Some Progress in Cooling and 3D Packaging for EV/HEV Inverters

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Rapid progress in packaging technologies enables cheaper, smaller and more reliable EV/HEV inverter.

More 3D integrated packaging solutions
- From power module to the components below
- From power module to the components above

Fast adoption of more 3D integrated packaging technologies
- Fast design iterations and short design cycles
- EV/HEV inverter qualification testing are costly and time-consuming
- More integrated inverter can still lead to higher cost due to testing alone

Testing need to be well integrated with analysis (modeling) to lower the development cost
EV/HEV Inverter

- A critical component for electric powertrain system
- Typically convert 10~100 kW power from the battery to drive the motor
More 3D Integrated Solution

Integration from power module to the other components

Ref 1, 2

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Trends

- **Cheaper** (~1/4 of Electric Powertrain cost)
- Smaller (High power density) and lighter
- Reliability (15 years/100,000 miles or even longer)

Under extreme mechanical and climatic conditions
- Thermal related reliability due to high power
- Environmental conditions: from Death Valley to Alaska
- Vibrations (not discussed here)
“Emerging” Power Module Packaging Technologies

Enabler for lower cost, better reliability, smaller and lighter

- Double side cooling (Delphi, Hitachi, Toyota…)
- Heat sink (Al)

Joint (lead free solder)
- Sintering
- Diffusion soldering
- Brazing

Al wire bond
- Cu Wirebond
- Sintering
- Direct Lead Bonding (Mitsubishi)
- Cu Pin (Fuji)

Bolted power connections
- Pressfit
- Spring
- …

Substrate (DBC)
- Non-ceramic based substrate
- DBA

Cooling:
- Double side cooling (Delphi, Hitachi, Toyota…)

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Both Cu and Al heat sink have been used in EV/HEV
- Cu is preferred in high power power module over its excellent thermal conductivity
- Al has its advantages over cost, manufacturability, and density

<table>
<thead>
<tr>
<th></th>
<th>Thermal conductivity (W/mK)</th>
<th>Density (g/cc)</th>
<th>CTE (10E-6/K)</th>
<th>Elastic Modulus (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu</td>
<td>385</td>
<td>7.76</td>
<td>16.4</td>
<td>110</td>
</tr>
<tr>
<td>Al</td>
<td>210</td>
<td>2.70</td>
<td>24</td>
<td>68</td>
</tr>
</tbody>
</table>
Al Heat Sink

- Al heat sink are becoming more popular in EV inverters
- Provided a more integrated solution between cooling manifold and heat sink
- Possibility of reducing process steps and components

Heat sink used in Nissan Leaf (source: ORNL report)

2010 Prius (Source: ORNL report)
**Cu vs Al Thermal Resistance Comparison**

- Although Cu has much better conductivity, thermal resistance of Cu heat sink typically only occupy 30~40% resistance of the whole power module stackup.
- Cu provide better thermal performance, yet Al heat sink can be acceptable, depending on the requirement and the whole system optimization.

![Cu vs Al Thermal Resistance Comparison](http://www.iPowerPak.com)

**Graph Details:**
- **Y-axis:** Relative thermal resistance
- **X-axis:** Cu vs Al

**Diagram:*
- Die (10mmx10mm)
- DBC substrate
- Coolant
- Forced cooling 50/50 Ethylene glycol /water

Analysis
Thermo-Mechanical Reliability

- Reliability is related to CTE mismatch and temperature fluctuations
- Typically Cu heat sink is related to better thermo-mechanical reliability
- Al heat sink can also have acceptable reliability if carefully designed

CTE of AlO substrate is estimated for 0.3mmCu/0.625mmAlO/0.3mmCu
Selection of EV/HEV Inverter Packaging Technology

- Al heat sink is preferred as a more 3D integrated solution
  - Considering cost, performance, thermal, reliability and size
  - Based on the whole inverter system

- Limiting factor for inverter cooling system?

- **Power loss** is a major factor deciding inverter packaging design
  - Thermal (cooling)
  - Reliability (CTE mismatch, temperature change due to power loss on/off)

- Reducing power loss is the fundamental solution to increase inverter power density, improve reliability and reduce the cost
Reduce Power Loss is the Key to Improve Power Density

- Progress in packaging technology is helping, but still not enough (at most x2).
- SiC is one possible solution to significantly reduce power loss.

![Graph showing inverter power density comparison between different models: Leaf 2012 (Ref 4), GM Gen2 Voltec (Ref 6), Prius 2010 (Ref 4), Lexus 2008 (Ref 4), Denso SiC 2014 prototype (Ref 5).]
Impact of SiC on Inverter Packaging

- Increased efficiency (1/3 of power loss)
  Significant reduce cooling needs (from forced liquid cooling to forced air cooling)
- High switching frequency
  Packaging need to ensure low inductance loop between DC link and the switches

* Ref 5
3D Integration from Power Module to Capacitors

- Power module is more integrated with capacitor to ensure low inductance
- In traditional module a large portion of inductance comes from the bolted connections
- Several non-traditional packaging are potential solutions for low inductance

Concept 2 reduces the inductance by ~40% compared to concept 1

Concept 1
Traditional

Concept 2
Low inductance
(likely Double side, Cu stud, pressfit...)

ANSYS Q3D Simulation
Low Inductance SiC Power Module and Subsystems

GPTG 1200V 320A SiC MOSFETs Half Bridge Module
- Low profile (17mm height)
- Low inductance less than 10nH
- Ultra low power loss

Under Development
Transfer molded ultra low inductance SiC power module (automotive rated)

GPTG 3.5kW On-Board Vehicle Charger
- Size = 2.9L displaced
- Mass = 3.2kG
- Conversion Efficiency => 94%

GPTG Ultra High Efficiency 50kW SiC Inverter

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Challenges: Costly and Time Consuming Testing

Testing alone can cause more integrated inverter expensive, even with low process and material cost

- Testing is one major factor contributing to cost of EV/HEV inverter

<table>
<thead>
<tr>
<th>Item</th>
<th>Category</th>
<th>Industrial use</th>
<th>Automotive use</th>
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<tbody>
<tr>
<td>Temperature cycle test</td>
<td>100 cycles</td>
<td>1,000 cycles</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Temperature conditions: -40 to +125°C</td>
<td>Temperature conditions: -40 to +125°C</td>
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<tr>
<td>Power cycle test</td>
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<td>30,000 cycles</td>
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<tr>
<td></td>
<td>Temperature conditions: $\Delta T_j = 100°C$</td>
<td>Temperature conditions: $\Delta T_j = 100°C$</td>
<td></td>
</tr>
<tr>
<td>Vibration test</td>
<td>Acceleration = 10 G 2 h for each of X, Y and Z axes</td>
<td>Acceleration = 20 G 2 h for each of X, Y and Z axes</td>
<td></td>
</tr>
</tbody>
</table>

Power Module OEM's qualification test  Ref 18

- More integrated inverter systems → more failure? more uncertainty?
  1. Influence of more components: cooling components, capacitors…
  2. Different failure mechanisms: sintering joint, press fit, …
Testing Integrated with Analysis = More Efficient Testing

Analysis (modeling) helps to make design/testing more efficient in several areas:

- **Thermal Analysis** using analytical model or CFD
  - Cooling design
  - Temperature
- **Thermo-mechanical analysis** using analytical or FEM software
- **Interconnect reliability**
- **Vibration analysis** using FEM (resonant frequency)

[Images: CFD analysis and FEM analysis]
Thermo-Mechanical Analysis (Modeling)

- Interconnect reliability (wire bond, joint, …)
- Most failures share the **same fundamentals** and can be modeled at some level: **deformation due to CTE mismatch and temperature change**
- The level of modeling depends on the physics and individual process
  1. Design comparison in the early design stages
  2. It is possible to roughly estimate life for some process, but not always.
- For a lot of technologies, modeling is individual OEM process based
  - Solder joints
  - Sintering joints
  - …

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[Image of wire bond failure]

[Image of joint fatigue failure]
Example: Analysis to Reduce Test Iterations

Thermo-mechanical interconnect fatigue failure (non traditional package)

- Initial designed module failed before required cycles
- Roughly estimated the range of expected cycles to failure for new design based on the analysis and lessons learned
- Reached design goals in second round of testing

Deformation factor determined by thermo-mechanical analysis

Cycles to Failure

Initial design

New design

Deformation Factor

Cycle to failure determined by testing

Cycle to failure estimated

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Summary

• EV/HEV inverter needs to be cheaper, smaller and reliable, not there yet
• In response, more 3D integrated packaging solutions are emerging
  – Power module integrated with cooling components
  – Power module integrated with capacitors
• Changes are inevitable and need to be rapid and reliable
• More integrated inverters can be expensive just because of testing alone
• In the long term, the winning low-cost inverters need to have analysis well integrated with testing
  – Optimize designs with fewer iterations
  – Fast/fewer test iterations

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Acknowledgement

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ANSYS

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7. Ralph Taylor, “Development, Test and Demonstration of a Cost-Effective, Compact, Light-Weight, and Scalable High Temperature Inverter for HEVs, PHEVs, and FCVs”, 2008 DOE Merit Review
10. Yunqi Zheng, University of Maryland PhD thesis 2005