# Dielectrics for Power Electronics Applications

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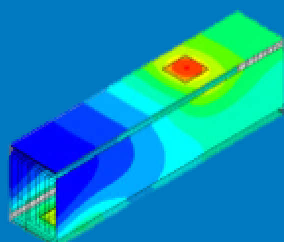
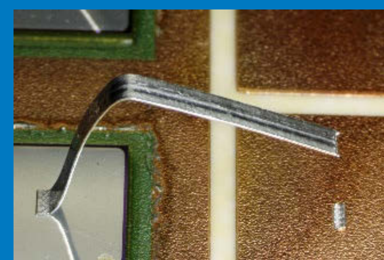
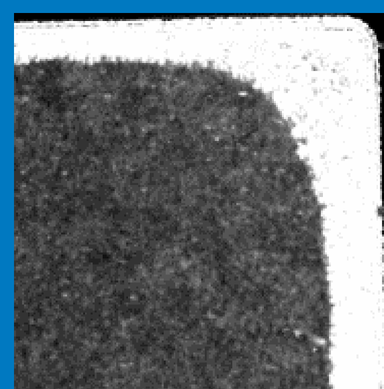
Next Generation Dielectric Materials for Electrical Applications
Massachusetts Institute of Technology, MA
December 4, 2019

# NREL APEEM Group Research Focus Areas

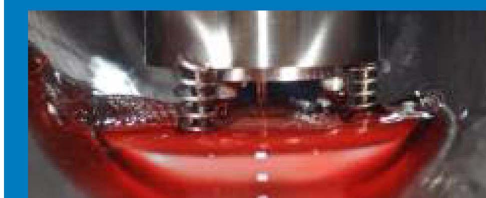
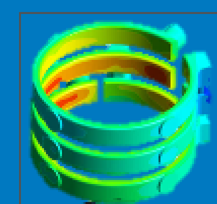
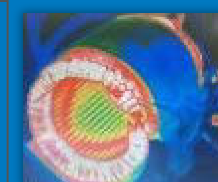
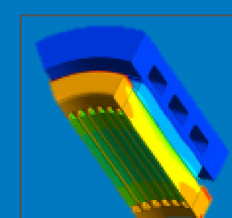
## Power Electronics Thermal Management


## Advanced Packaging Designs and Reliability

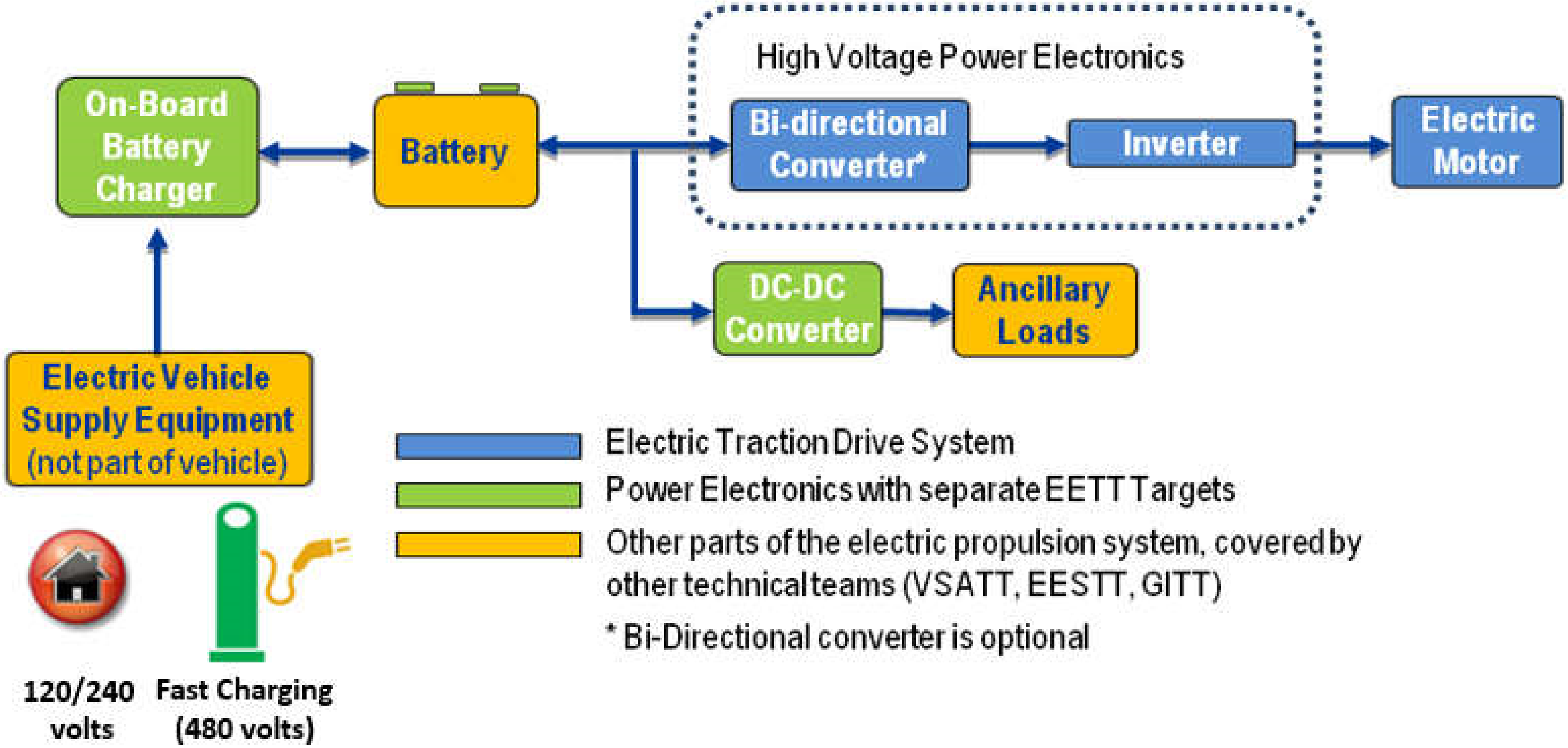



## Electric Motor Thermal Management

*APEEM: advanced power electronics and electric machines*

# Background

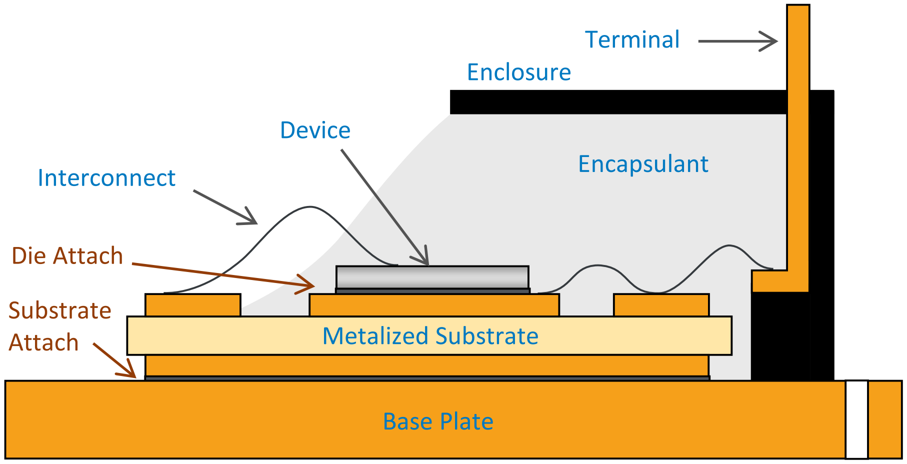



Automotive electric drive system

- Cost
- Power density
- Reliability

*Schematic from 2017 Electrical and Electronics Technical Team (EETT) Roadmap*
*VSATT – Vehicle Systems Analysis Tech Team*
*EESTT – Electrochemical Energy Storage Tech Team*
*GITT – Grid Interaction Tech Team*

# Background

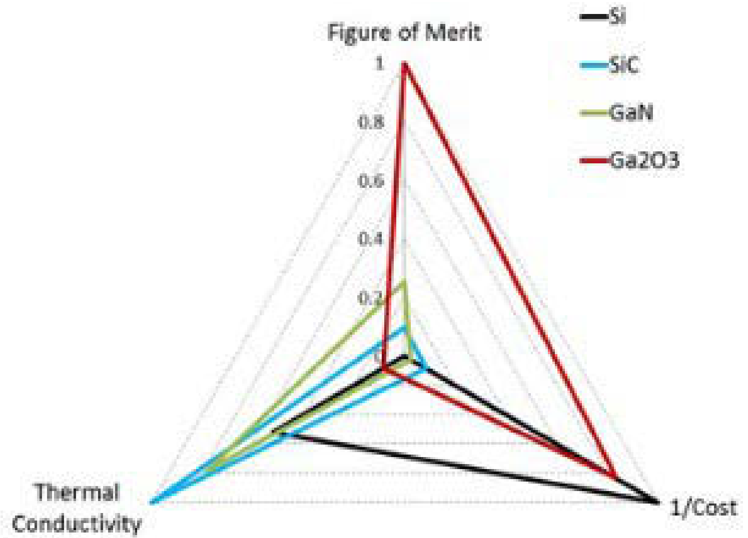



Traditional Power Electronics Package

Maximum operating temperature – 150°C


Cree Wide Bandgap Device Package

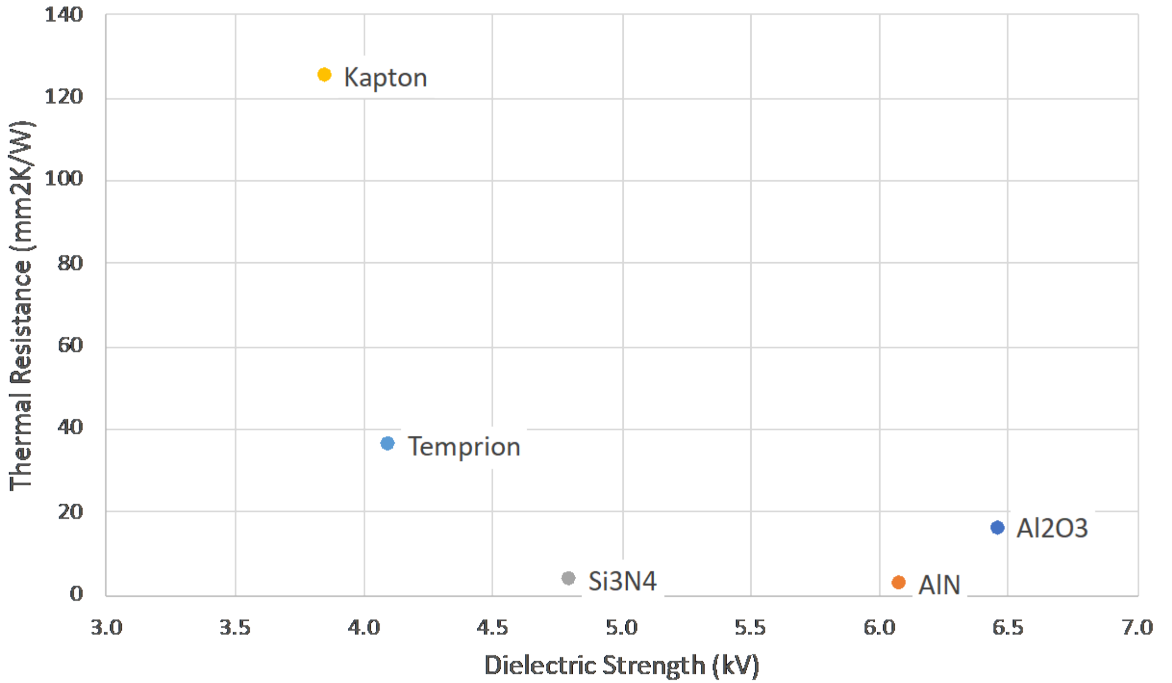
- For wide bandgap devices to operate at higher temperatures, existing packaging configurations need to be modified.



# Part 1 - Dielectric Film

Project in collaboration with DuPont

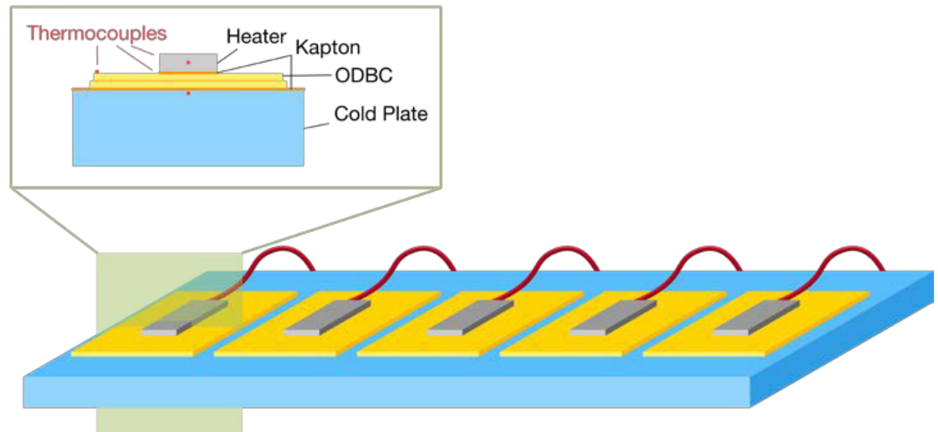
# Substrate Comparison




| Insulator | Thickness (µm) | Dielectric Strength (kV/mm) | Dielectric Strength (kV) | Thermal Conductivity (W/m-k) | Thermal Resistance ($mm^2$-K/W) |
|---|---|---|---|---|---|
| $Al_2O_3$ | 380 | 17 | 6.5 | 24 | 16 |
| AlN | 380 | 16 | 6.1 | 180 | 2 |
| $Si_3N_4$ | 320 | 15 | 4.8 | 90 | 4 |
| Kapton | 25 | 154 | 3.9 | 0.2 | 125 |
| Temprion | 25 | 164 | 4.1 | 0.7 | 36 |

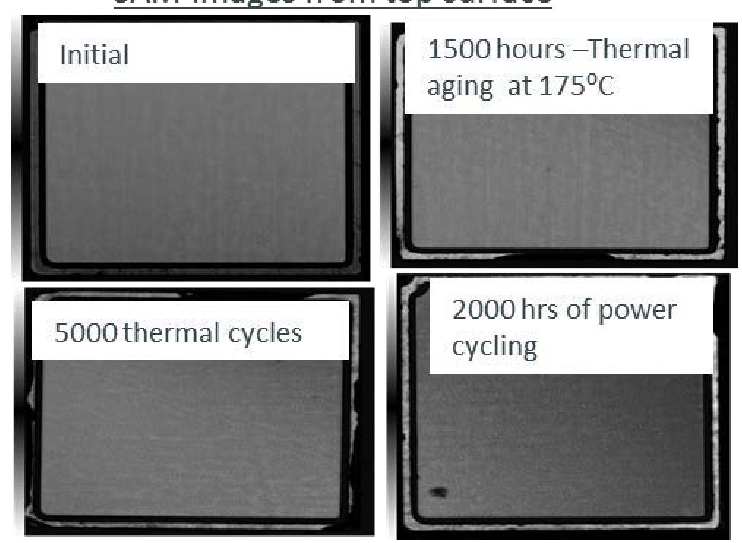
# Reliability Evaluation

- Thermal Shock: -40°C to 200°C, 5-minute dwells
- Thermal Aging: 175°C
- Power Cycling: 40°C to 200°C
- ODBC substrates have reached 5,000 thermal shock cycles, 1,900 thermal aging hours aging, and 2,200 power cycles
- No significant decrease in electrical or thermal performance has been observed




Power Cycling Test Setup

SAM images from top surface

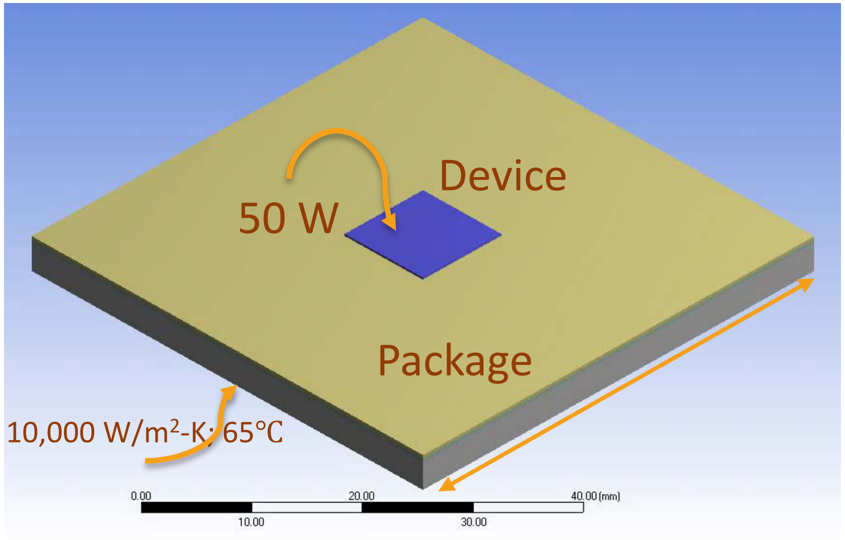


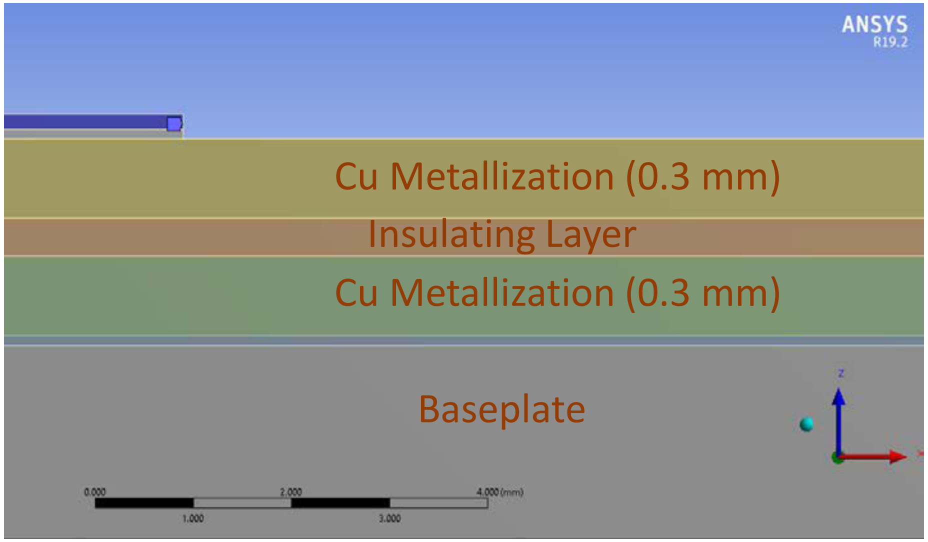


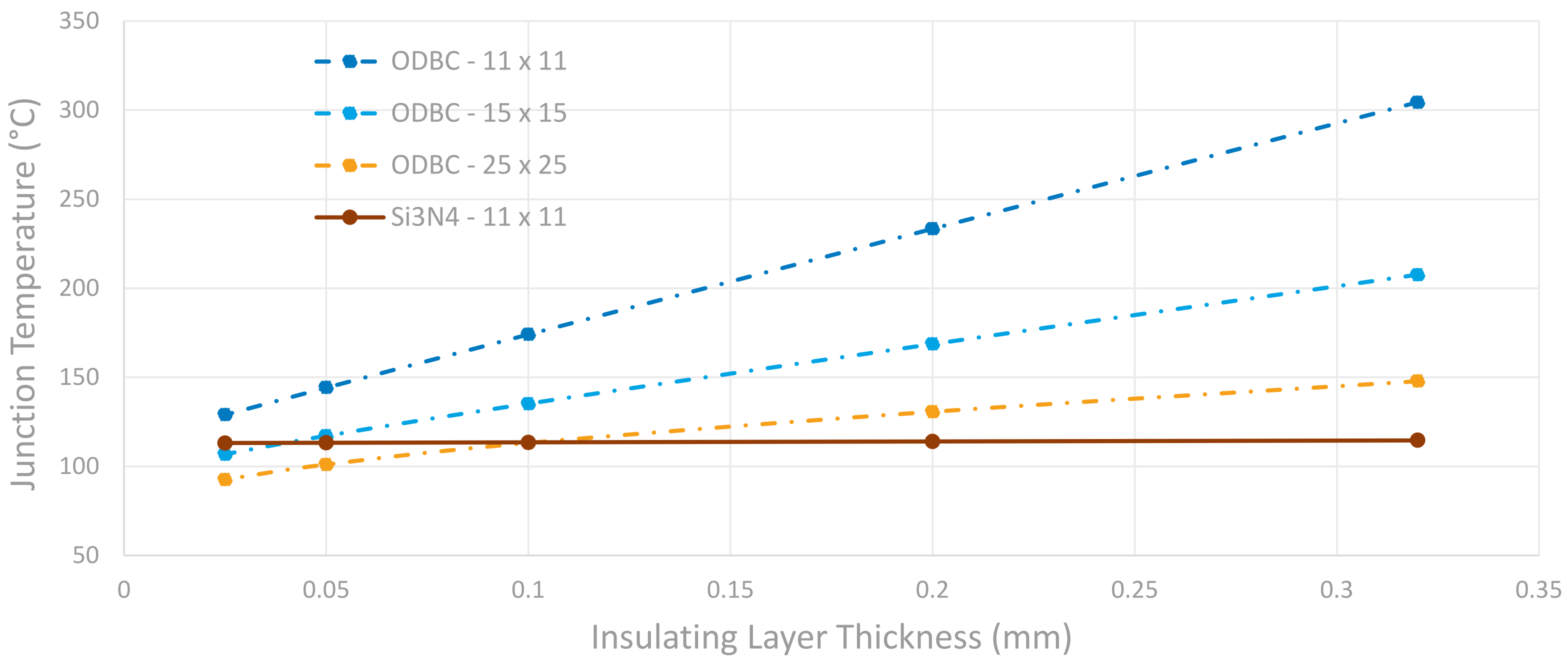
Samples under Thermal Cycling

*ODBC – Organic Direct Bond Copper*
*SAM – Scanning Acoustic Microscope*

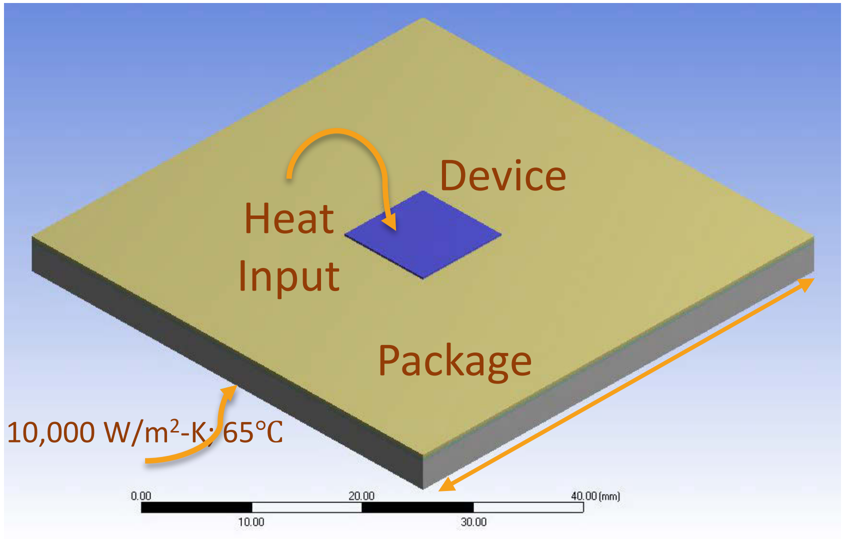
# Thermal Modeling

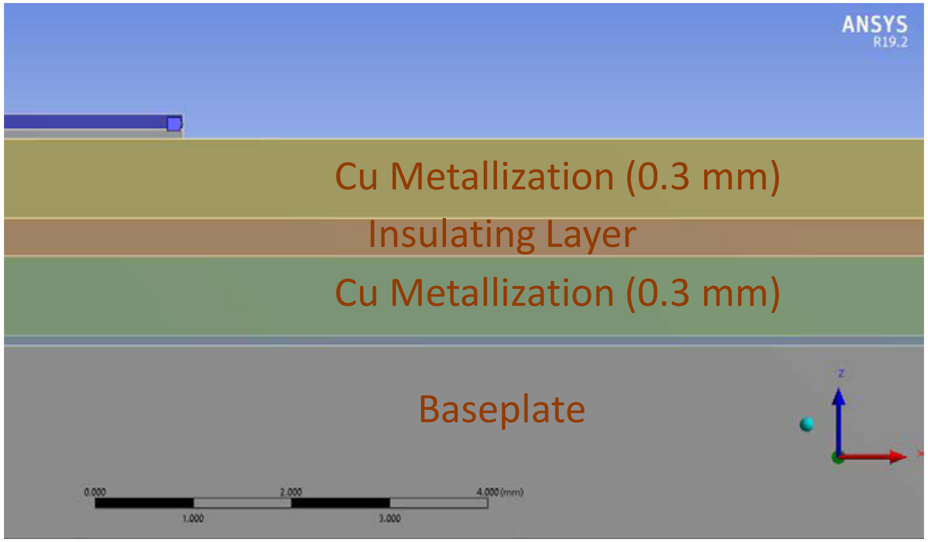


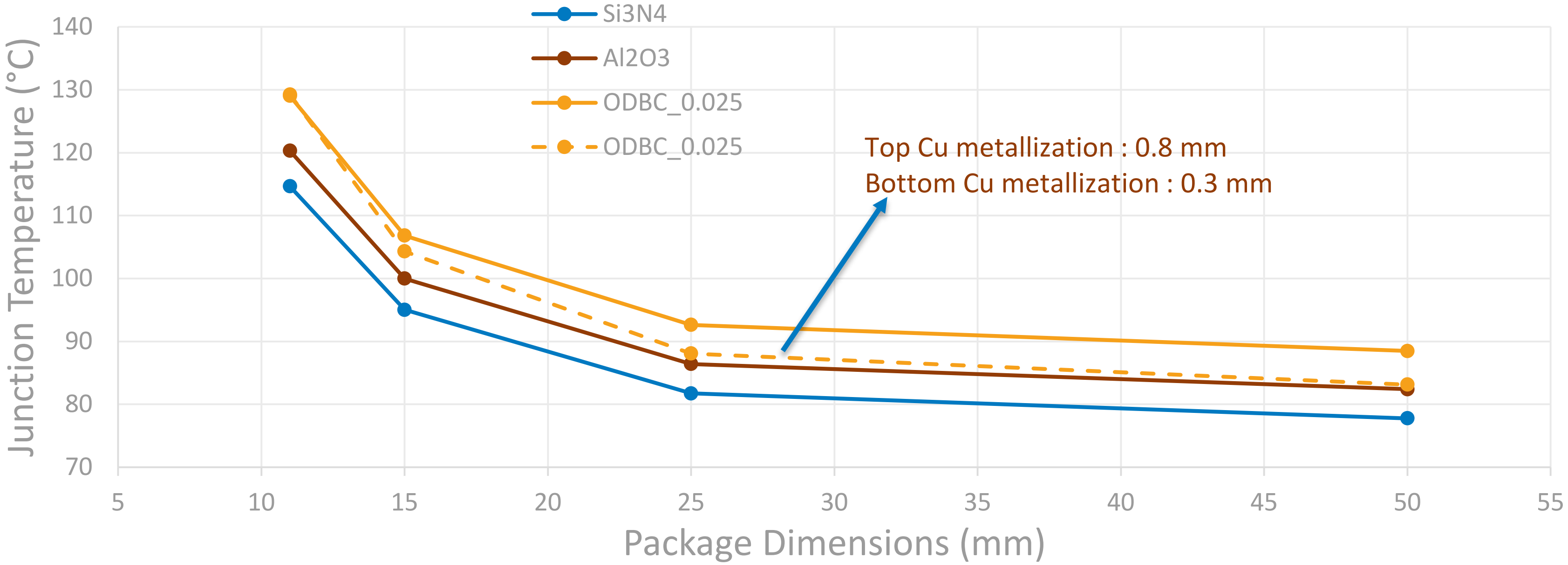



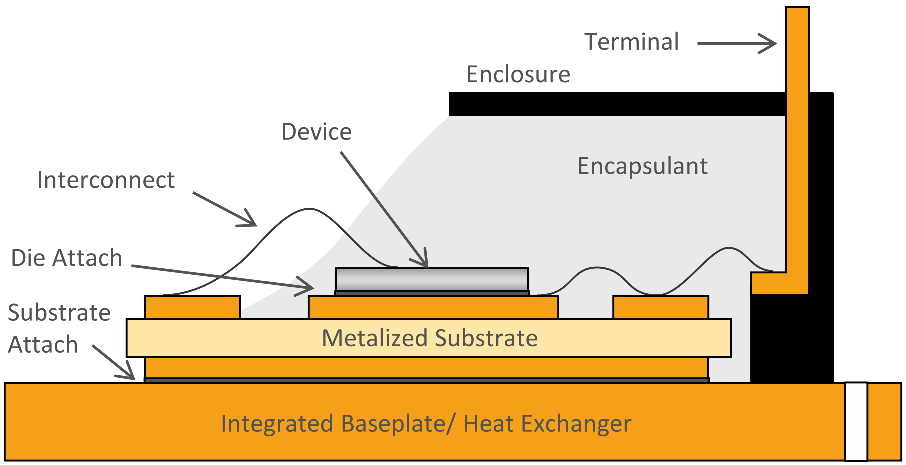
# Thermal Modeling

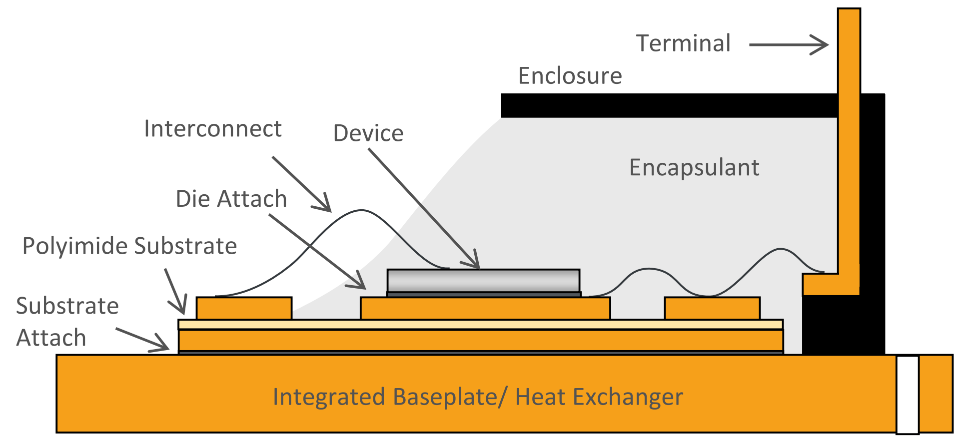


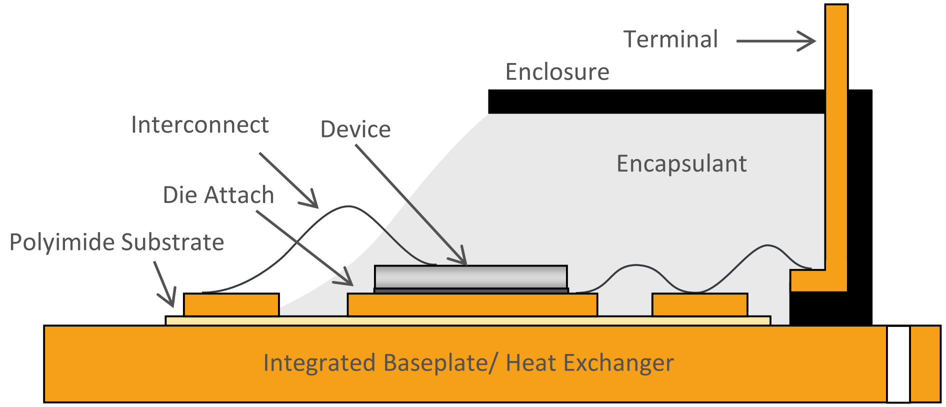



# ODBC Package Designs



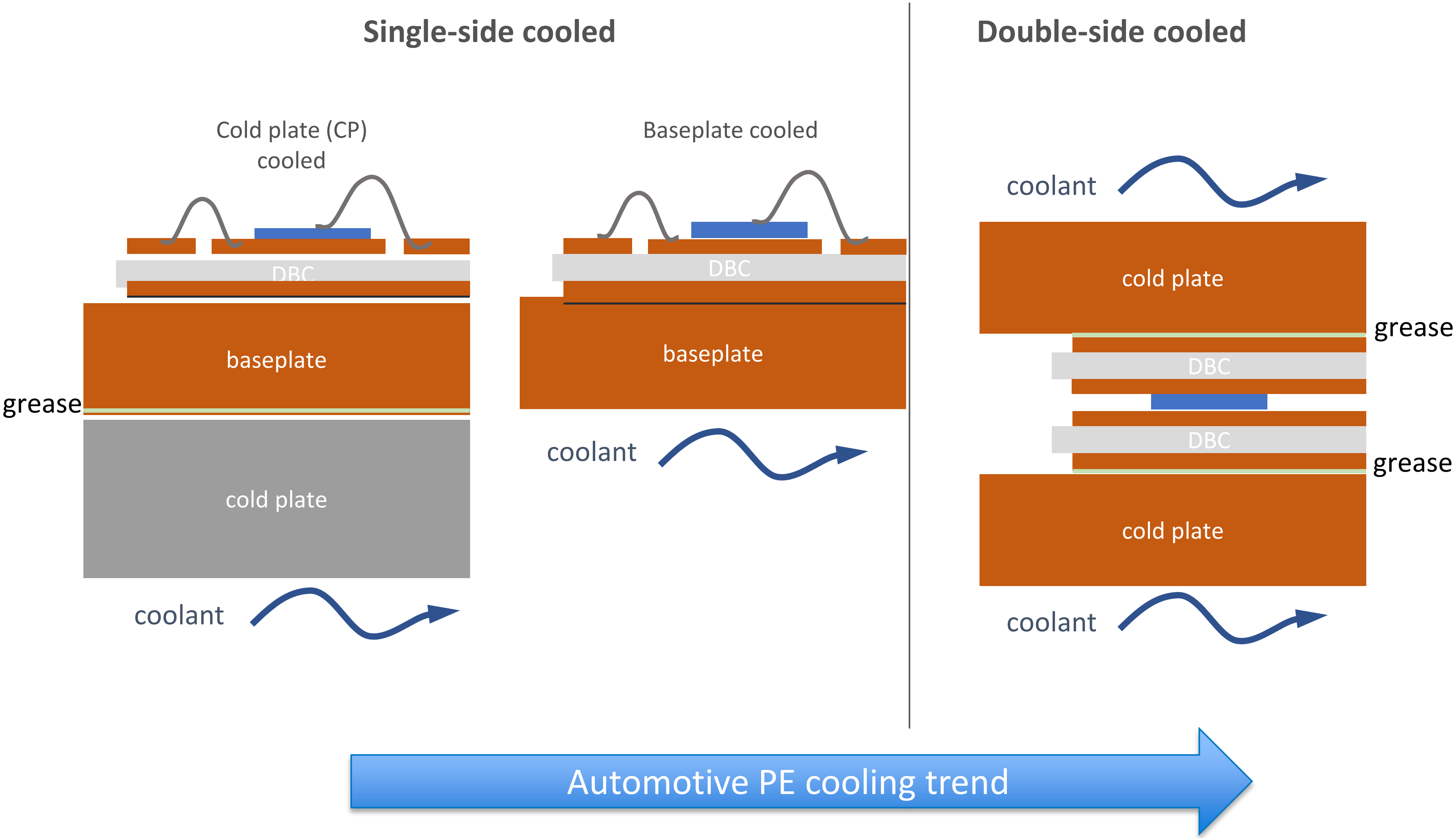



# Part 2 - Dielectric Fluid

Power electronics thermal management

# Thermal Management Strategies



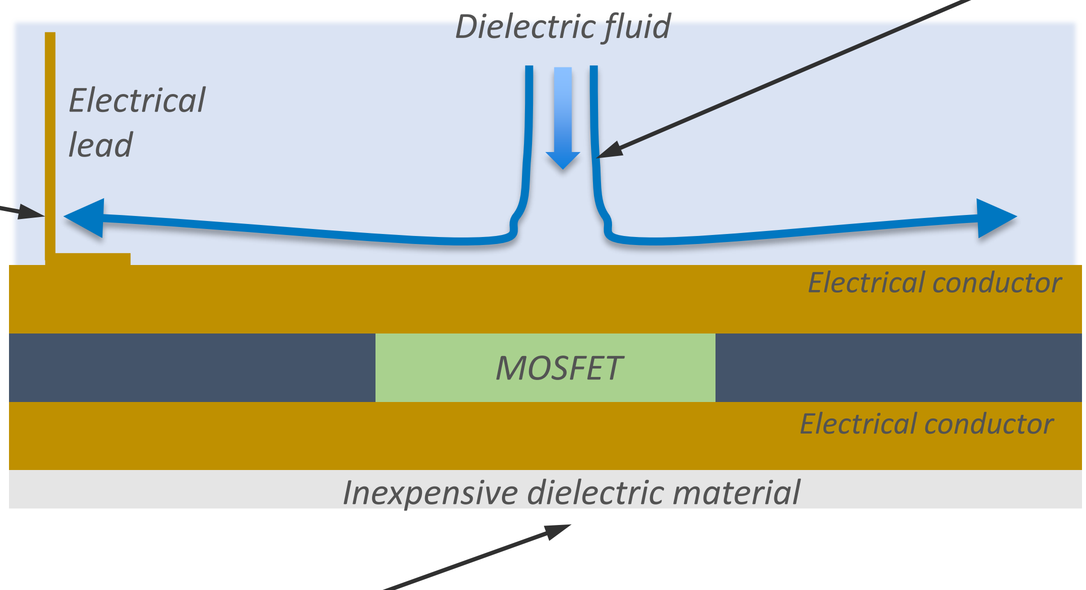

Variations for each cooling configuration exist

*DBC = direct bond copper*

# Dielectric Cooling Concept

Cooling of the bus bars/electrical interconnects to lower capacitor and gate driver temperatures

Improved cooling (single-phase) via jet impingement and finned surfaces




Eliminates expensive ceramic materials

Improved performance over conventional DBC-based designs

*MOSFET - Metal–Oxide–Semiconductor Field-Effect Transistor*
*DBC – Direct Bond Copper*

# Dielectric Fluid Selection

- Selected synthetic hydrocarbons that are used in electronics cooling (single-phase) applications:
  - Alpha 6: DSI Ventures
  - AmpCool (AC)-100: Engineered Fluids
- Potential to use automatic transmission fluid (ATF) to decrease cost, use fluid already qualified for automotive use, and enable motor–inverter integration
- Challenge is to create a cooling system with high thermal performance using fluids with relatively poor thermal properties as compared to water-ethylene glycol (WEG).

| Fluid *(properties at 70°C)* | Thermal Conductivity [W/m-K] | Specific Heat [J/kg-K] | Density [kg/m³] | Viscosity [Pa·s] | Flash Point [°C] | Pour Point [°C] |
|---|---|---|---|---|---|---|
| Alpha 6 [a] | 0.14 | 2,308 | 792 | 0.0091 | 246 | -57 |
| AC-100 [a] | 0.13 | 2,326 | 761 | 0.0025 | 180 | -55 |
| ATF [b] | 0.16 | 2,131 | 836 | 0.012 | 199 | -45 |
| *WEG (50/50)* [c] | *0.42* | *3,513* | *1,034* | *0.0013* | *>121* [d] | *-36* [e] *(freeze point)* |

[a] Communications with vendor (DSI Ventures or Engineered Fluids)
[b] Kemp, Steven P., and James L. Linden. "Physical and Chemical Properties of a Typical Automatic Transmission Fluid." In *1990 Society of Automotive Engineers (SAE) International Fuels and Lubricants Conference and Exposition*, Tulsa, OK, Oct. 22-25, 1990.
[c] Alshamani, Kaisar. "Equations for Physical Properties of Automotive Coolants." In *SAE 2003 World Congress & Exhibition*, Detroit, MI, March 3-6, 2003.
[d] Valvoline. 2016. "Safety Data Sheet ZEREX HD Nitrite Free Extended Life 50/50 Antifreeze Coolant." Accessed April 1, 2019. https://sds.valvoline.com/valvoline-sds/sds/materialDocumentResults.faces.
[e] Valvoline. 2018. "Product Information: Valvoline ZEREX G05 Antifreeze Coolant." https://sharena21.springcm.com/Public/Document/18452/f93a8057-fe75-e711-9c10-ac162d889bd3/c264d227-0dbd-e711-9c12-ac162d889bd1.

# Cooling System Design: Modeling Results

**Optimized dimensions**

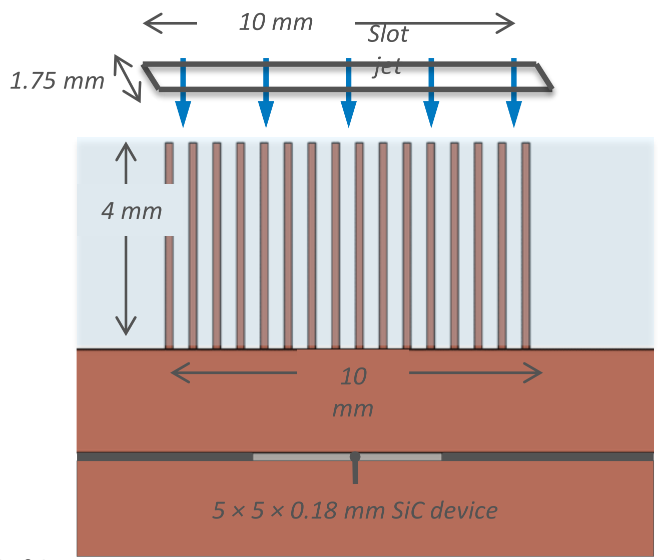
- Slot jet (1.75 × 10 mm) impinging on fins (0.2 × 4 × 10 mm)

**Achieved high thermal performance**

- Heat transfer coefficient 17,300 $W/m^2$-K at a relatively low jet velocity of 0.3 m/s
- Higher performance possible

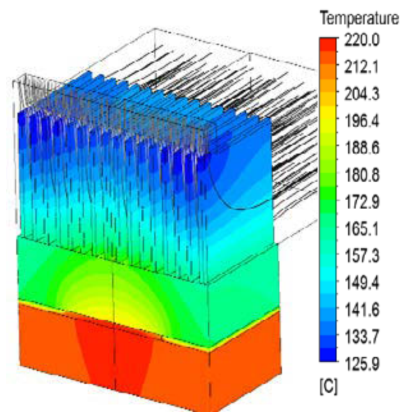
**Decreased size**

- Predict we can dissipate 2.2 kW with 12 devices. Results in a heat flux ~718 $W/cm^2$ at $T_j \approx 220°C$
- **50% lower thermal resistance compared to 2014 Accord Hybrid[1]**




Results using Alpha 6 fluid at $T_{inlet}$ = 65°C

*Planar module, dielectric cooling concept*




*Module temperature contours*

[1] Moreno, G., K. Bennion, C. King, and S. Narumanchi. "Evaluation of Performance and Opportunities for Improvements in Automotive Power Electronics Systems." In *2016 15th IEEE Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems (ITherm)*, Las Vegas, NV, May 31–June 3, 2016, 185–192. https://doi.org/10.1109/ITHERM.2016.7517548.

# Summary

- Automotive power electronics research driven by
  - Cost
  - Power density
  - Reliability.
- ODBC (DuPont) substrates demonstrate excellent thermomechanical reliability.
  - Allows for novel package designs with wide-bandgap devices.
- Dielectric fluids are a viable pathway towards improving the power density of the power electronics package.

## Team Members

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# Thank You

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