Integration of Cooling Function into 3-D Power Module Packaging

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Outline

- **Introduction**
  - Power Electronics Packaging Functions
  - Power Electronics Packaging Assessment
  - Advancement of 3-D Power Electronics Packaging Integration

- **Development of Integrated Cooling Packaging**
  - Power Electronics Packaging Thermal Performance Characterization
  - Integrated packaging I: Pin_fin Baseplate
  - Integrated packaging II: Cold-Baseplate

- **Integration of Cooling Function into 3-D Power Module Packaging**
  - Planar-Bond-All: 3-D Power Module Packaging
  - Process Integration
  - 3-D Packaging of Cooling and Power Modules

- **Summary**
Power Electronics Packaging: Assembly of Multiple Components

Passive Component

Power Module

Cold Plate

Power Electronics System

Control and Drive Boards

Sensors
Power Electronics Packaging: Multi-function Integration

- Multiple Power Semiconductor Devices Integration
- Monitoring and Protection
- Electrical Interconnection
- Cooling (Thermal Management)
- Thermo-mechanical and Mechanical Support
Power Electronics Packaging: State-of-the-Art

- Discrete Components
- Hierarchical Electrical Interconnection
- Interfacial Thermal Management
- Complicated Manufacture

- Cost
- Performance
- Power Density
- Reliability
Power Electronics Packaging: Technical Metrics

Thermal Impedance

Thermal-mechanical Property

Power Conversion Performance

Efficiency $\rightarrow \eta = 1 - (P_{con} + P_{sw} + P_{lp} + Pr_{p}) / P_{in}$

Cost $\rightarrow \frac{S}{kW} = A + B \cdot (1 - \eta) \cdot \theta_{ja,sp} \cdot \frac{(T_{j} - T_{a})}{(T_{j} - T_{a})}$

Reliability $\rightarrow N_{f} = \alpha \cdot \left(\frac{1}{T_{j} - T_{a}}\right)^{\beta} \cdot \exp\left(\frac{E_{a}}{kT_{m}}\right)$
3-D Power Electronics Packaging: Schemes for Integration

- Built-in Passives and Circuitry
- Embedded or Stacked Power Semiconductors
- Reduced Electrical Interconnection
- Cost-effective Manufacturability
- Integrated Electronics
- Embedded Sensors and Monitoring
- Integral Efficient Cooling

Key Features:
- Low Cost
- High Performance
- High Reliability
- High Density
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- Summary
3-D Thermal Model of Power Module with Cooler

- IGBT, Diode Power loss;
- Coolant flow rate;
- Pressure Drop;
- Coolant inlet temperature;
- Single- or Double-sided cooling.
Thermal Resistance In State of the Art Power Module Assembly

Thermal Network

Material Layer in Package

Thermal Resistivity of layer (Kcm²/W)

Thermal Grease

Cu Baseplate

DBC Ceramic

DBC Solder

Si Die
Integrated Cooling Packaging I: Pin-fin Baseplate

- Die
- Insulated Substrate (DBC)
- Baseplate with pin fin
- Cold plate element

<table>
<thead>
<tr>
<th>Specific Thermal Resistance (°C·cm²/W)</th>
<th>Wirebond</th>
<th>Integrated Single Cooling</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.541</td>
<td>0.470</td>
<td></td>
</tr>
</tbody>
</table>
Integrated Cooling Packaging II: Cold-baseplate

Diagram showing the components of a cold-baseplate system, including a SiC die, insulated substrate (DBC), metal on substrate (Cu), substrate attach (solder), die attach (solder), coolant inlet, and coolant outlet.
Thermal Performance Characterization

Thermal Resistance Comparison

Vf-T calibration curve of body diode in SiC MOSFET

\[ y = -2.45x + 900.25 \]
\[ R^2 = 0.9988 \]

CFD Simulation:
Temperature distribution in an Integrated SiC power module

Vf decay of body diode in SiC MOSFET during cooling down

Thermal Resistance Comparison

<table>
<thead>
<tr>
<th>Rja,sp (cm²°C/W)</th>
<th>Conventional</th>
<th>Integrated</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>0.88</td>
<td>0.45</td>
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</table>
Performance Evaluation in a High Frequency Converter

100A/1200V SiC Power Modules: Conventional packaging (left); Integrated cooling packaging (right)

Two 100A/1200V SiC Power Modules in a HF (48KHz) converter: Converter packaging (left); Waveforms (right)
Performance Estimation in a System

Current density allowed for different power semiconductor and cooling combinations at $\Delta T_j=100^\circ C$ for a typical operation ($D=0.5$, $f=5\text{kHz}$)

<table>
<thead>
<tr>
<th>Item</th>
<th>Si_Con. Cooling</th>
<th>SiC_Con. Cooling</th>
<th>Si_Integ. Cooling</th>
<th>SiC_Integ. Cooling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current Density $J_d$ (A/cm²)</td>
<td>65.35</td>
<td>144.97</td>
<td>97.57</td>
<td>184.98</td>
</tr>
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- Summary
Planar Bond All Integrated Power Module

- 3-D, Planar Power Interconnection
- Integrated, Double Sided Cooling
- Symmetrically Mechanical Structure
- Simplified Manufacture

*Patent Pending: Pub No: 2013/0020694 A1
Develop Integration Packaging Process Technology

Planar_Bond_All*

Wire Bond Packaging

1 Substrate Preparation
2 Die Attach
3 Substrate Attach
4 Terminal Frame Attach
5 Wire Bond
6 Encapsulate
7 assembly

*Patent Pending: Pub No: 2013/0020694 A1
Prototype: Planar_Bond_All Power Modules

Bare Semiconductor Dies

Planar Bond Power Module Stage

Electrical Connection

Double Cooled Power Module

Patent Pending: Pub No. 2013/0020694 A1
Electrical Performance Characterization

IGBT I-V Curve

Planar Bond Module

Wire Bond Module

IGBT Switching Curve

∆Vce(WB)=156V
∆Vce(PB)=72V

Electrical Parameters Comparison

<table>
<thead>
<tr>
<th></th>
<th>Experimental Value</th>
<th>Calculated Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Planar Bond_Lower IGBT</td>
<td>10.5</td>
<td>6.3</td>
</tr>
<tr>
<td>Wire Bond-Lower IGBT</td>
<td>31.9</td>
<td>23.5</td>
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Thermal Performance Characterization

Flow rate: 0.52 gpm
Pressure drop: 22 psi

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<td>0.470</td>
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Design of 3-D Packaging of Cooling and Power Modules

Flow rate: 0.5 gpm, pressure drop: 22 psi
0.291 °C/W for center module

Flow rate: 1.3 gpm
Pressure drop: 38 psi
Summary

➢ Advance power module packaging technologies, focusing on improvements in cost, reliability, power efficiency and density through structure, material and processing integration.

➢ A group of power modules with double sided planar interconnections and integrated heat exchangers has been prototyped.

➢ Their three dimensional power interconnection configuration has been proven to offer low parasitic electric inductance and resistance, leading to high efficiency power conversion.

➢ The double sided cooling reduces dramatically thermal resistance. Additionally, the package allows for ease of fabrication and low manufacturing costs.
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Thanks and Questions?