effect of Failure</th>
<th>Failure Rate (FITs)</th>
<th>Potential Failure Causes</th>
<th>Avoidance Action(s)</th>
<th>OCC</th>
<th>Detection Actions(s)</th>
<th>Component Diagnostics Capability</th>
<th>DET</th>
</tr>
</thead>
<tbody>
<tr>
<td>162</td>
<td>C135</td>
<td>C135</td>
<td>Open</td>
<td>2 Parametric Failure</td>
<td>0.16300</td>
<td>Cracked dielectric layers</td>
<td>Comp. Qualification D001 PCB Dep Std</td>
<td>1</td>
<td>Comp. Qualification In-Circuit Test Validation Test</td>
<td>2 4</td>
<td></td>
</tr>
<tr>
<td>163</td>
<td>C190</td>
<td>01008577</td>
<td>Short</td>
<td>5 Circuit Failure</td>
<td>0.16500</td>
<td>Cracked dielectric layers</td>
<td>Comp. Qualification D005 Part Derating Layout Review</td>
<td>2</td>
<td>Comp. Qualification In-Circuit Test Validation Test</td>
<td>2 20</td>
<td></td>
</tr>
<tr>
<td>164</td>
<td>C190</td>
<td>01008577</td>
<td>Leakage/Value Shift</td>
<td>2 Parametric Failure</td>
<td>0.16300</td>
<td>Diaphragm aging</td>
<td>Comp. Qualification D005 Part Derating Layout Review</td>
<td>1</td>
<td>Comp. Qualification In-Circuit Test Validation Test</td>
<td>5 10</td>
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</table>
 ICT Module (optional)

- Uses embedded FEA engine to compute board deflection and strain cause by ICT fixture
Results Summary

- Results tabulated into a score
- Easy report generation
  - PDF Format
  - Includes results and inputs
Only software tool that provides a complete life curve

- Constant Failure Rate
- Generic Actuarial MTBF Database
- PTH Thermal Cycling Fatigue
- Vibration Fatigue
- Thermal Cycling Solder Fatigue
- Over All Module Combined Risk
- Probability of Failure Goal = 10%
- Service Life = 10.0 yrs

Probability of Failure (%) vs. Lifetime (Years)
Fully Validated

BGA Validation Graph

QFN Validation Graph

Chip Component Validation Graph
“Following discussions with DfR and confirmation of the PCB material, from the supplier, I was able to refine the model for the QFN package and the PCB construction to predict the first failure of a QFN package at around 700 cycles.

It was interesting to note that the PCB material choice significantly altered Sherlock’s predicted solder joint life and choice of PCB material needs to be carefully considered from this perspective.

Subsequent real cycling of the test board has indeed produced a failure at around 770 temperature cycles and so appearing to add some (albeit limited) validation of the Sherlock prediction.

With the refined model failures of well soldered BGA joints were not predicted by Sherlock till around 3000 cycles. Our supplier has now finished the thermal cycles on the real boards seeing no BGA failures after about 1200 cycles.”
With all material and design information received, Sherlock predicted failure of I200 (Actel Microcontroller) in just over 300 thermal cycles of -55C to 125C.
Why Did I200 Fail Thermal Cycling?

- The Atmel device has two die
  - This information is in the Atmel datasheet
  - Results in a ball grid array (BGA) with a low coefficient of thermal expansion (CTE)

- The PCB was constructed with TU-622-5 laminate
  - This material has a high coefficient of thermal expansion (CTE)
  - This material is in the Sherlock laminate library

- Certain part packages (e.g., BGAs) are very sensitive to differences in CTE
DfR created an ad-hoc Sherlock project using only a picture and a component.

- No stackup info
  - Polyimide board
  - Solder fatigue calculator was also used as a standalone tool

DfR predicted 1016 cycles to first failure and 1693 cycles to characteristic life.

Test data showed 750 cycles to first failure.
Summary - What is Physics of Failure (PoF)?

- **Common Definition:**
  - The process of using modeling and simulation based on the fundamentals of physical science (physics, chemistry, material science, mechanics, etc.) to predict reliability and prevent failures.
  - Mechanisms that can be modeled include fatigue, creep, diffusion, etc.

- **The foundation of a reliable product is a robust design:**
  - Provides margin
  - Mitigates risk from defects
  - Satisfies the customer
Thank You!

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