Improved Organics for Power Electronics and Electric Motors

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Overview

Timeline
• Project start: October 2010
• Project end: September 2013
• Percent complete: 50%

Budget
• Total project funding
  – DOE 100%
• FY11: $250k
• FY12: $150k
• FY13: $150k

Barriers*
• Barriers Addressed
  – Reliability and lifetime of power electronic devices (PEDs) and motor components degrade rapidly with temperature increase.
  – PEDs and motor components need improved thermal management to operate at higher temperatures.
  – New paradigms in cooling would enable achievement of higher power densities without compromise to device reliability.

• Targets:
  – DOE VTP* 2020 target: 105°C Coolant
  – DOE VTP* 2020 target: 4 kW/liter power density

Partners
• NTRC – ORNL
• SolEpoxy (EMC manufacturer)
• Ube (powder manufacturer)

* VTP Multi-Year Program Plan 2011-2015
Objectives

• Identify and develop lower-cost and better-performing organic compounds or "epoxy molding compounds" or EMCs for dielectric and thermal management applications in power electronics, electric motors, and film capacitors.

• Reduce volume and improve thermal reliability of power electronics, electric motors, and film capacitors through improved thermal management strategies.

• Develop EMCs that have:
  – Sustained dielectric performance
  – Optimized filler particle size distribution and volume %
  – High thermal conductivity (> 5 W/mK)
  – Use non-toxic and inexpensive filler
  – Equivalent potting and injection molding characteristics to existing EMCs
Milestones

- **FY11**: Established baselines by measuring thermal properties of unused and serviced organic molding compounds from power electronic devices, electric motors, and film capacitors.

- **FY12**: Model, design, and fabricate filler-containing-EMC having 10x thermal conductivity increase over monolithic epoxy.
• Optimize filler particle size distribution and volume fraction.
• Fabricate EMCs with organic matrices that allow transfer molding and potting.
• Demonstrate thermal conductivity ($\kappa$) > 5 W/mK.

### Candidate Filler Properties

<table>
<thead>
<tr>
<th>Material</th>
<th>Electrical Resistivity at 25°C ($\Omega \cdot$cm)</th>
<th>Thermal Conductivity at 25°C (W/m·K)</th>
<th>Heat Capacity (J/kg·K)</th>
<th>Density (kg/m³)</th>
<th>Coefficient of Thermal Expansion (x 10⁻⁶/°C)</th>
<th>Estimated Cost ($/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silica ($SiO_2$) silicon dioxide</td>
<td>$&gt; 10^{14}$</td>
<td>2</td>
<td>700</td>
<td>2600</td>
<td>0.5</td>
<td>2</td>
</tr>
<tr>
<td>Alumina ($Al_2O_3$) aluminum oxide</td>
<td>$&gt; 10^{14}$</td>
<td>30</td>
<td>900</td>
<td>3900</td>
<td>8</td>
<td>5</td>
</tr>
<tr>
<td>Boron nitride (BN) * Anisotropy</td>
<td>$&gt; 10^{14}$</td>
<td>275*</td>
<td>1600</td>
<td>1900</td>
<td>1*</td>
<td>100</td>
</tr>
<tr>
<td>Magnesia (MgO)</td>
<td>$&gt; 10^{14}$</td>
<td>40</td>
<td>900</td>
<td>3600</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>Silicon carbide (SiC)</td>
<td>$&gt; 10^2$</td>
<td>120</td>
<td>800</td>
<td>3100</td>
<td>4</td>
<td>40</td>
</tr>
<tr>
<td>Aluminum nitride (AlN)</td>
<td>$&gt; 10^{14}$</td>
<td>250</td>
<td>700</td>
<td>3200</td>
<td>5</td>
<td>400</td>
</tr>
<tr>
<td>Beryllia (BeO) beryllium oxide</td>
<td>$&gt; 10^{14}$</td>
<td>280</td>
<td>600</td>
<td>2900</td>
<td>9</td>
<td>800</td>
</tr>
<tr>
<td>Epoxy</td>
<td>$&gt; 10^{12}$</td>
<td>0.05 - 0.4</td>
<td>1500</td>
<td>1200</td>
<td>30-60</td>
<td>5</td>
</tr>
</tbody>
</table>
Technical Accomplishments (1 of 8)

- Identified approximate filler particle size distribution (PSD) and volume fraction (Vol%)
- Transient thermal model developed using PDS and Vol%
- Modeled effect of higher $\kappa$ on components
- Established interaction with EMC manufacturer to make first set of high $\kappa$ EMCS
- Thermal conductivity of 2.8 W/mK achieved with first set
Software Was Developed to Create 2D Images of PSDs That in Turn Enables Thermal Conductivity Modeling

- Particle size distribution (PSD)
- Volume fraction
- Percolation limit
- Effects on thermal conductivity
Transient Thermal Modeling Enables Estimation of EMC $\kappa$

Temperature as a function of time

\[
D = \frac{\kappa}{\rho \cdot C_p} = \frac{0.1388 \cdot T^2}{t_{50}}
\]

$D =$ diffusivity  
$\kappa =$ thermal conductivity  
$\rho =$ density  
$C_p =$ heat capacity  
$T =$ thickness  
$t_{50} =$ time to reach 50% max temp
Film Capacitor FEA Example: Effect of EMC $\kappa$

$\kappa = 0.5$ W/mK

$T_{\text{max}} = 116^\circ$C

$\kappa = 1.0$ W/mK

$T_{\text{max}} = 83^\circ$C

$\kappa = 3.0$ W/mK

$T_{\text{max}} = 57^\circ$C

$\kappa = 5.0$ W/mK

$T_{\text{max}} = 51^\circ$C

$\kappa = 10$ W/mK

$T_{\text{max}} = 47^\circ$C

$\kappa = 20$ W/mK

$T_{\text{max}} = 44^\circ$C
Motor Component FEA Example: Effect of EMC $\kappa$

- $\kappa = 0.5 \text{ W/mK}$
  - $T_{\text{max}} = 186^\circ \text{C}$

- $\kappa = 1.0 \text{ W/mK}$
  - $T_{\text{max}} = 182^\circ \text{C}$

- $\kappa = 3.0 \text{ W/mK}$
  - $T_{\text{max}} = 168^\circ \text{C}$

- $\kappa = 5.0 \text{ W/mK}$
  - $T_{\text{max}} = 158^\circ \text{C}$

- $\kappa = 10 \text{ W/mK}$
  - $T_{\text{max}} = 144^\circ \text{C}$

- $\kappa = 20 \text{ W/mK}$
  - $T_{\text{max}} = 132^\circ \text{C}$
Technical Accomplishments (6 of 8)

Power Module FEA Example: Effect of EMC $\kappa$

$\kappa = 0.5 \text{ W/mK}$

$T_{\text{max}} = 170^\circ C$

$\kappa = 1.0 \text{ W/mK}$

$T_{\text{max}} = 160^\circ C$

$\kappa = 3.0 \text{ W/mK}$

$T_{\text{max}} = 141^\circ C$

$\kappa = 5.0 \text{ W/mK}$

$T_{\text{max}} = 130^\circ C$

$\kappa = 10 \text{ W/mK}$

$T_{\text{max}} = 115^\circ C$

$\kappa = 20 \text{ W/mK}$

$T_{\text{max}} = 101^\circ C$
Technical Accomplishments (7 of 8)

EMCs Fabricated for ORNL by EMC Manufacturer
## Technical Accomplishments (8 of 8)

### Properties of First Set of EMCs

<table>
<thead>
<tr>
<th></th>
<th>Sample A</th>
<th>Sample B</th>
<th>Sample C</th>
<th>Sample D</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Epoxy (only)</strong></td>
<td>Epoxy</td>
<td>SiO$_2$-EMC</td>
<td>new-EMC</td>
<td>new-EMC</td>
</tr>
<tr>
<td></td>
<td>(only)</td>
<td>Vf-1</td>
<td>Vf-2</td>
<td>Vf-1</td>
</tr>
<tr>
<td><strong>Thermal Conductivity, W/m•K</strong></td>
<td>0.23</td>
<td>1.42</td>
<td>1.89</td>
<td>2.80</td>
</tr>
<tr>
<td><strong>Surface Resistivity, Ω</strong></td>
<td>1.72E+17</td>
<td>1.46E+17</td>
<td>1.88E+10</td>
<td>7.3E+9</td>
</tr>
<tr>
<td><strong>Volume Resistivity, Ω•cm</strong></td>
<td>3.13E+16</td>
<td>6.41E+16</td>
<td>6.10E+10</td>
<td>2.0E+8</td>
</tr>
</tbody>
</table>
Future Work

- Attention in FY12 has turned to consideration and use of:
  - MgO as a filler, its PSD, and Vol %
  - Higher temperature-capable epoxy
- Fundamental studies using monosized spheres with known thermal conductivity as filler
- Seeking EMC thermal conductivity > 10 W/mK
- Greater interaction with VTP PEEM motor project with NTRC/ORNL's J. Miller
• Identifying and developing lower-cost and better-performing organic compounds for dielectric and thermal management applications in power electronics, electric motors, and film capacitors.

• Comparing epoxy molding compounds (EMCs) of unused and used components through thermal and microstructural characterization.

• Developing new EMCs with high thermal conductivity, that have predictable and simple processing characteristics, and are inexpensive.