# $Ga_2O_3$ Packaging and Thermal Management Challenges and Opportunities

**Third Ultrawide-Bandgap Workshop**
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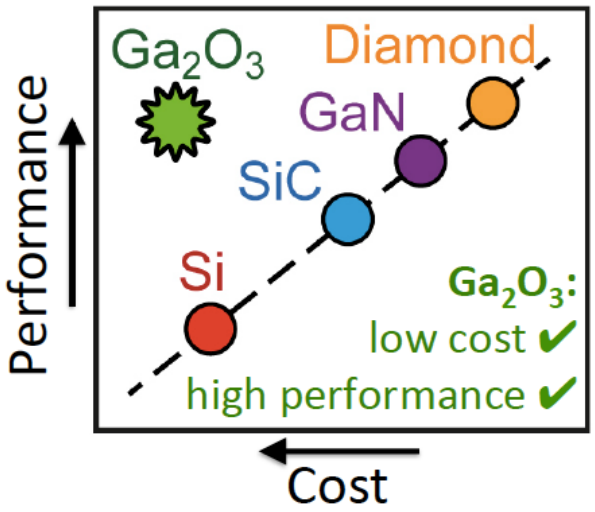
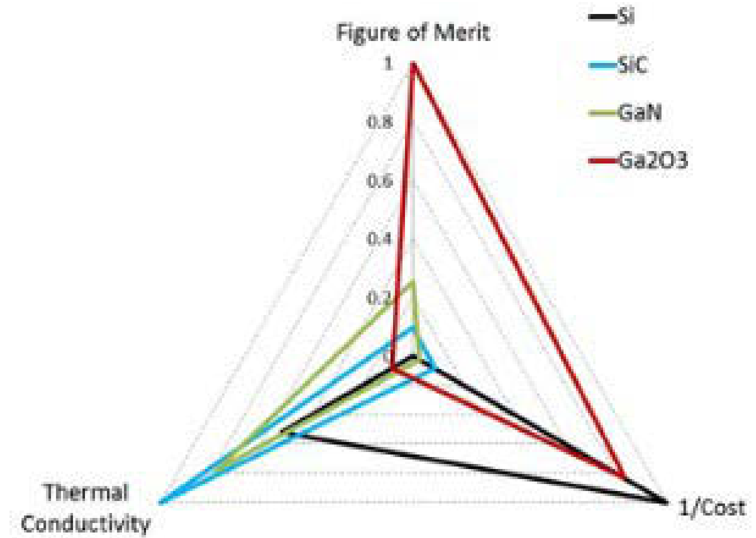
NREL/PR-5400-73902

# **Background**: Why $Ga_2O_3$ WBG Semiconductor

- Currently, most power electronics are made of silicon (Si).
- Wide-bandgap (WBG) semiconductors (SiC, GaN) have better performance but higher cost.
- $Ga_2O_3$ offers a promise to achieve performance of SiC and GaN at the cost of Si.



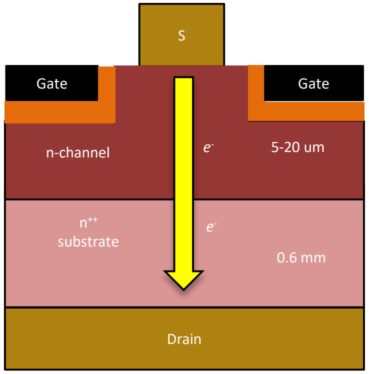

- The theoretical $Ga_2O_3$ figure of merit is ~10x larger compared to SiC.
- The $Ga_2O_3$ crystals may be **3–5x** cheaper compared to SiC crystals.
- Fast-growing field: publications increased 250% in past few years.

GaN: gallium nitride
$Ga_2O_3$: gallium oxide
Si: silicon
SiC: silicon carbide

# **Objective**: $Ga_2O_3$ Packaged Devices and Modules

## Approach

Device modeling → Device fabrication → Device packaging and thermal management



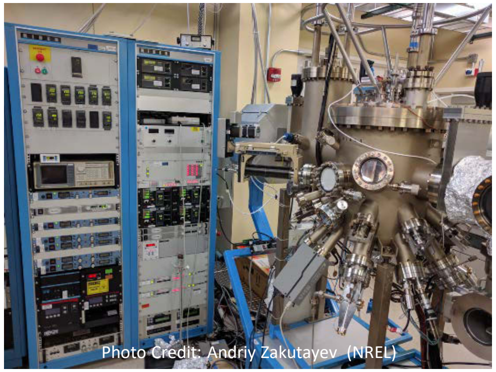



Photo Credit: Andriy Zakutayev (NREL)

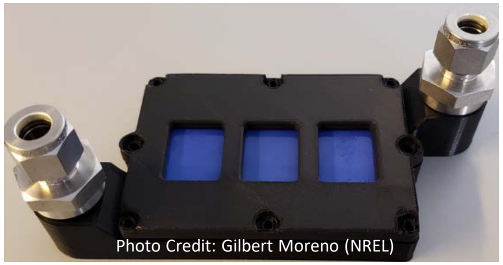
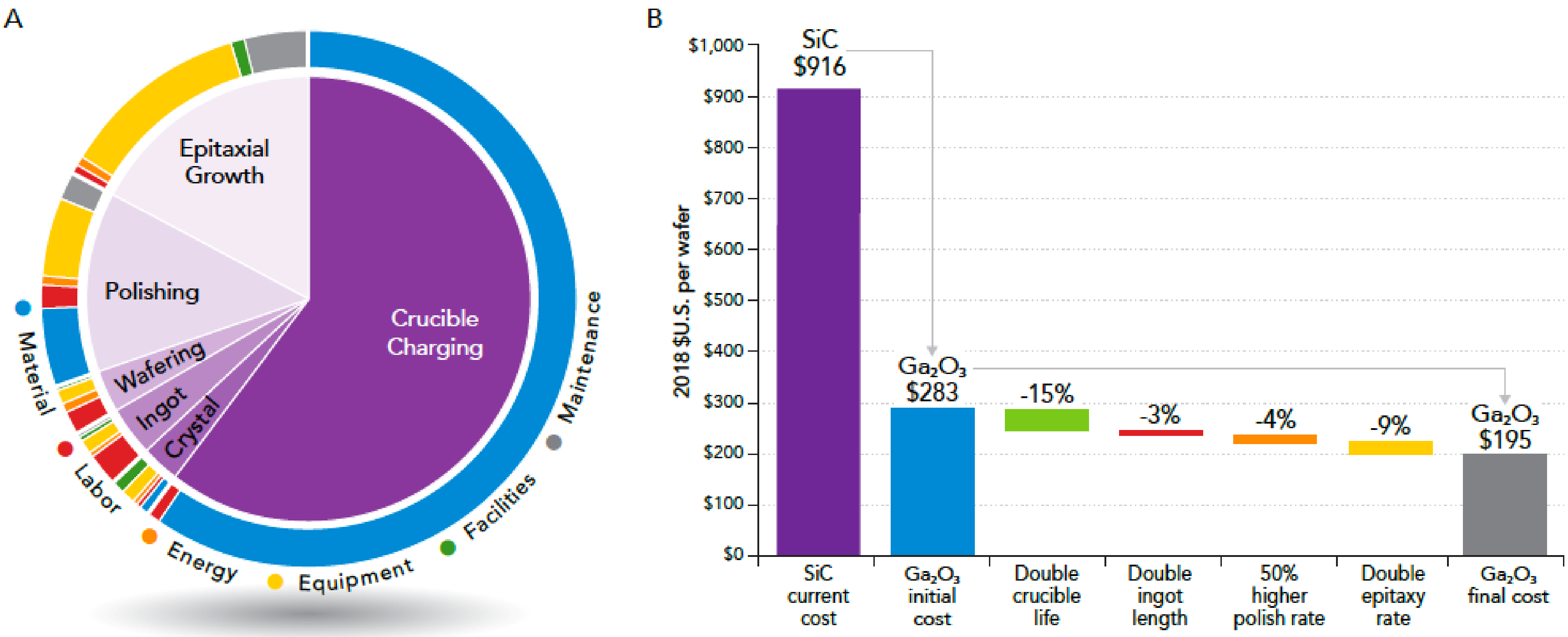


Photo Credit: Gilbert Moreno (NREL)

# Technoeconomic Analysis of $Ga_2O_3$ Wafer Cost

**Method**: Bottom-up technoeconomic analysis with inputs from industry and literature.
**Calculated**: $Ga_2O_3$ wafer cost breakdown, in comparison with verified SiC model.

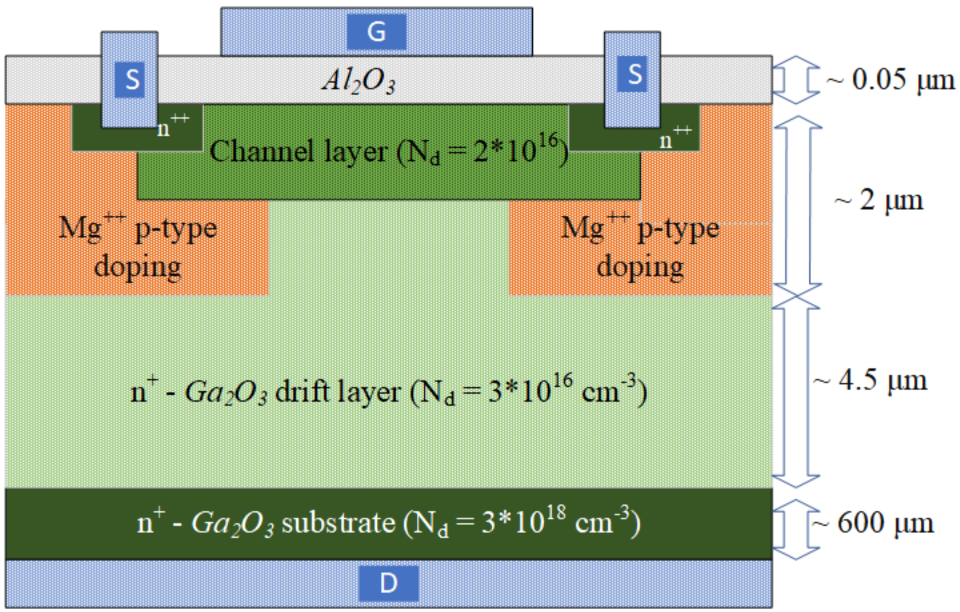



**Preliminary result**: $Ga_2O_3$ wafer cost can be >3–5x lower than SiC – 2x-4x cheaper devices
**Next steps**: Technoeconomic analysis model for $Ga_2O_3$ device and half-bridge modules

S. B. Reese, A. Zakutayev et al. “How Much Will Gallium Oxide Power Electronics Cost?” *Joule* (2019) DOI: 10.1016/j.joule.2019.01.011

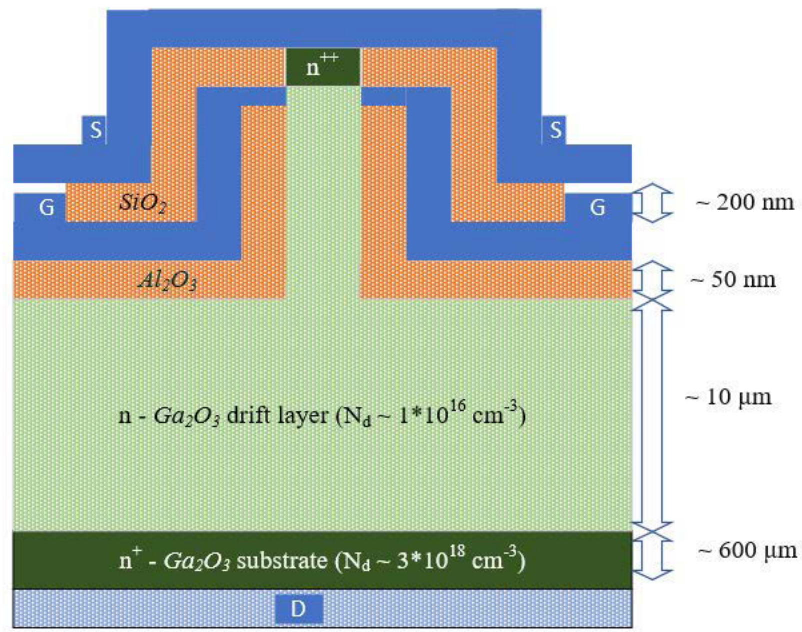
# TCAD Model of $Ga_2O_3$ Device Electrical Performance

**Challenge**: Fabricating power transistors is difficult, modeling is needed as a guide
**Method**: TCAD Finite Element Modeling in Sentaurus Synopsys S.-P. 2D solver
**Inputs**: Device geometry and doping levels
**Outputs**: Transistor *I-V* curves, *CV* curves, transient and thermal curves



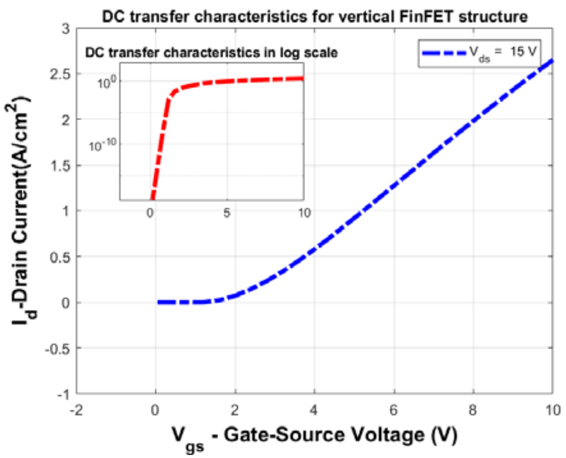

Vertical Planar Structure

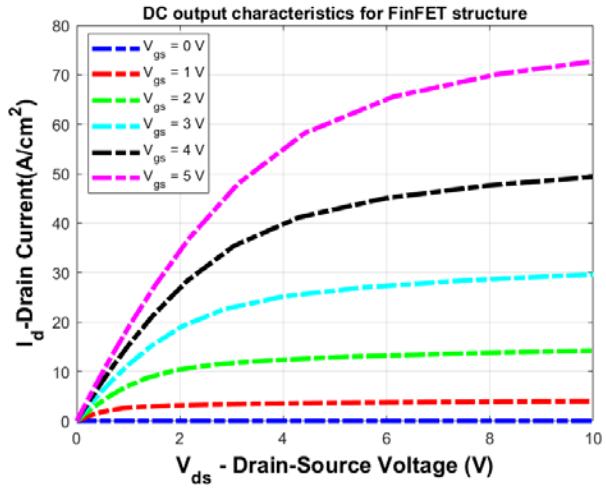
Vertical FinFET structure

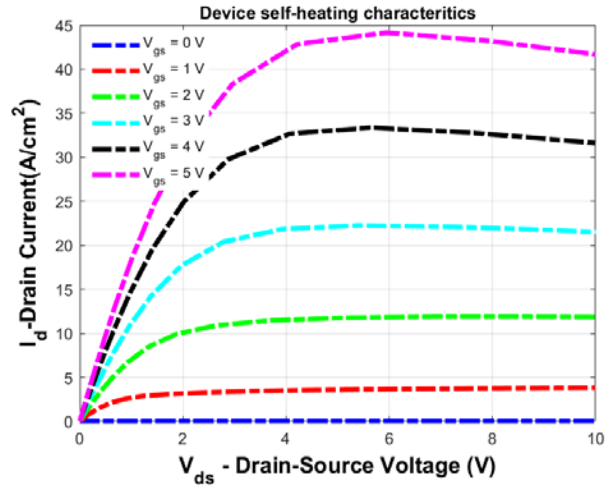


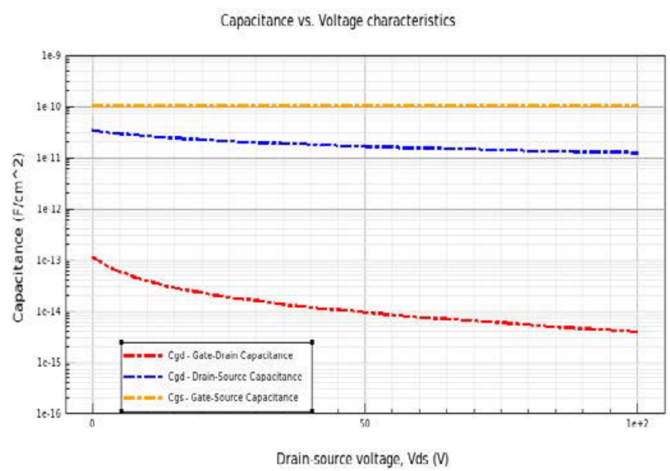

$Al_2O_3$: aluminum oxide
FinFET: Fin Field Effect Transistor
Mg: magnesium
TCAD: Technology computer-aided design

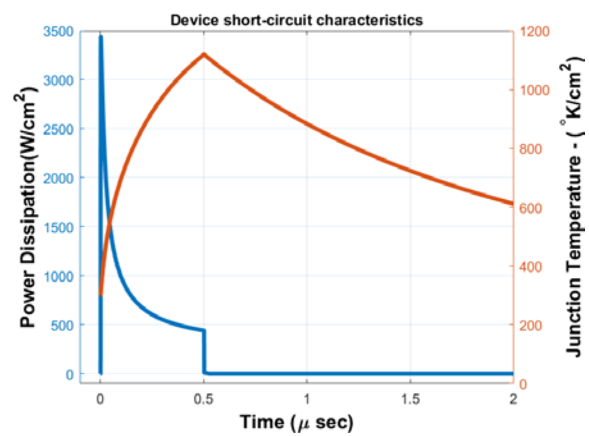
# TCAD Model of $Ga_2O_3$ Device Electrical Performance



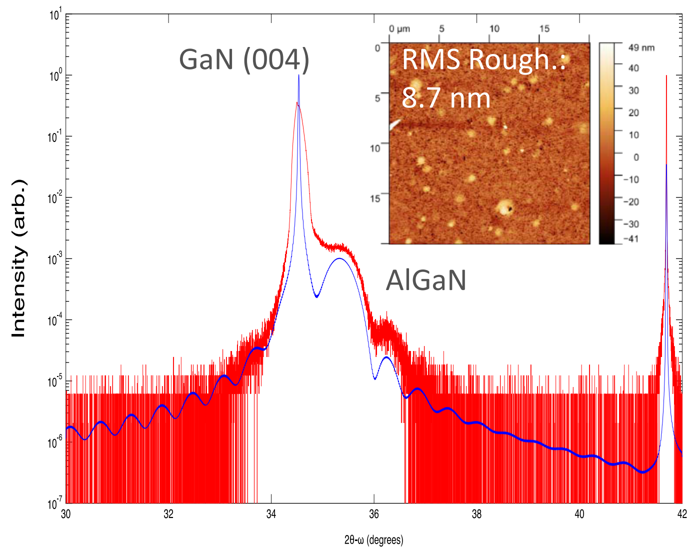



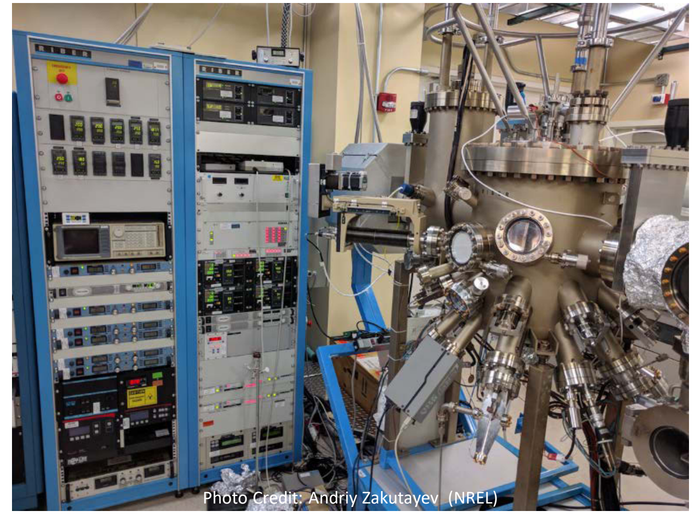



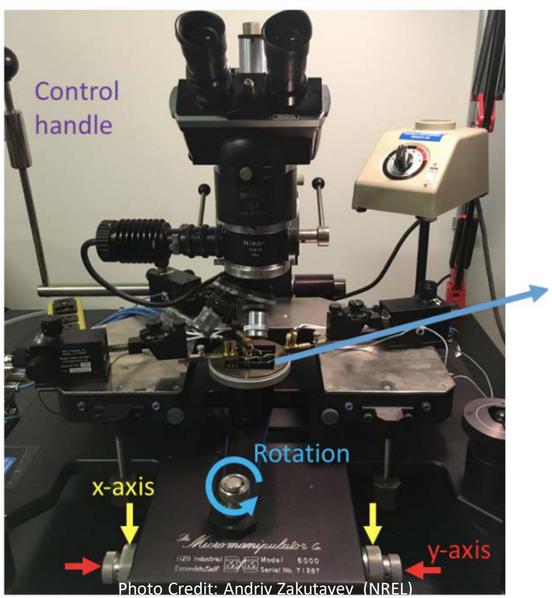



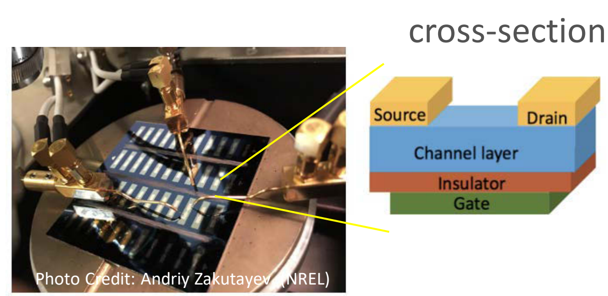

- **Preliminary result**: Good transistor performance is expected from vertical FinFET devices.
- **Next steps**: Thermal performance model, use this data as input to SPICE modeling.

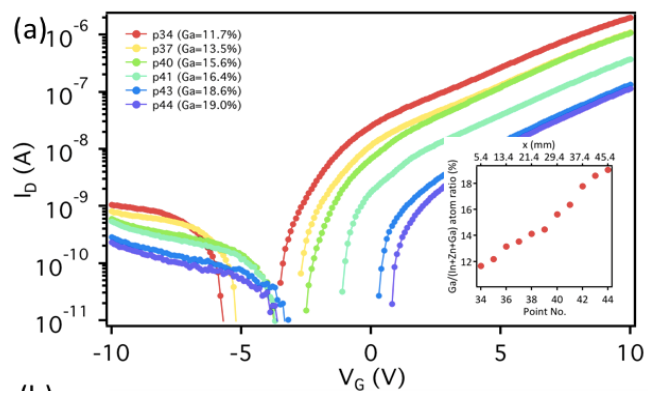
# Oxide Transistor Fabrication and Measurements




AlGaN: aluminum gallium nitride

# $Ga_2O_3$ Thermal Challenges

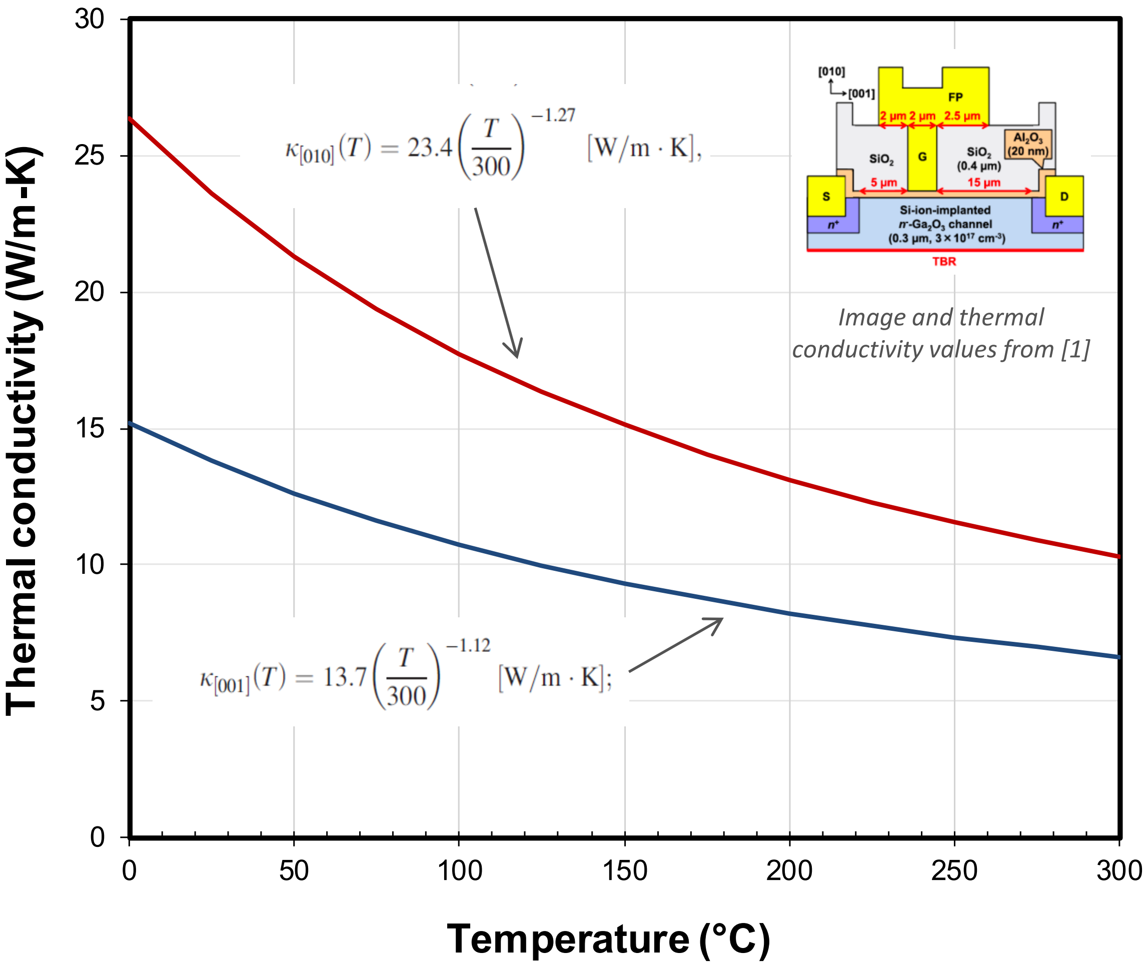



*Image and thermal conductivity values from [1]*

Thermal conductivity at 150°C:

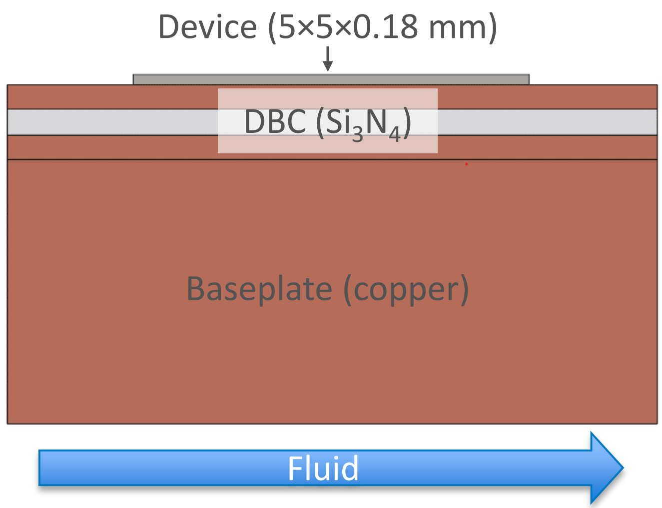
- **$Ga_2O_3$**: 15 W/m-K *[1]*
- **Si**: 92 W/m-K *[2]* ($Ga_2O_3$ is 84% lower)
- **SiC**: 210 W/m-K *[3]* ($Ga_2O_3$ is 93% lower)

Used these temperature-dependent, anisotropic properties for modeling.


[1] Wong, Man Hoi, et al. "Characterization of channel temperature in Ga2O3 metal-oxide-semiconductor field-effect transistors by electrical measurements and thermal modeling." *Applied Physics Letters* 109.19 (2016): 193503.
[2] Lau, John H., and Yi-Hsin Pao. *Solder joint reliability of BGA, CSP, flip chip, and fine pitch SMT assemblies*. McGraw-Hill Professional Publishing, (1997).
[3] Wang, Zhiqiang, et al. "Temperature-dependent short-circuit capability of silicon carbide power MOSFETs." *IEEE Transactions on Power Electronics* 31.2 (2016): 1555-1566.

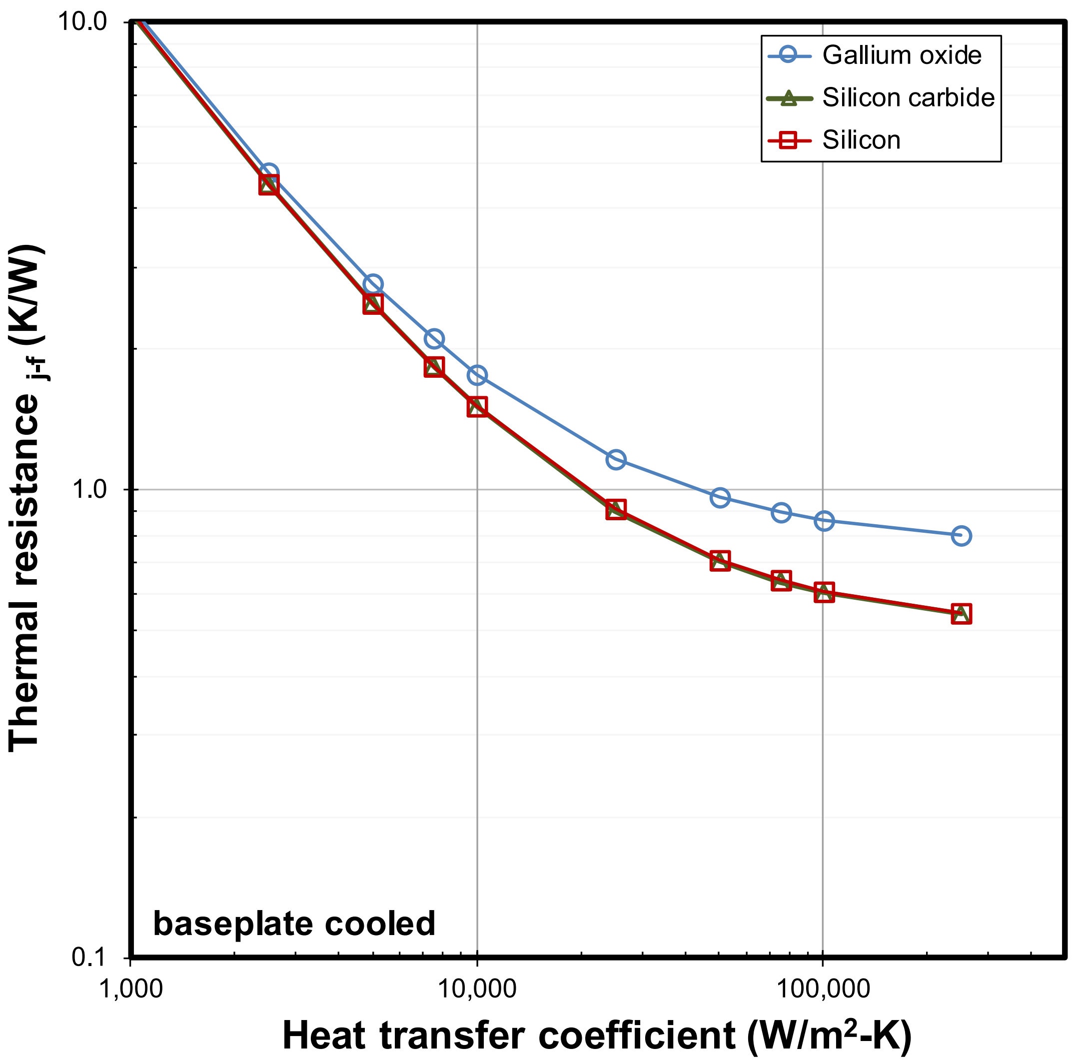
# Comparing $Ga_2O_3$ to SiC and Si

## FEA model




$Ga_2O_3$ has 12% higher thermal resistance compared to SiC (at 10,000 $W/m^2$-K)

## FEA steady-state results



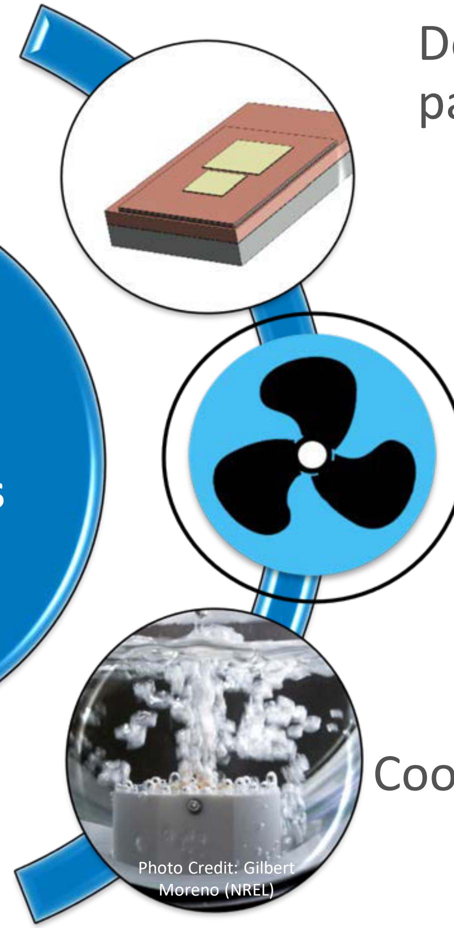

DBC: direct-bond copper
FEA: finite element analysis
$Si_3N_4$: silicon nitride

# Thermal Management Design Approach

**Thermal strategy to reach a power density of 100 kW/L**

**Define the thermal target to achieve 100 kW/L**

**Design the cooling strategies**




Device packaging

Convective cooling

Cooling fluid

Heat load (100 kW inverter): 2,150 W
Maximum device temperature: 250°C
Module and cold plate volume: < 240 mL

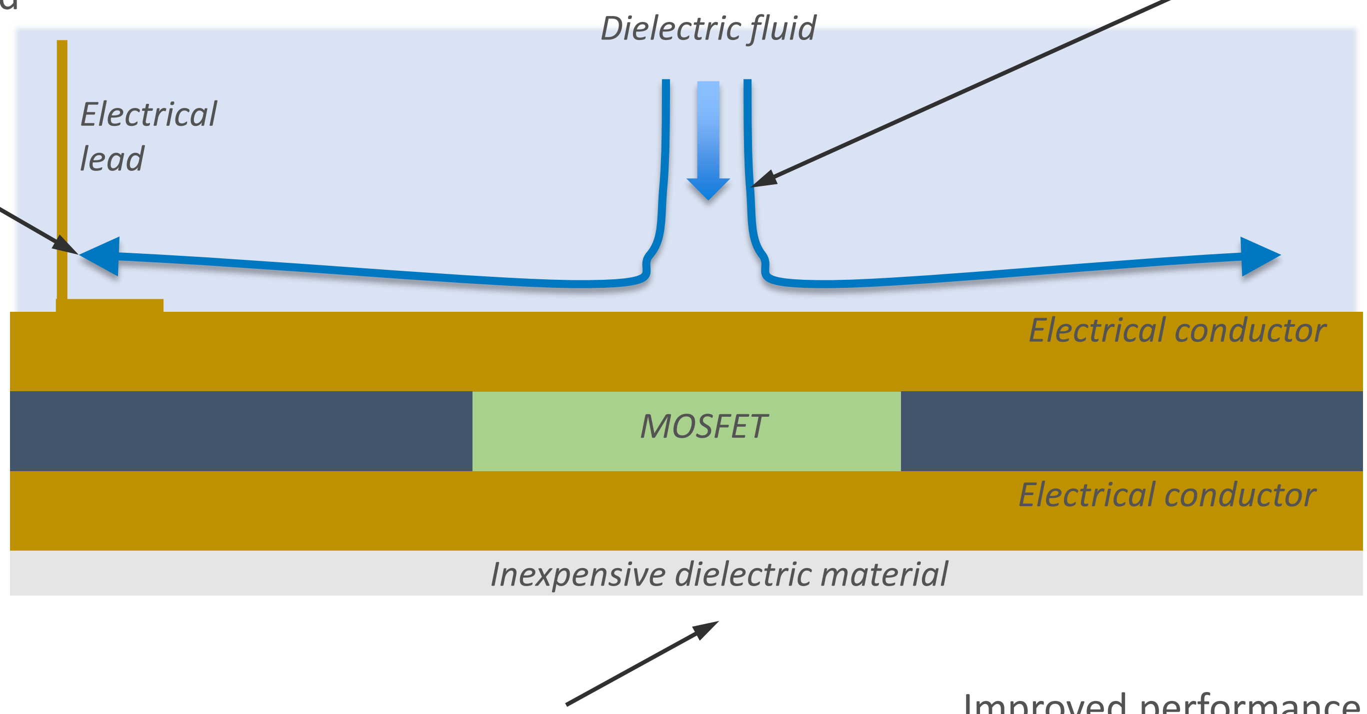
**Volumetric thermal resistance target: 21 $cm^3$-K/W**

**Dielectric cooling (single-phase heat transfer) planar package concept**

# 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

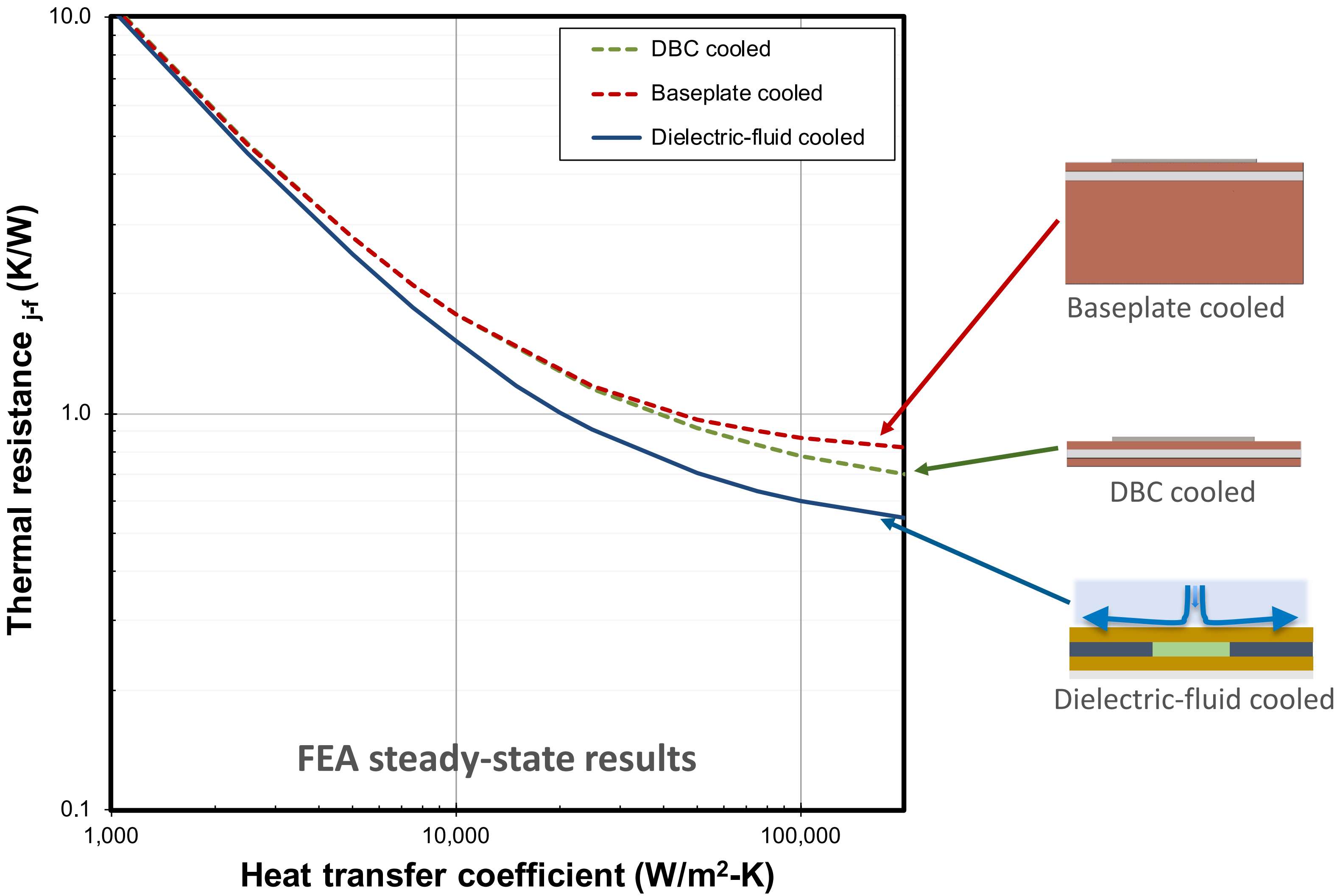
# Dielectric Fluid Selection

- 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, enable motor–inverter integration.
- Challenge is to create a cooling system with high thermal performance using fluids with relatively inferior heat transfer 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 [1] | 0.14 | 2,308 | 792 | 0.0091 | 246 | -57 |
| AC-100 [1] | 0.13 | 2,326 | 761 | 0.0025 | 180 | -55 |
| ATF [2] | 0.16 | 2,131 | 836 | 0.012 | 199 | -45 |
| *WEG (50/50) [3]* | *0.42* | *3,513* | *1,034* | *0.0013* | *> 121 [4]* | *-36 [5] (freeze point)* |

[1] Communications with vendor (DSI Ventures or Engineered Fluids)
[2] Kemp, Steven P., and James L. Linden. 1990. "Physical and Chemical Properties of a Typical Automatic Transmission Fluid." SAE Technical paper.
[3] Alshamani, Kaisar. 2003. "Equations for Physical Properties of Automotive Coolants." SAE Technical Paper.
[4] "Safety Data Sheet ZEREX HD Nitrile Free Extended Life 50/50 Antifreeze Coolant." Valvoline. Accessed April 1, 2019. https://sds.valvoline.com/valvoline-sds/sds/materialDocumentResults.faces.
[5] "Product Information: Valvoline ZEREX G05 Antifreeze Coolant." 2018. US_Val_ZXG05_AFC_HD_EN.Pdf. 2018. https://sharena21.springcm.com/Public/Document/18452/f93a8057-fe75-e711-9c10-ac162d889bd3/c264d227-0dbd-e711-9c12-ac162d889bd1.

# $Ga_2O_3$ Cooling Strategy Comparisons




- Dielectric-fluid concept provides 14% lower thermal resistance compared to other cooling strategies (at 10,000 $W/m^2$-K).
- Improved performance at higher heat transfer coefficients.

# Cooling System Design: Modeling Results

**Optimized dimensions using Alpha 6 fluid at $T_{inlet}$ = 65°C**

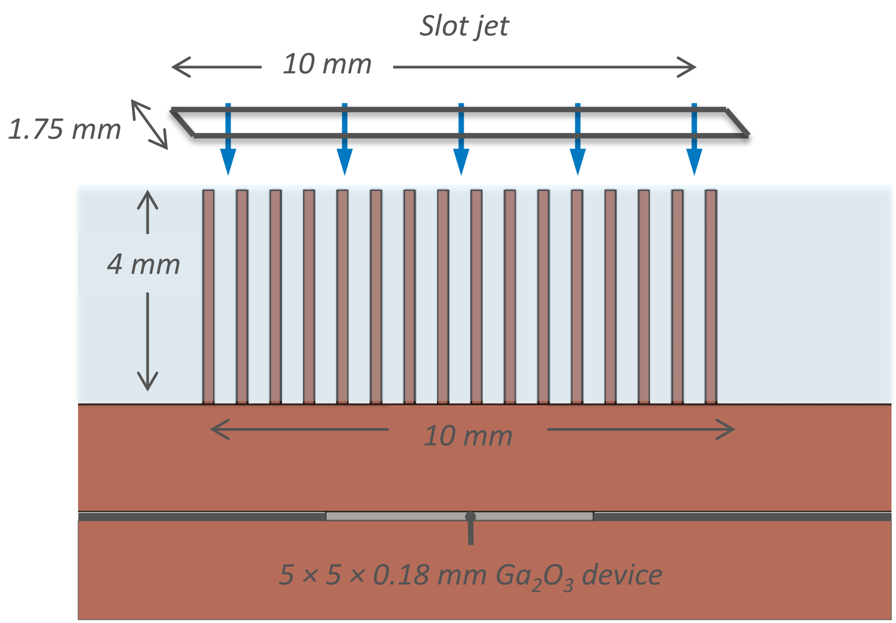
- Slot jet (1.75 × 10 mm) impinging on fins (0.2 × 4 × 10 mm)

**Achieved high thermal performance**

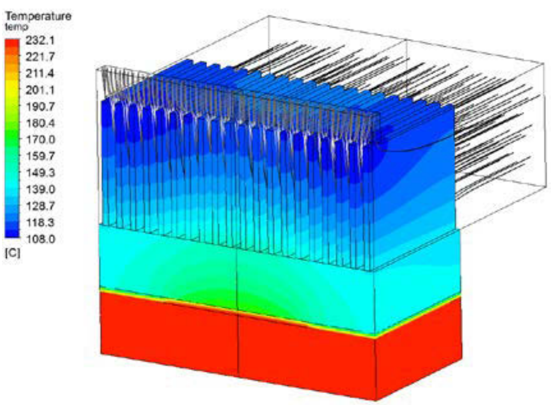
- Heat transfer coefficient 23,000 W/m$^2$-K at a relatively low jet velocity of 0.3 m/s
- Higher performance possible

**Decreased size**

- Predict we can dissipate 2.2 kW with 12 devices. Results in a heat flux ~718 W/cm$^2$ at $T_j \approx$ 233°C
- **~50% lower thermal resistance compared to 2014 Accord Hybrid** *[Accord data taken from [1]]*




*Planar module, dielectric cooling concept*

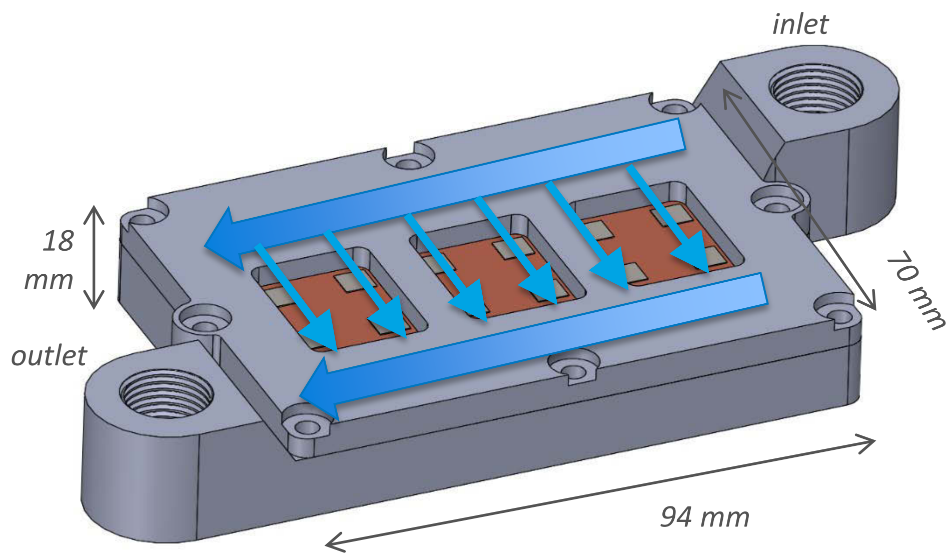



[1] Moreno, Gilberto, et al. "Evaluation of performance and opportunities for improvements in automotive power electronics systems." *2016 15th IEEE Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems (ITherm)*. IEEE, 2016.

# Cooling System Design: Modeling Results

Designed fluid manifold to distribute flow to 12 devices.

- Total flow rate: 4.1 Lpm
- Reduced size: 120 mL total cold plate and power module volume.
- Reduced thermal resistance: Volumetric thermal resistance is 9.4 $cm^3$-K/W (compared to resistance target of 21 $cm^3$-K/W)
- Modeling results indicate that it is possible to create power-dense $Ga_2O_3$-based modules.

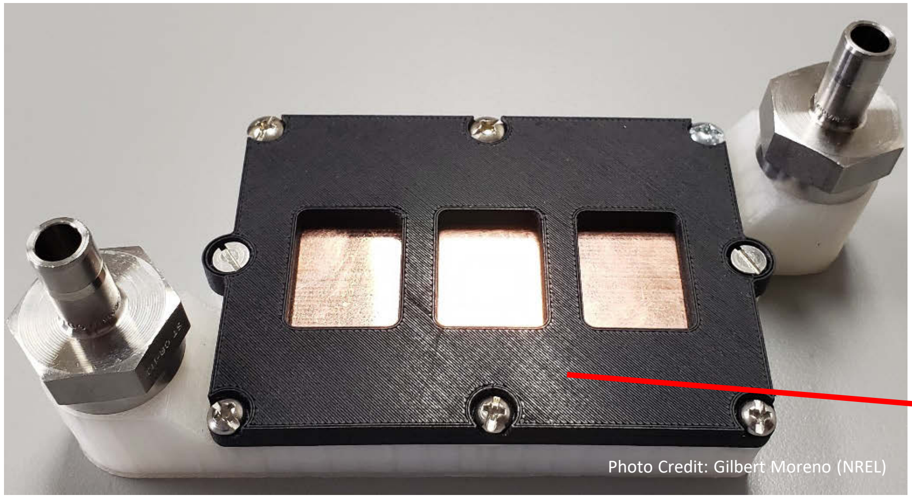


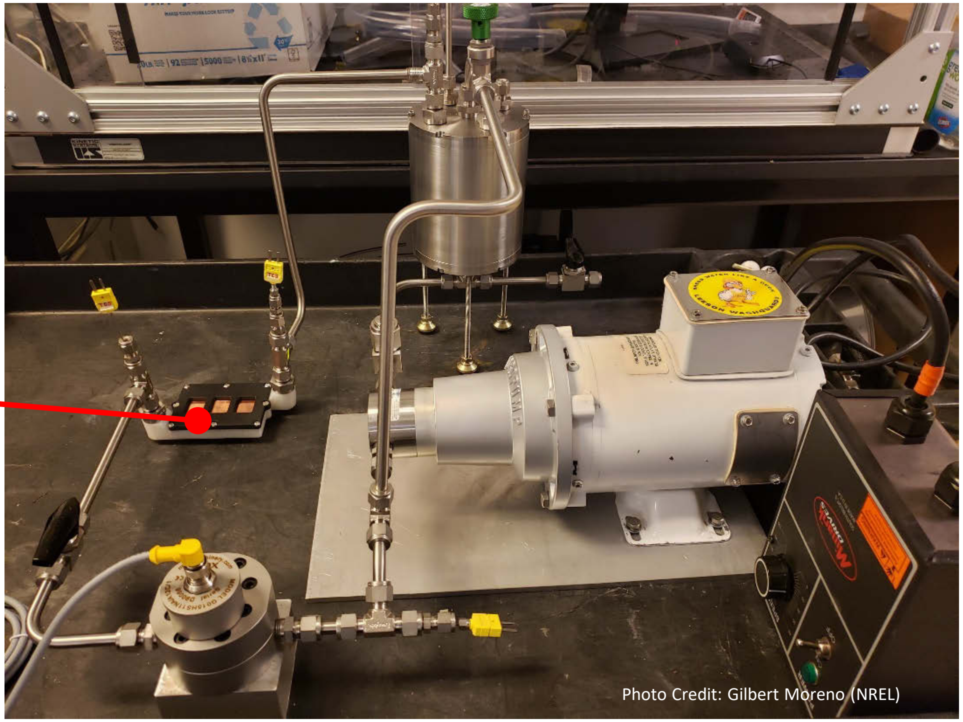

*CAD model of the cold plate with finned heat spreaders*

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

CAD: computer-aided design

# Experimental Validation



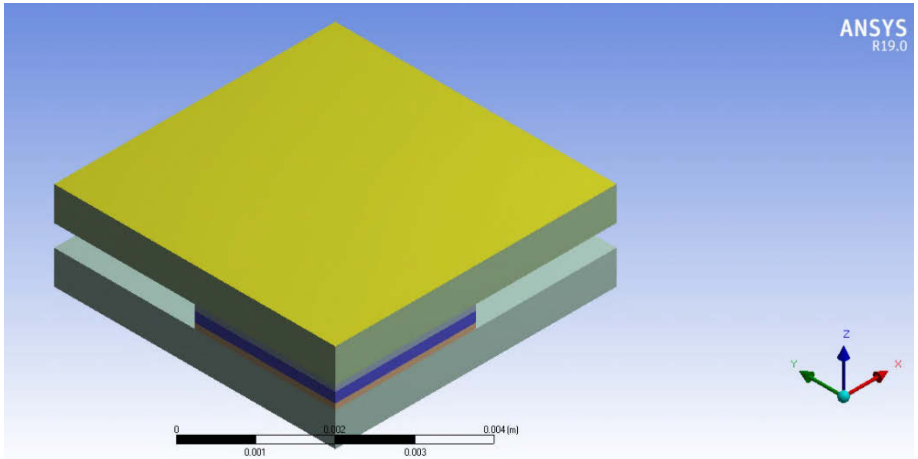

**3D printed cold plate prototype**

- Use resistance heater to simulate devices

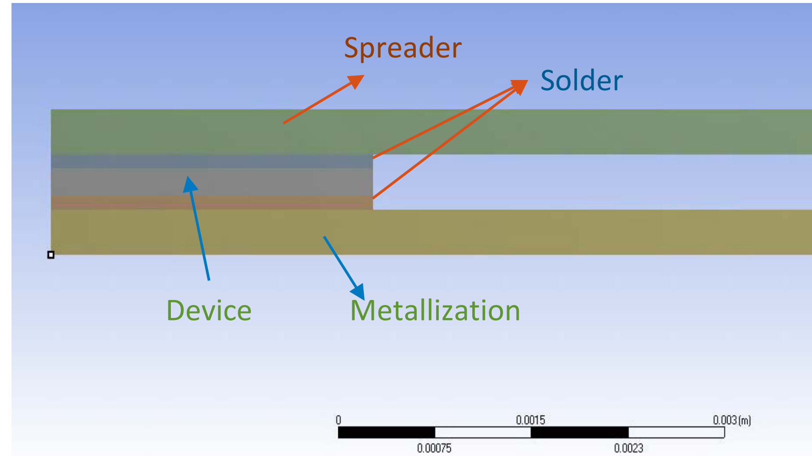
**Fabricated new flow loop**

- Characterize the thermal performance using different dielectric fluids at various fluid temperatures (-40° – 70°C) and flow rates

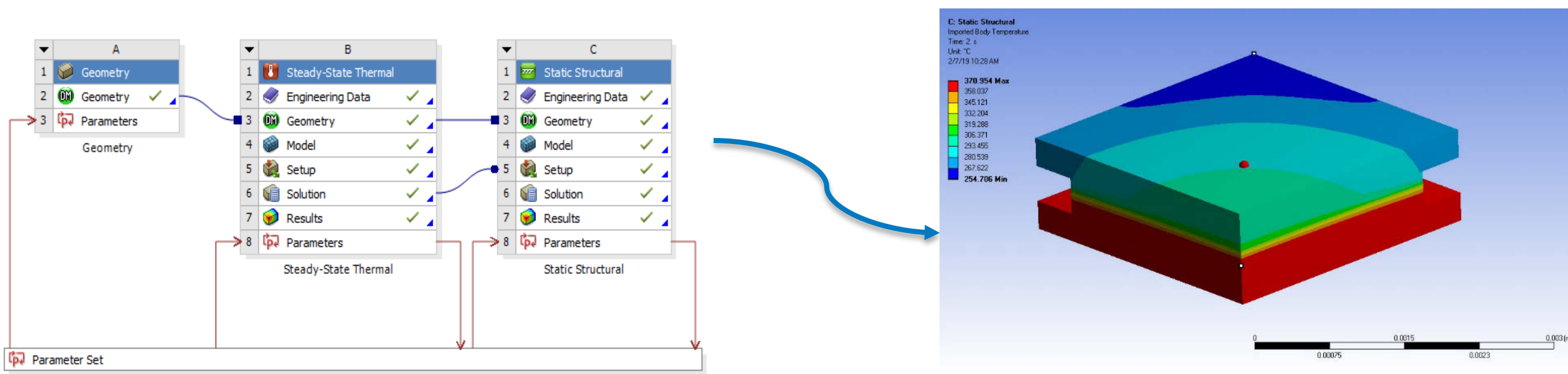
# Thermomechanical Modeling




Device heat generation (blue region) – 39.77 W/mm$^3$
Heat transfer coefficient – 23,200 W/m$^2$K




Double-sided package




Coupled thermal-mechanical analysis

# Conclusions and Future Work

## Conclusions

- Device modeling shows that vertical FinFET can give promising device performance.
- Growth capability of new materials using molecular beam epitaxy (MBE) was developed, based on prior track record in semiconductor growth at NREL.
- Developed a compact, high-performance, dielectric fluid-based thermal management solution.
- Results indicate a pathway to power dense, low cost, high performance, and reliable $Ga_2O_3$-based power modules.

## Future work

- Perform transient thermal simulations to characterize the short-circuit behavior.
- Conduct experiments to validate the dielectric cooling concept.

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# Thank you!

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