Lightweight, Low-Cost Heat Sink for High-Heat Flux Applications

Art Fortini
ULTRAMET
TFAWS Meeting
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Basic Concept

- Use open-cell SiC foam as an extended surface or cooling fin for SiC integrated circuits (ICs).

Advantages

- Perfect CTE match with SiC ICs
- High thermal conductivity
- High surface area
- Low pressure drop
- Immune to corrosion
Silicon Carbide Foam

- High surface area
- Important for transferring heat to cooling medium
Pressure Drop

- Silicon carbide foam
  - 0.5 x 2 x 3” slab
  - Water flow parallel to long axis.
  - Important for flowing large quantities of coolant without pressure drop penalty.

![Graph showing pressure drop versus flow rate for different water flows and foam conditions.](image)
Pressure Drop

- Carbon foam
  - 1” thick slab
  - Air flow perpendicular to thickness
  - Very low pressure drop
Ultrafoams

- Begin with polyurethane
- Impregnate with resin
- Pyrolyze to form glassy carbon
  - 3-1000 pores per inch (ppi)
- CVI with SiC
  - 5-30% relative density
  - Other materials: Si, Gr, pyC, Si(C), refractory metals, etc
Ultrafoam

Vitreous carbon

Silicon carbide
Basic Concept

- IC heat source
- Faceplate
- SiC foam
- Coolant in
- Coolant out
Experimental

Copper block w/ resistive heaters

SiC foam

Thermocouple (at heater/foam bondline)

Insulation

Coolant inlet

Coolant outlet

$T_i$, $P_i$ (at heater/foam bondline)

$T_e$

Bondline

$\Delta P$
Unique Thermal Control Challenges
(High Heat Flux, High Power, Low Temperature)

- Phase II goal was to reach 1000 W/cm² with temperature below 150°C
## Experimental Results

<table>
<thead>
<tr>
<th>Foam PPI / density</th>
<th>Heat Flux (W/cm²)</th>
<th>Flow Rate (GPM)</th>
<th>Heat Flux / Flow Rate (W min /cm² G)</th>
<th>Cooler Surface Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100ppi/ 9.8%</td>
<td>711</td>
<td>0.5</td>
<td>1422</td>
<td>113</td>
</tr>
<tr>
<td>1000ppi / 12%</td>
<td>867</td>
<td>0.5</td>
<td>1734</td>
<td>122</td>
</tr>
<tr>
<td>100ppi/ 10%</td>
<td>612</td>
<td>0.5</td>
<td>1224</td>
<td>47.8</td>
</tr>
<tr>
<td>1000ppi/ 5%</td>
<td>1006</td>
<td>0.64</td>
<td>1572</td>
<td>165</td>
</tr>
<tr>
<td>300ppi/ 20%</td>
<td>1011</td>
<td>0.5</td>
<td>2022</td>
<td>53</td>
</tr>
<tr>
<td>100ppi/ 20%</td>
<td>1000</td>
<td>1.0</td>
<td>1000</td>
<td>135</td>
</tr>
<tr>
<td>300ppi/ 20%</td>
<td>758</td>
<td>0.3</td>
<td>2527</td>
<td>42.4</td>
</tr>
</tbody>
</table>

- Phase II goal: 1000 W/cm² while below 150°C.
- Ultramet SiC foam 1011 W/cm² at only 53°C!
Experimental Results
Experimental Results

Heat Stress = Heat Flux/ Flow rate (Gallons per minute)

Heat Stress (W*min/cm²*G) vs. Cooler Surface Temperature (°C)

- 300ppi 2-28-06
- 300ppi with Cu flap
- 600ppi-copper flap 9-14-05
- 1000(2)(9-9-05)
- 100PPI-10%
- 100ppi-20%
- 100-20%
- 300ppi-20%
- 600ppi
Thermal Modeling

X-Ray Tomography

Ultramet SiC Foam
### Thermal Model Input

<table>
<thead>
<tr>
<th>Part</th>
<th>Side Dimensions</th>
<th>Thickness</th>
<th>Thermal Conductivity (W/m°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiC Foam</td>
<td>2 x 2”</td>
<td>0.5”</td>
<td>40</td>
</tr>
<tr>
<td>TIM1</td>
<td>2 x 2”</td>
<td>100 µm</td>
<td>40</td>
</tr>
<tr>
<td>SiC Heat spreader</td>
<td>2 x 2”</td>
<td>250 µm</td>
<td>200-500 (4H-SiC)</td>
</tr>
<tr>
<td>Die Attach (TIM2)</td>
<td>5 x 5 mm</td>
<td>50 µm</td>
<td>40</td>
</tr>
<tr>
<td>Die</td>
<td>5 x 5 mm</td>
<td>380 µm</td>
<td>200-500 (4H-SiC)</td>
</tr>
<tr>
<td>GaN active area</td>
<td>0.25 x 4 mm</td>
<td>n/a</td>
<td>n/a</td>
</tr>
</tbody>
</table>

*Only ¼ of the model is shown due to symmetry.*
Modeling Conclusions

1kW/cm² with Heat Spreader
0.1 and 0.5 GPM → 27 and 28 °C

1kW/cm² without Heat Spreader
0.1 and 0.5 GPM → 61 and 48 °C
Other Work- High Heat Flux GaN-Based RF Components and Cooling Methods

Jeff Calame, Steve Binari, Robert Myers †, and Frank Wood †
Naval Research Laboratory, Washington, DC 20375

Experimentally measured temperatures
(Cooler surface under heat probe source center)

- Micromachined to 500µm

• Ultramet SiC foam has comparable performance to micromachined OFHC copper and single crystal silicon with diamond heat spreader.
Summary

- Effects of SiC foam:
  - 1011 W/cm² @53C w/ 0.5 GPM water

- Thermal Model predicts improvements by going to heat spreader configuration.
  - 27 °C with heat spreader w/ 0.1 GPM
  - 61 °C for 100ppi. 10% density (stock item) at low flow rate.

- Excellent heat transfer → little material is required (small volume/ light and inexpensive).

- Low coolant flow rates requires less in way of supporting systems- pumping, filtration, etc.