Thermal Packaging Challenges for Next-Generation Power Electronics

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Applied Power Electronics Conference
New Orleans
March 15-19, 2020
Overview

• Characteristics of Wide Band-Gap Devices
• Requirements of Next-Generation Packaging
• Packaging Trends for Power Electronics
• Relevant Future Technologies
  • Near-Junction Cooling
  • Thermal Ground Planes
  • Transient Liquid Phase Bonding
  • Self-Healing Die Attach
• Conclusions
Characteristics of Wide Band-Gap Devices

• Increased device breakdown electric field
• High temperature operation
• High switching frequency, low switching loss
  • Reduced passive size
    • E.g. inductor, capacitor
  • Higher power density

* Ref.: Ogawa, et al., 2016
Requirements of Next-Generation Packaging

• Packaging strategies that support higher maximum junction temperature: 150 °C → 250 °C
  • E.g. new material systems must be developed for bonding, substrate, encapsulation

• Thermal management techniques that enable higher power density (orders-of-magnitude)
  • E.g. new approaches needed beyond conventional remote cooling techniques

• Careful consideration of package for low parasitic inductance and electromagnetic interference (EMI)
Packaging Trends for Power Electronics

- Historical approaches in automotive:

  Toyota Prius 2004
  - Multiple layers and single-phase remote cooling dominate applications, but limit packaging breakthrough

  Toyota Prius 2010

  Lexus LS 600h 2008

  Nissan Leaf 2012

  Honda Accord 2014
  - Ref.: Broughton, et al., 2018

  Chevrolet Volt 2016

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Multiple layers and single-phase remote cooling dominate applications, but limit packaging breakthrough
Packaging Trends for Power Electronics

• Efforts towards higher levels of integration:

Substrate (e.g. PCB, DBC) Embedding

New Form Factors & Motor Integration

Device Embedded Cooling

High power density → embedding + integration → novel packaging and different process workflows

* Ref.: Buttay, et al., 2018
* Ref.: Hose, et al., 2017
* Ref.: Wits, et al., 2010
* Ref.: Marz, et al., 2010
* Ref.: Vladimirova, et al., 2013
Packaging Trends for Power Electronics

• Future transition to wide band-gap (WBG) devices; e.g., SiC or GaN
  • Device breakdown voltage ↑
  • Temperature tolerance ↑
  • Switching speed ↑, passive size ↓, power control unit (PCU) size ↓

• Trend in device heat flux and cooling technology

Power density drives (conductive path) packaging approach and (convective path) cooling technology

Radiative Heat Flux at Sun Surface
Nuclear Reactor Rod
SiC MOSFET *, 100 kHz (<10^{-4} m)
SiC MOSFET *, 20 kHz (<10^{-4} m)
Si IGBT *, 20 kHz (<10^{-3} m)
Plasma Torch
Power Circuit/Gate Drive IC (10^{-2} - 10^{-1} m)
Logic Circuit/Ambient PCB (10^{-1} m)

1000 W/cm²
100 W/cm²
10 W/cm²
0.01 W/cm²

Near Junction
Remote

Embedded Cooling
Two-Phase Cooling
Liquid Cooling
Active Air Cooling
Natural Convection

Note: * 650 V, 50 A device

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Near-Junction Cooling – Motivation

• Order-of-magnitude downsizing requires new packaging concepts
  • Package conductive thermal resistance → driving factor

- Si-based
- SiC-based

- 1000 W/cm²
- 100 W/cm²
- 10 W/cm²
- 0.01 W/cm²

Embedded Cooling (h~30-150 kW/m²K)
Two-Phase Cooling
Liquid Cooling
Active Air Cooling
Natural Convection

Conventional Power Card Structure

Fluid Flow → Current Flow

2X TIM + Electrical Isolation
Spacer (Metal)
Si Device
3X Solder
2X Heat Spreader / Electrode (Metal)
2X Cooler (Metal)
Near-Junction Cooling – Concepts

• Three concepts for vertical current WBG devices

Concept A
(μChannels Fabricated in Device)

Concept B
(μChannels Fabricated in Electrode)

Concept C
(μChannels Fabricated in Cooling Chip)

Qualitative Comparison of Concepts

<table>
<thead>
<tr>
<th></th>
<th>Concept A</th>
<th>Concept B</th>
<th>Concept C</th>
</tr>
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<tbody>
<tr>
<td>Thermal Performance</td>
<td>○</td>
<td>○</td>
<td>△</td>
</tr>
<tr>
<td>Electrical performance</td>
<td>△</td>
<td>○</td>
<td>○</td>
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<tr>
<td>Fabrication feasibility</td>
<td>△</td>
<td>×</td>
<td>○</td>
</tr>
</tbody>
</table>

Leverage established MEMS microfabrication processes in silicon to explore Concept C cooling chip

Ref.: Dowling, et al., 2017. DOI: 10.1109/JMEMS.2016.2621131
Near-Junction Cooling – 1\textsuperscript{st} Prototype Fab

- Straight microchannel prototype fabrication using Bosch process

1\textsuperscript{st} layer

- Dice line + Microchannels

2\textsuperscript{nd} layer

- Fluid Inlet/Outlet Via

Wafer Bonding

Metal Deposition & Dice

Microchannels (38 \, \mu m \times 313 \, \mu m – Qty 200)

Manifold Pocket

SEM Image of 1\textsuperscript{st} Layer

SEM Image of Bonded Assembly Cross-Section

Si Cooling Chip Prototype

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Near-Junction Cooling – 2nd Prototype Design

- Microchannel unit cell design optimized for conjugate heat transfer

Pareto Front of Multi-Objective Design Optimization in 3-D for Thermal-Fluid Problem

![SEM Image of 1st Layer Microchannel Structure](image)

*Ref.: Dede, et al. (2014) Springer*
Near-Junction Cooling – 2nd Prototype Fab

2nd prototype cooling chip design is one-quarter footprint size of straight microchannel cooling chip
Near-Junction Cooling – Experimental Results

For same $\Delta P$, UC microchannel design supports 3X higher flow rate $\rightarrow$ larger heat transfer coefficient
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Air Cooling – Technology Breakdown

- Ultimate simplicity, but inherently poor coolant

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0.01 W/cm²
10 W/cm²
100 W/cm²
1000 W/cm²

Near Junction

Remote

Embedded Cooling

Two-Phase Cooling

Liquid Cooling

Active Air Cooling

(h~25-2000 W/m²K)

Natural Convection

(h~2-25 W/m²K)

* Ref.: Kim, et al., 1996
```

- Key technologies for air cooling system

1) Efficient air movement
2) High performance heat sink
3) Extreme heat spreading

Air is least effective

**Embedded Cooling**

Air Cooling

- Technology Breakdown

**Liquid Cooling**

**Active Air Cooling**

(h~25-2000 W/m²K)

**Natural Convection**

(h~2-25 W/m²K)

**Ref.: Kim, et al., 1996**

- Key technologies for air cooling system

1) Efficient air movement
2) High performance heat sink
3) Extreme heat spreading

**Ref.: Kim, et al., 1996**
Air Cooling – High Performance Heat Sink

- Optimization of basic 2-D finned element

- Application to 3-D heat sink design
Air Cooling – Extreme Heat Spreading

- Efficient heat spreading required to utilize aggressive air cooling

![Graph showing heat transfer coefficient vs. substrate max. temp.](image)

Thermal Ground Plane (TGP) Concept

<table>
<thead>
<tr>
<th>Evaporator Porous Structure</th>
<th>Maximum Heat Flux [W/cm²]</th>
<th>Superheat [K]</th>
<th>Heated Area [mm²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrodeposited Cu [16]</td>
<td>&gt;1200</td>
<td>~10</td>
<td>0.6</td>
</tr>
<tr>
<td>Cu μ-posts + nano-CuO coating [18]</td>
<td>~800</td>
<td>~35</td>
<td>4</td>
</tr>
<tr>
<td>Biporous silicon μ-posts [19]</td>
<td>~730</td>
<td>~13</td>
<td>~6</td>
</tr>
<tr>
<td>Sintered Cu [20]</td>
<td>~590</td>
<td>~23</td>
<td>25</td>
</tr>
<tr>
<td>Biporous sintered Cu [21]</td>
<td>~990</td>
<td>~147</td>
<td>32</td>
</tr>
<tr>
<td>Sintered Cu + feed arteries [17]</td>
<td>~580</td>
<td>~72</td>
<td>100</td>
</tr>
</tbody>
</table>

Technology Gap

- > 1000 W/cm² required
- < 35 K generally increasing superheat
- > 100 mm² generally increasing heated area

*Ref.: Bar-Cohen, et al., 2015

*Ref.: Dede, et al., 2016
Air Cooling – Extreme Heat Spreading

- Novel wick structures to enable high heat fluxes

Vapor Chamber & Wick Design

**TGP Heat Flux vs. Thermal Resistance**

*Ref.: Zhou, et al., 2018

**Wick Heat Flux vs. Thermal Resistance**

*Ref.: Sudhakar, et al., In press

At high heat flux, liquid menisci recede to separate liquid feed and vapor vent mechanism

*Ref.: Sudhakar, et al., 2019

*Ref.: Sudhakar, et al., In press
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Transient Liquid Phase Bonding Overview

- Technology benefits

Assembly

Diffusion

Isothermal solidification

Homogenization

<table>
<thead>
<tr>
<th>Candidates</th>
<th>Re-melting temp.</th>
<th>Process temp.</th>
<th>Fabrication difficulty</th>
<th>Material cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pure metal sintering</td>
<td>(○)</td>
<td>(○)</td>
<td>(✗)</td>
<td>(✗)</td>
</tr>
<tr>
<td>Solder bonding</td>
<td>(△)</td>
<td>(△)</td>
<td>(○)</td>
<td>(○)</td>
</tr>
<tr>
<td>TLP bonding</td>
<td>(○)</td>
<td>(○)</td>
<td>(△)</td>
<td>(○)</td>
</tr>
</tbody>
</table>

*Ref.: Noguchi et al., 2016*
Die Attach Challenges & Higher Compliance Concept

TLP IMCs brittle & susceptible to cracking

Introduce compliance via laminated preform w/Al core

Copper Substrate Die-Attachment

Substrate shrinkage (intense)

Chip shrinkage (mild)

Copper, high CTE, $\alpha=17$ ppm/K

Si, low CTE, $\alpha=3$ ppm/K

Thermal stress

Stress

Strain

Intermetallic compound (IMC)

Solder

High young’s modulus

Low young’s modulus

High yield strength

Low yield strength

Failure strength

Strain to fail

Plasticity

Ni plated Si chip

Cu

Al core layer

Sn

Ni plated Cu substrate

*(Ref.: Liu et al., 2019)*

Post fabrication cross-section of TLP bonding sample

Maximum thermal stress on IMC layer [MPa]

Temperature [°C]

IMC of Single layer TLP

Upper IMC of Laminated TLP

Fast diffusion kinetics of ($Cu,Ni$)$_x$ Sn = fast process time

Stress reduction from soft Al (60% stress reduction)

Residual metal for high fracture toughness
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Self-Healing Die Attach Concept

Chip shrinkage (mild)

Substrate shrinkage (intense)

Copper, high CTE, $\alpha=\sim17$ ppm/K

Thermal stress

Copper Substrate Die-Attachment

1. Without crack

2. Crack ruptures a capsule

3. High temperature to melt indium and to fill crack

Self-healing capsule (indium)

Solder (Sn0.7CuNiP; $T_m=227$ °C)

Copper Substrate Die-Attachment

Atomic layer deposition (ALD) fabrication of In-Pt core-shell capsule for material system proof-of-concept
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Conclusions

• Higher power density requires consideration of embedding and integration
  • Remote cooling fundamentally limits order-of-magnitude size reduction
  • New packaging strategies and process workflows required

• Near-junction cooling explored as ultra-compact packaging paradigm
  • Straight channel and arrayed hierarchical unit cell flow structures explored
  • Unit cell design exhibits reduced pressure drop and higher heat transfer rates
  • Packaging explored as next step → heterogeneous integration

• Air cooling is robust and simple but requires effective heat spreading for high power density application
  • Heat sink optimization coupled with thermal ground plane technologies may be a solution

• High temperature operation bonding materials are critical
  • Transient liquid phase bonding with increased compliance has potential
  • Self-healing die attach may be disruptive technology to increase package reliability
Acknowledgements

• Toyota Research Institute of North America
  • Dr. Shailesh Joshi
  • Mr. Yanghe Liu
  • Dr. Feng Zhou

• Toyota Motor Corporation
  • Mr. Yuji Fukuoka
  • Mr. Masao Noguchi
  • Mr. Naoya Take

• Purdue University
  • Srivathsan Sudhakar
  • Prof. Justin A. Weibel
  • Prof. Suresh V. Garimella

• Stanford University
  • Ki Wook Jung
  • Prof. Mehdi Asheghi
  • Prof. Ken Goodson