Thermally Conductive Organic Dielectrics for Power Electronics and Electric Motors

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Overview

Timeline

- Project start: October 2010
- Project end: September 2013
- Percent complete: 83%

Budget

- Total project funding
  - DOE 100%
- FY11: $250k
- FY12: $150k
- FY13: $100k

* VTP Multi-Year Program Plan 2011-2015

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

- OVT Advanced Power Electronics and Electric Motor (APEEM) Program – ORNL/NTRC
- SolEpoxy (Epoxy molding compound, EMC, manufacturer)
- Ube (powder manufacturer)

Objectives

- **Develop low-cost, high-performance epoxy molding compounds (EMCs) for automotive (AEV, HEV) power electronics and electric motors.**
- **Reduce volume and improve thermal reliability of power electronics and electric motors via improved or new thermal management strategies.**
- **Develop EMCs that have:**
  - **Sufficient low cost for automotive applications**
  - **Sustained dielectric performance**
  - **High thermal conductivity (≥ 5 W/mK)**
  - **No magnetic susceptibility**
  - **Use non-toxic and inexpensive filler**
  - **Equivalent potting and injection molding characteristics to existing EMCs**

Milestones

- **FY12: Model, design, and fabricate filler-containing-EMC having 10x thermal conductivity increase over monolithic epoxy. *Achieved: 3.0 W/mK compared to 0.2 W/mK.***

- **FY13: Fabricate a thermally conductive EMC structure with a Joule-heated, surrogate electronic device, measure its maximum temperature, and compare to the maximum temperature when a conventional EMC is used. *30 Sep 2013 – On track.***

Technical Approach

- Optimize filler particle size distribution and volume fraction.
- Fabricate EMCs with organic matrices that allow transfer molding and potting.
- Demonstrate thermal conductivity (κ) ≥ 5 W/mK.

Candidate Filler Properties

FY12 Focus → Boron nitride hexagonal (h-BN)

SOA → Silica (SiO_2) or silicon dioxide, crystalline quartz

Material	Electrical Resistivity at 25°C - ρE - (Ω•cm)	Thermal Conductivity at 25°C - κ - (W/m•K)	Heat Capacity - Cp - (J/kg•K)	Density - ρ - (g/cm³)	Coefficient of Thermal Expansion - CTE - (x 10^{-6}/°C)	Knoop Hardness (GPa)	Estimated Cost ($/kg)
Alumina (Al_2O_3) or aluminum oxide	> 10^{14}	30	900	3.9	8	14	5
Aluminum nitride (AlN)	> 10^{14}	250	700	3.2	5	12	50-200
Beryllia (BeO) or beryllium oxide	> 10^{14}	280	600	2.9	9	12	800-1000
Boron nitride hexagonal (h-BN) * Anisotropic	> 10^{14}	275*	1600	1.9	1*	4	40-50
Magnesia (MgO) or magnesium oxide	> 10^{14}	40	900	3.6	10	7	5
Mullite ($2SiO_2$•$3Al_2O_3$)	> 10^{14}	5	900	2.8	6	8	5
Silica (SiO_2) or silicon dioxide *crystalline quartz*	> 10^{14}	14	700	2.6	0.5	7	0.3
Silica (SiO_2) or silicon dioxide *fused silica or fused quartz*	> 10^{16}	1	700	2.2	0.5	5	1
Epoxy	> 10^{14}	0.05 - 0.5	1500	1.2	30-60	N/A	5

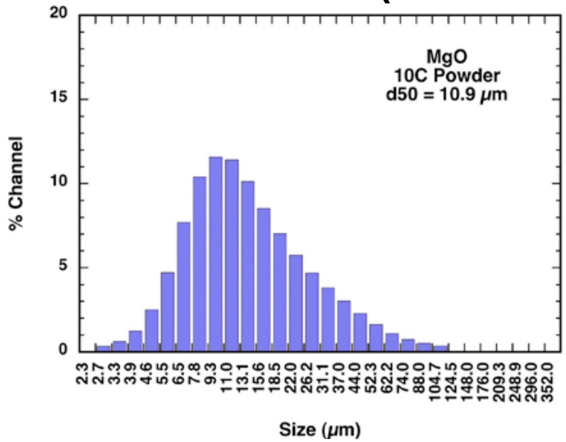
Technical Accomplishments (1 of 8)

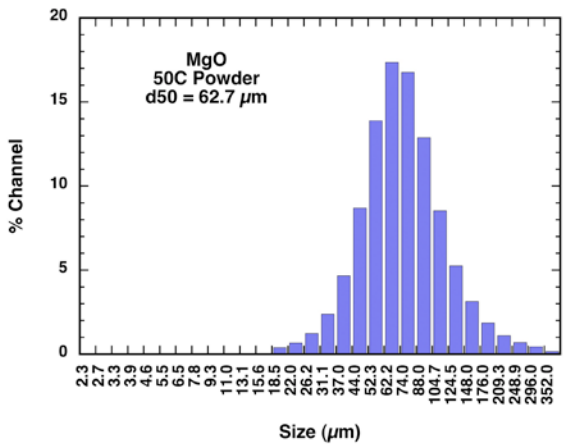
Overview of Year's Accomplishments:

- **Identified approximate filler particle size distribution (PSD) and volume fraction (Vol%)**
- **Developed software to predict thermal diffusivity as a function of PSD and Vol%**
- **Transient thermal model developed using PDS and Vol%**
- **Modeled effect of higher κ on components**
- **Thermal conductivity of 3 W/mK achieved with MgO-filled EMCs which is 2x higher than state-of-the-art EMCs**
- **Invention disclosure submitted on hybrid-filled EMCs**

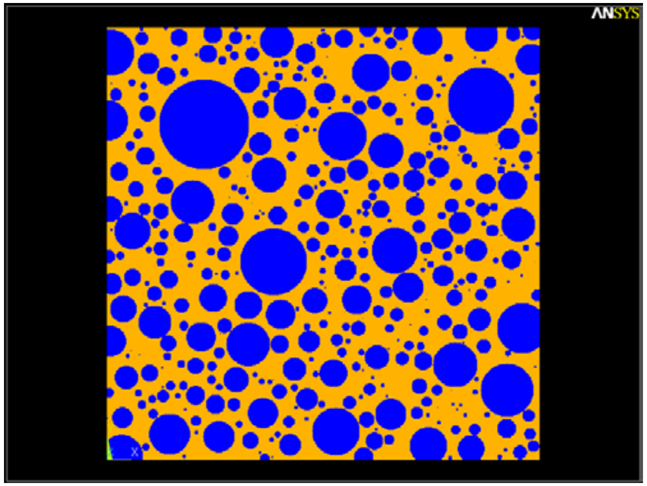
Software Was Developed to Create 2D Images of PSDs That in Turn Enables Thermal Conductivity Modeling

Measured PSDs (bimodal)



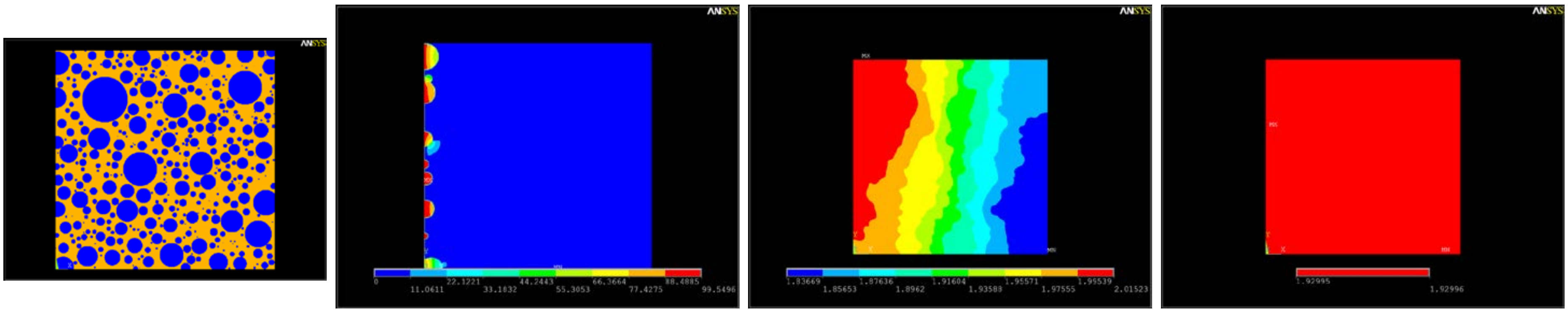


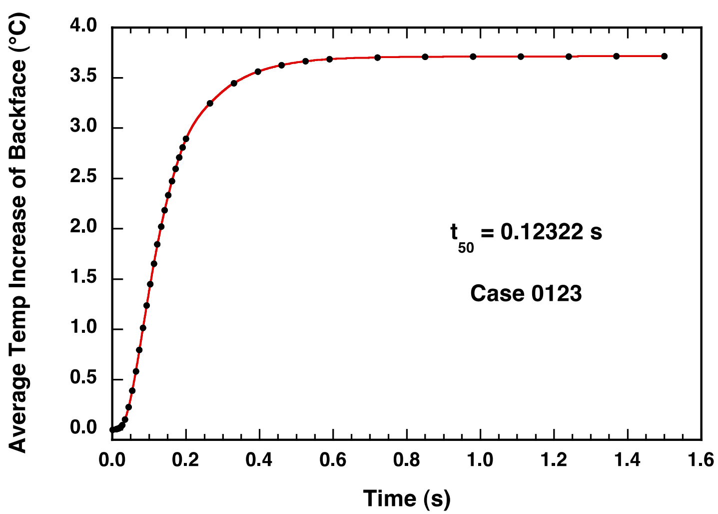
- Particle size distribution (PSD)
- Volume fraction
- Percolation limit
- Effects on thermal conductivity



Transient Thermal Modeling Enables Estimation of EMC κ

Temperature as a function of time →





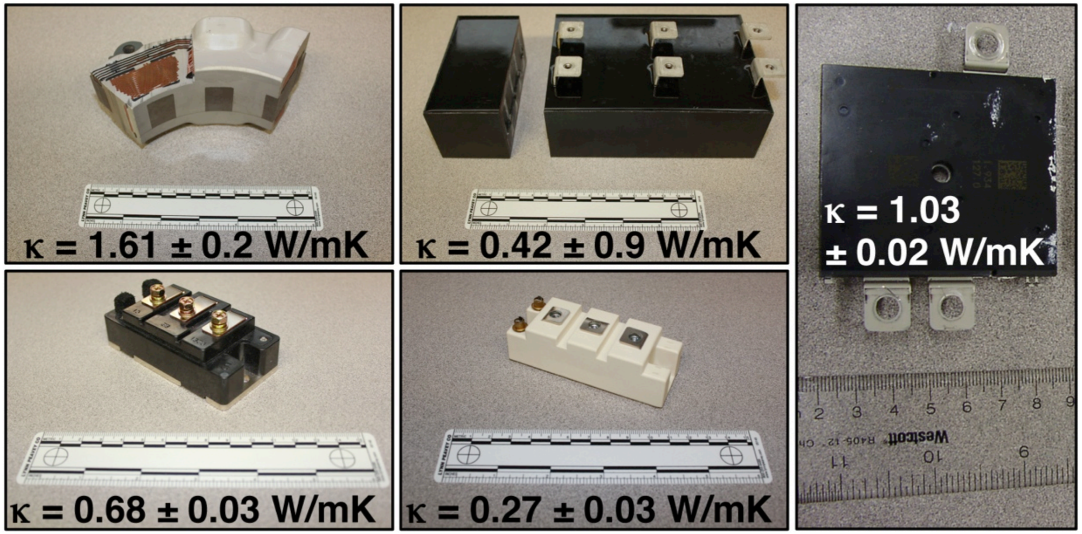
$$D = \frac{\kappa}{\rho \bullet Cp} = \frac{0.1388 \bullet T^2}{t_{50}}$$

D = diffusivity
κ = thermal conductivity
ρ = density
Cp = heat capacity
T = thickness
t_{50} = time to reach 50% max temp

Technical Accomplishments (4 of 8)

- **Power electronic and electric motor component exteriors have low thermal conductivity**
- **Strive to increase their thermal conductivity and enable additional approaches to thermal management**
- **Improved cooling, performance, and reliability**

Electric Motor Component | **Film Capacitor** | **Power Module**

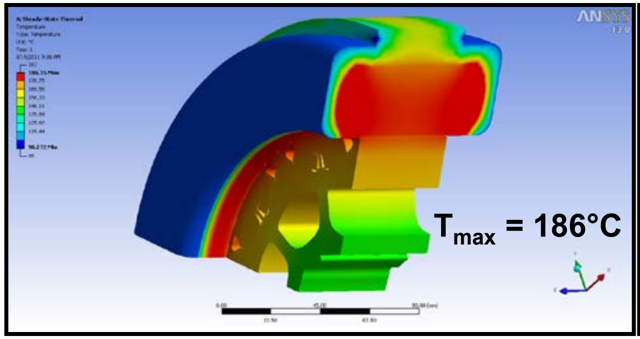


IGBT Module | **IGBT Module**

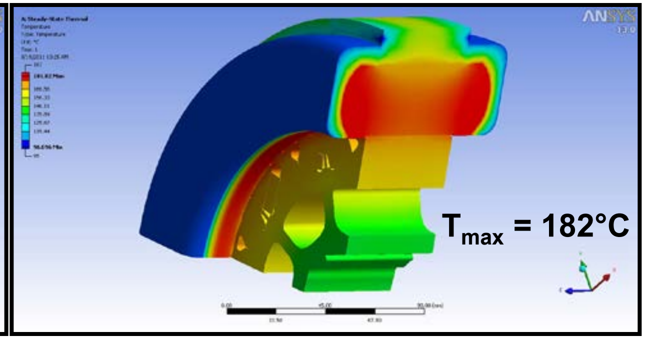
Technical Accomplishments (5 of 8)

Motor Component FEA Example: Effect of EMC κ

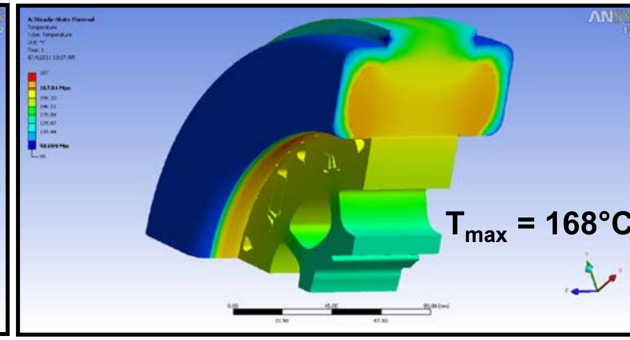
κ = 0.5 W/mK



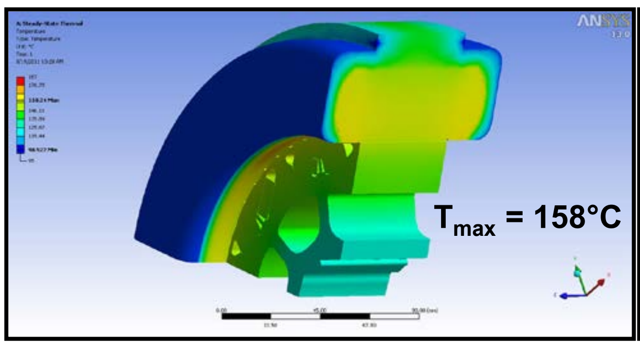
κ = 1.0 W/mK



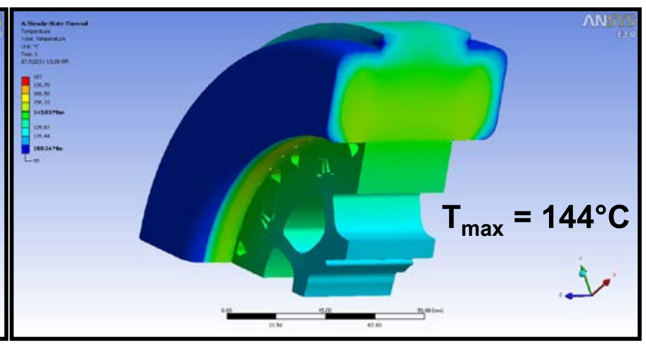
κ = 3.0 W/mK



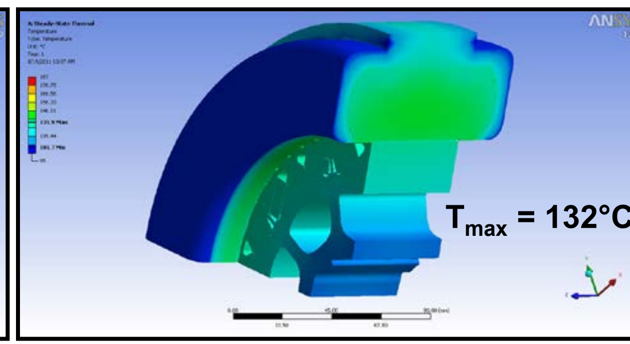
κ = 5.0 W/mK



κ = 10 W/mK



κ = 20 W/mK

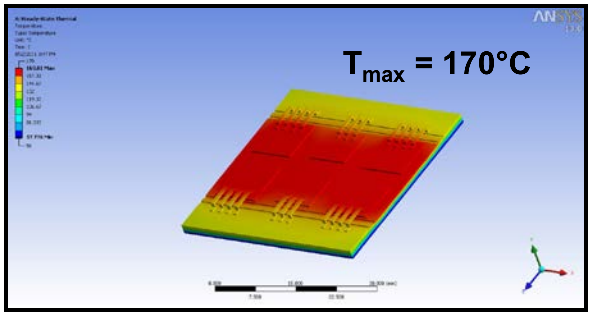


10% temperature decrease with 3 W/mK for this example

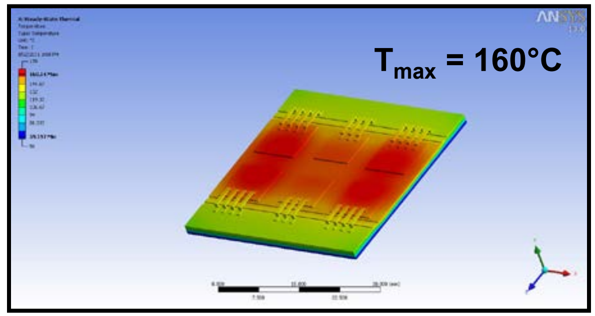
Technical Accomplishments (6 of 8)

Power Module FEA Example: Effect of EMC κ

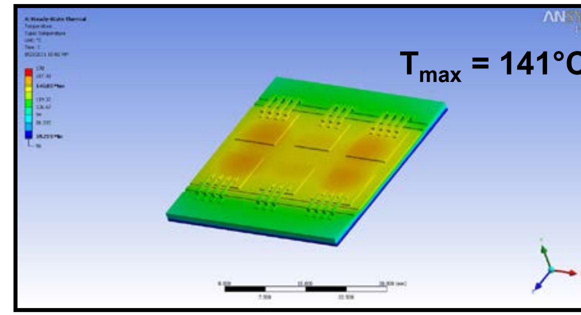
κ = 0.5 W/mK



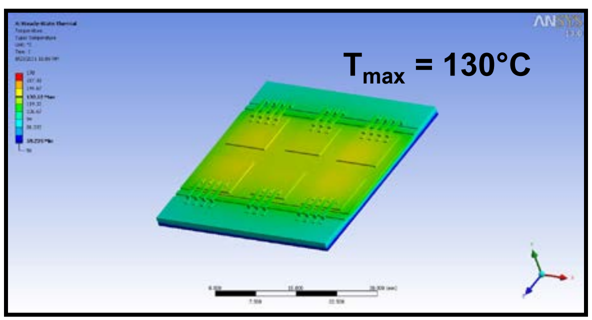
κ = 1.0 W/mK



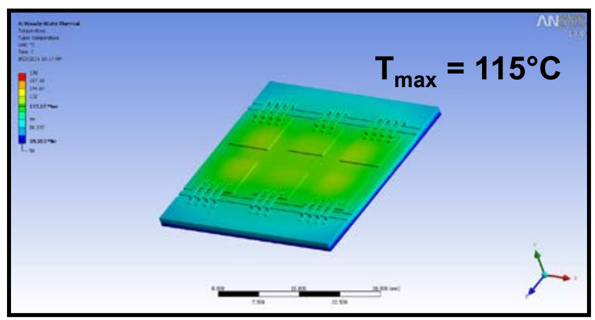
κ = 3.0 W/mK



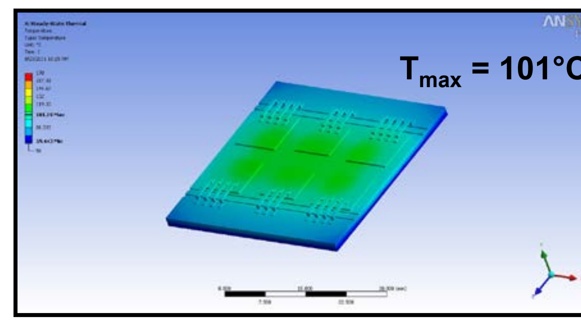
κ = 5.0 W/mK



κ = 10 W/mK



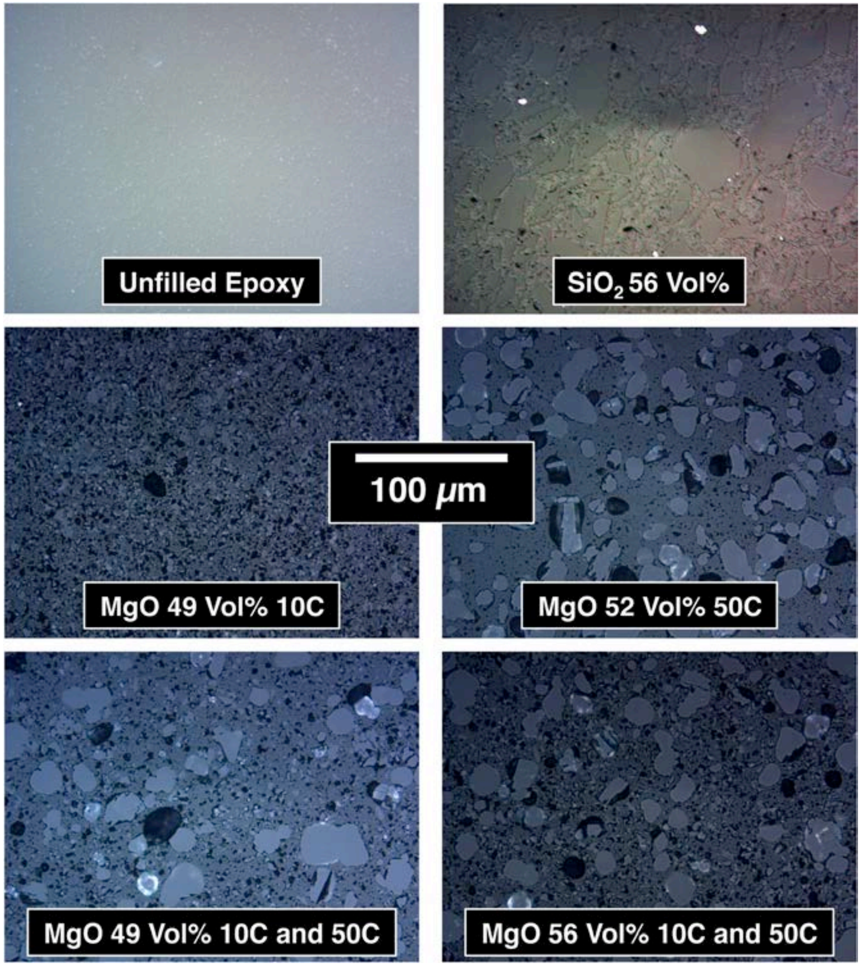
κ = 20 W/mK

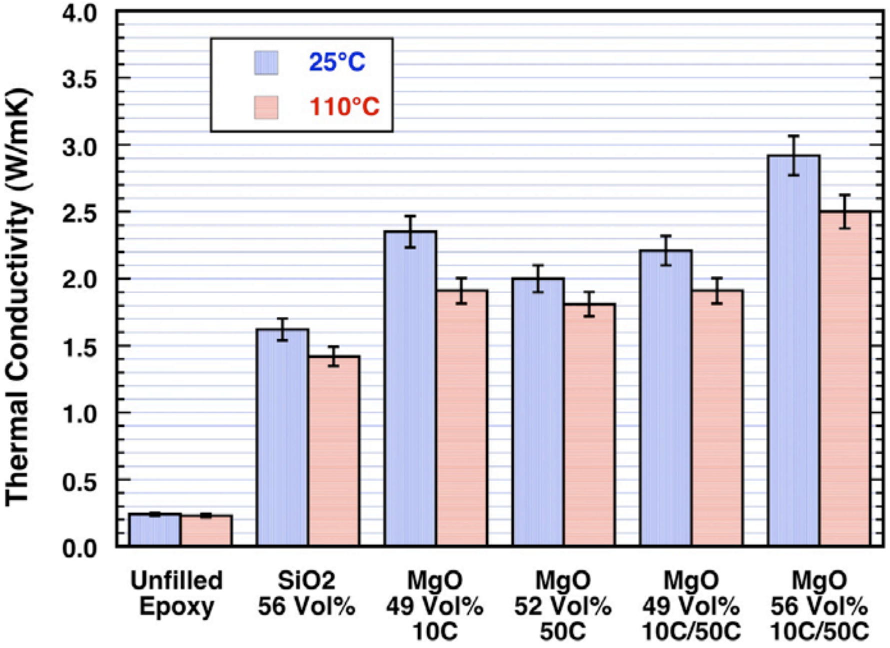


17% temperature decrease with 3 W/mK for this example

Technical Accomplishments (7 of 8)

Thermal Conductivity of 3 W/mK Achieved with MgO-EMCs





Technical Accomplishments (8 of 8)

Property	Unfilled Epoxy	SiO_2 56 Vol%	MgO 49 Vol% 10C	MgO 52 Vol% 50C	MgO 49 Vol% 10C-50C	MgO 56 Vol% 10C-50C
Filler	None	SiO_2	MgO	MgO	MgO	MgO
Weight % Filler	0	74	74	76	74	79
Volume % Filler	0	56	49	52	49	56
Spiral Flow (cm)	250+	61	104	101	109	86
Gel Time (sec)	22	24	22	17	19	23
Density (g/cc)	1.19 ± 2%	2.00 ± 2%	2.35 ± 2%	2.42 ± 2%	2.36 ± 2%	2.52 ± 2%
Dielectric Strength of 900 µm thick film (kV/mm)	54	40	37	32	40	32
Surface Resistivity at 500 V (Ω)	4.8×10^{15}	1.5×10^{17}	4.9×10^{15}	5.1×10^{15}	5.0×10^{15}	4.2×10^{15}
Volume Resistivity at 500 V (Ω•cm)	7.2×10^{15}	6.4×10^{16}	4.9×10^{15}	5.9×10^{15}	6.0×10^{15}	5.4×10^{15}
Dielectric Constant at 10kHz	3.54	3.82	5.51	5.13	5.66	6.18
Dissipation Factor at 10kHz	0.0089	0.0060	0.0048	0.0030	0.0063	0.0065
Thermal Conductivity at 25°C (W/mK) ORNL hot disk method	0.24 ± 5%	1.62 ± 5%	2.35 ± 5%	2.00 ± 5%	2.21 ± 5%	2.92 ± 5%
Thermal Conductivity at 110°C (W/mK) SolEpoxy hot disk method	0.23	1.42	1.91	1.81	1.91	2.50
Estimated Softening Temperature from Dilatometry (°C)	132 ± 5%	170 ± 5%	145 ± 5%	147 ± 5%	147 ± 5%	146 ± 5%
Coefficient of Thermal Expansion (x 10^{-6}/°C)	64 ± 5%	32 ± 5%	30 ± 5%	30 ± 5%	32 ± 5%	30 ± 5%
Elastic Modulus (GPa)	3.0 ± 5%	18.4 ± 5%	18.7 ± 5%	19.7 ± 5%	18.1 ± 5%	24.1 ± 5%
Poisson's Ratio	0.32 ± 5%	0.25 ± 5%	0.28 ± 5%	0.25 ± 5%	0.27 ± 5%	0.25 ± 5%
Weight Gain After 800h in Water (mg) Nominal sample size: 50 mm dia. x 12.6 mm t or Area = 59 cm^2	90	27	57	59	58	60

MgO-EMCs:

- ✓ Good processibility
- ✓ High dielectric strength
- ✓ High electrical resistance
- ✓ Good thermal conductivity
- ✓ Equivalent structural properties to SOA SiO_2-EMCs

Collaborations

- SolEpoxy, Inc. (Olean, NY). An established, renowned EMC manufacturer
  - Supplier to power electronic and motor component manufacturers
  - Fabricated this project's MgO-EMCs in FY12
  - Fabricating this project's hybrid-filled EMC blends in FY13.
- Ube (Japan). An establish MgO supplier
- DOE EERE Office of Vehicle Technologies APEEM Program, J. Miller, ORNL/NTRC: motor components

Future Work

- Seeking EMC thermal conductivity to 5 W/mK via "hybrid" EMCs, which are a blend of MgO and a second filler with higher thermal conductivity
- Continue to collaborate with SolEpoxy and VTP APEEM motor R&D to adapt MgO-EMC compositions to coating of stator components
- Fabricate a thermally conductive EMC structure with a Joule-heated, surrogate electronic device, measure its maximum temperature, and compare to the maximum temperature when a conventional EMC is used

Summary

- **Relevance:** thermally-conductive EMCs will lower maximum operating temperature of automotive PEs and EMs and improve their reliability
- **Approach:** develop low-cost thermally-conductive MgO-EMCs
- **Collaborations:** a primary and established EMCs manufacturer and VTO APEEM power electronic and electric motor projects
- **Technical Accomplishments:**
  - κ = 3 W/mK achieved inexpensively, and MgO-EMCs are processable, electrically resistive, and magnetically insusceptible. 2x higher κ than state-of-the-art SiO2-EMCs
  - Identified a cost-performance compromise must be struck to get to 5 W/mK.
- **Future work:**
  - Demonstrate that a hybrid-filled EMC that blends (cheap) MgO with a (more expensive) high κ filler can produce κ = 5 W/mK.
  - Implement MgO-EMCs compositions in electric motor stator coatings for R&D in the VTO APEEM Program.