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Power Electronics Module with Integrated Ceramic Heat Exchanger

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Initial Motivation

- **Traditional manufacturing processes** restrict ceramic components to simple geometries (plates, tubes, etc.).
- **Additive ceramic manufacturing** promises more complex geometries but have significant limitations.
  - Post processing after printing of green part (debinding, sintering) causes volume reduction by at least 20% and risks crack formation and propagation.
  - The sintering chamber volume can restrict part sizes for some materials (AlN) due to high temperature requirements (~1,800°C).

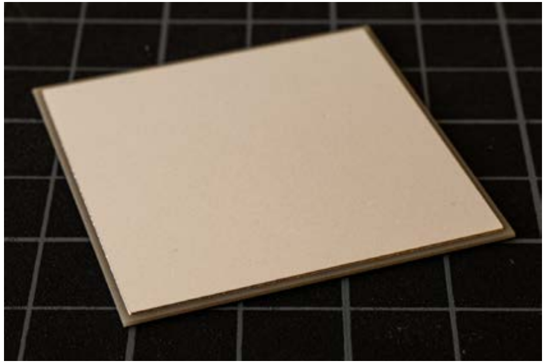
Initial Motivation

- The promise of **selective laser reaction sintering (SLRS)** led Synteris and NREL to pursue an ARPA-E OPEN 2021 award for integrating non-oxide ceramics (Aluminum Nitride (AlN), Silicon Carbide (SiC), Silicon Nitride (Si_3N_4)) into power module designs.
- Design constraints/goals:
  - Integrate a ceramic cold plate into a half-bridge module that is no larger than existing half-bridge modules.

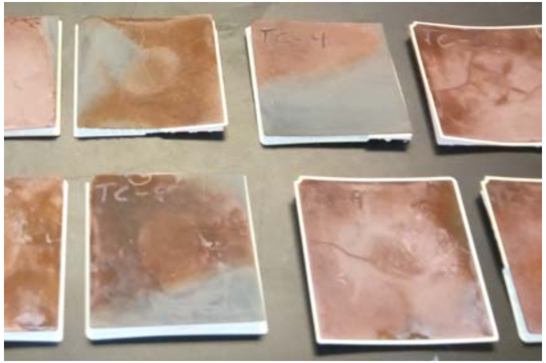
Benchmark Design

Traditional Substrates

- Traditional metalized ceramic substrate technologies:
  - Direct-bond copper (DBC)
    - Oxidation of copper (Cu) foils during bonding lowers melt temperature from 1,083°C to 1,065°C.
    - Maximum metallization thickness of 1 mm.
    - Must have metallization layers on both sides of the ceramic.
    - Examples include aluminum oxide (Al_2O_3), aluminum nitride (AlN), and zirconia (ZrO_2)-doped high-performance substrates (HPS).
  - Active metal brazing (AMB)
    - Brazing process with silver-copper (Ag-Cu) alloy between Cu and ceramic at 850°C in vacuum.
    - Requires more processing steps and is more expensive than DBC.
    - Silicon nitride (Si_3N_4) and AlN substrates are examples.



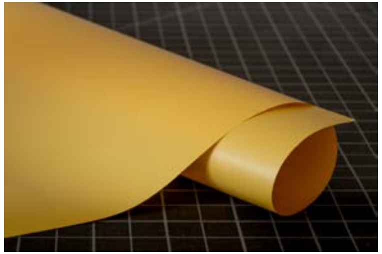
Traditional substrate



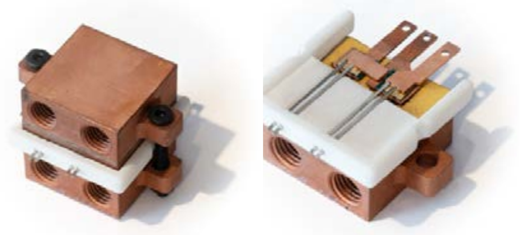
Substrates after thermal shock

Related NREL Substrate Work

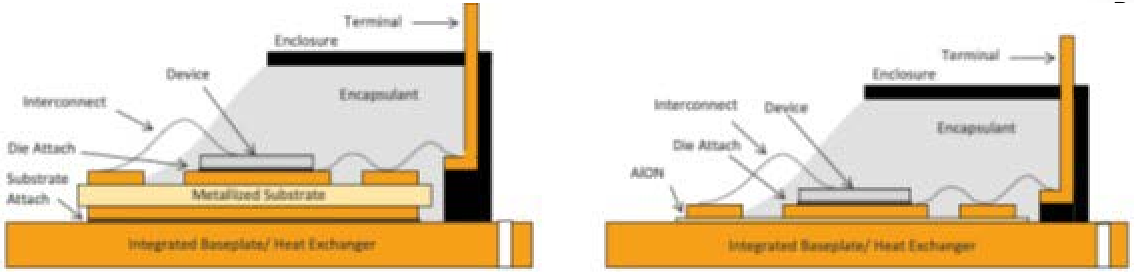
- Past VTO EDT work with DuPont ODBC
  - A polyimide dielectric is bonded with metal at elevated temperature (300°C) and pressure (2.41 MPa) under vacuum or inert atmosphere.
  - No limitations in metal material or metallization thickness.
  - Maintains electrical and thermal performance after 5,000 thermal shock cycles (−40°C to 200°C, 5-minute dwells).
- Current VTO EDT work with Nitride Global
  - Developing fabrication procedures to integrate aluminum oxynitride (AlON) coatings into power module designs.



DuPont Temprion polyimide film



DuPont ODBC substrate



Traditional Package   AlON Package

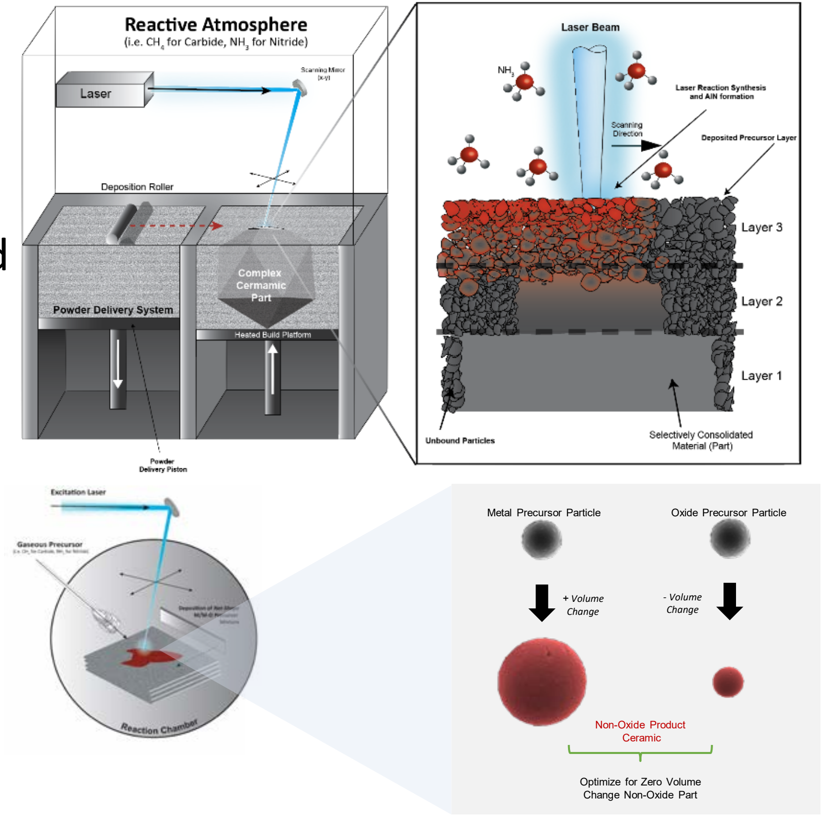
SLRS Process

- Selective Laser Reaction Sintering (SLRS) is a modification of a metal SLS printer.
- In place of an inert gas, a reactive gas, ammonia (NH_3) or methane (CH_4), fills the build chamber and is broken down by the laser.
- Thermally-induced reaction examples are:

$$2Al_{(s)} + 2NH_{3(g)} \rightarrow 2AlN_{(s)} + 6H_{2(g)}$$

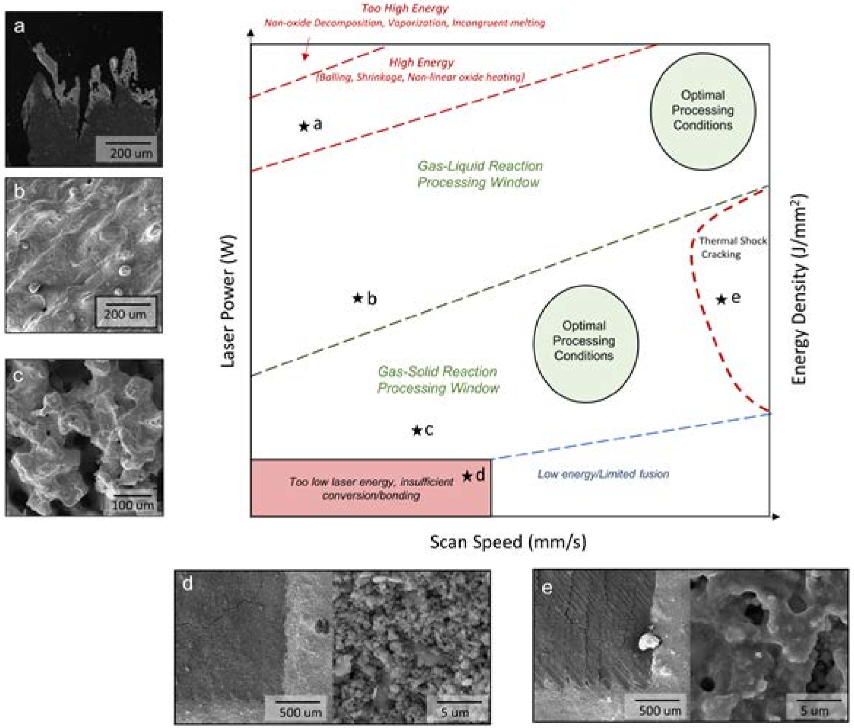
$$Si_{(s)} + CH_{4(g)} \rightarrow SiC_{(s)} + 2H_{2(g)}$$

  where composition of the metal/metal oxide precursor compositions (Al/Al_2O_3) are optimized to achieve an isovolumetric part.
- No further debinding and sintering is required.

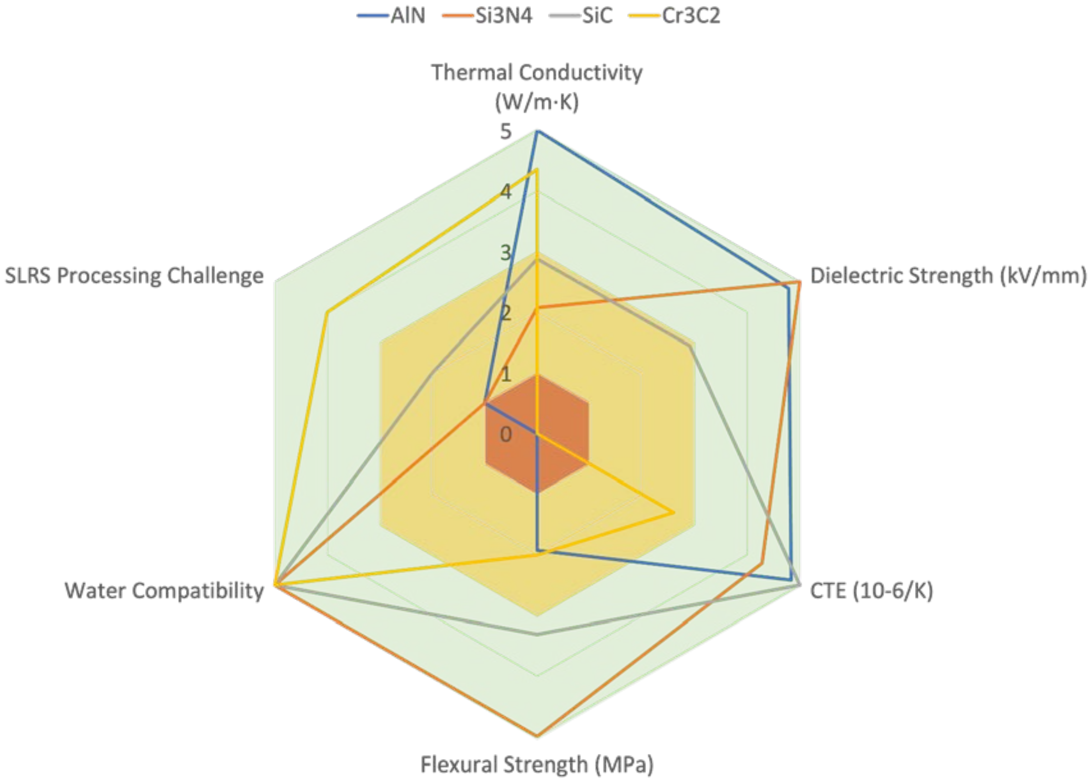


SLRS Process

- Key parameters include:
  - Metal/metal oxide precursor compositions.
  - Laser energy density
  - Scan speed
  - Gas composition
- A Renishaw AM400 printer was modified for the SLRS process, and a design of experiments was completed to optimize for AlN and SiC.



Ceramic Options



Material Concerns

AlN: water compatibility

Cr_3C_2: electrical conductor

Si_3N_4: low thermal conductivity

SiC: no critical concerns

Initial Design Concepts

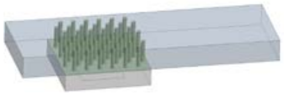
Evaluate different convective cooling configurations using device-scale CFD model to identify the best performing design

Optimized package dimensions to maximize thermal performance using FEA

Designed the module and cold plate with features and dimension of prior steps

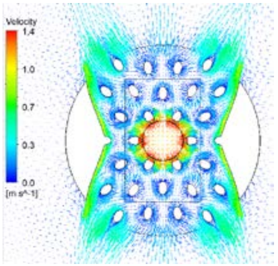
HTC boundary condition

package dimensions

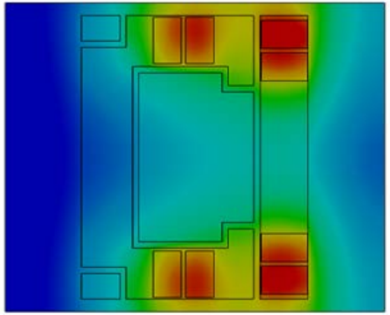


Channel flow

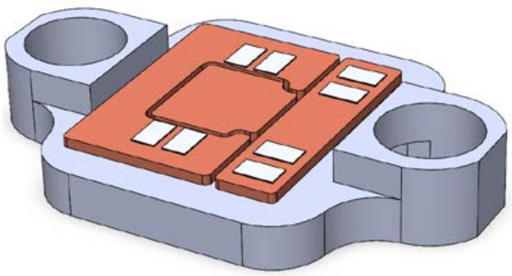
Jet impingement



Various fin structures and gyroids

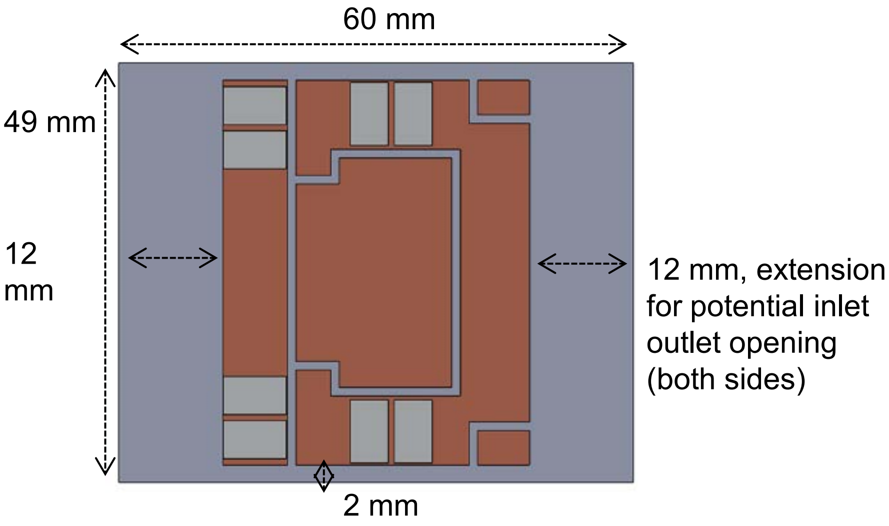


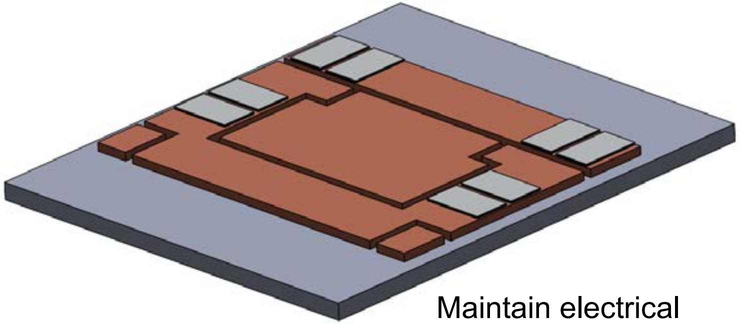
Optimized device location and layer thicknesses



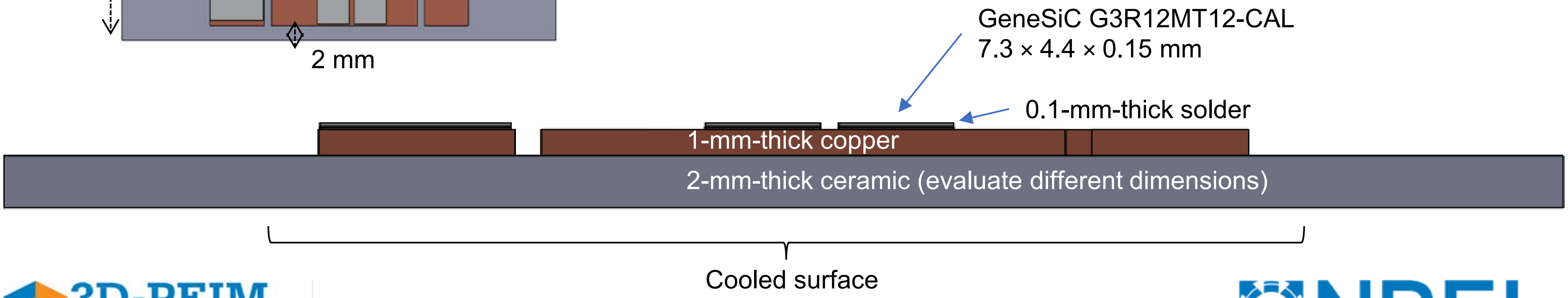
CFD: computational fluid dynamics, FEA: finite element analysis

Package Thermal Performance

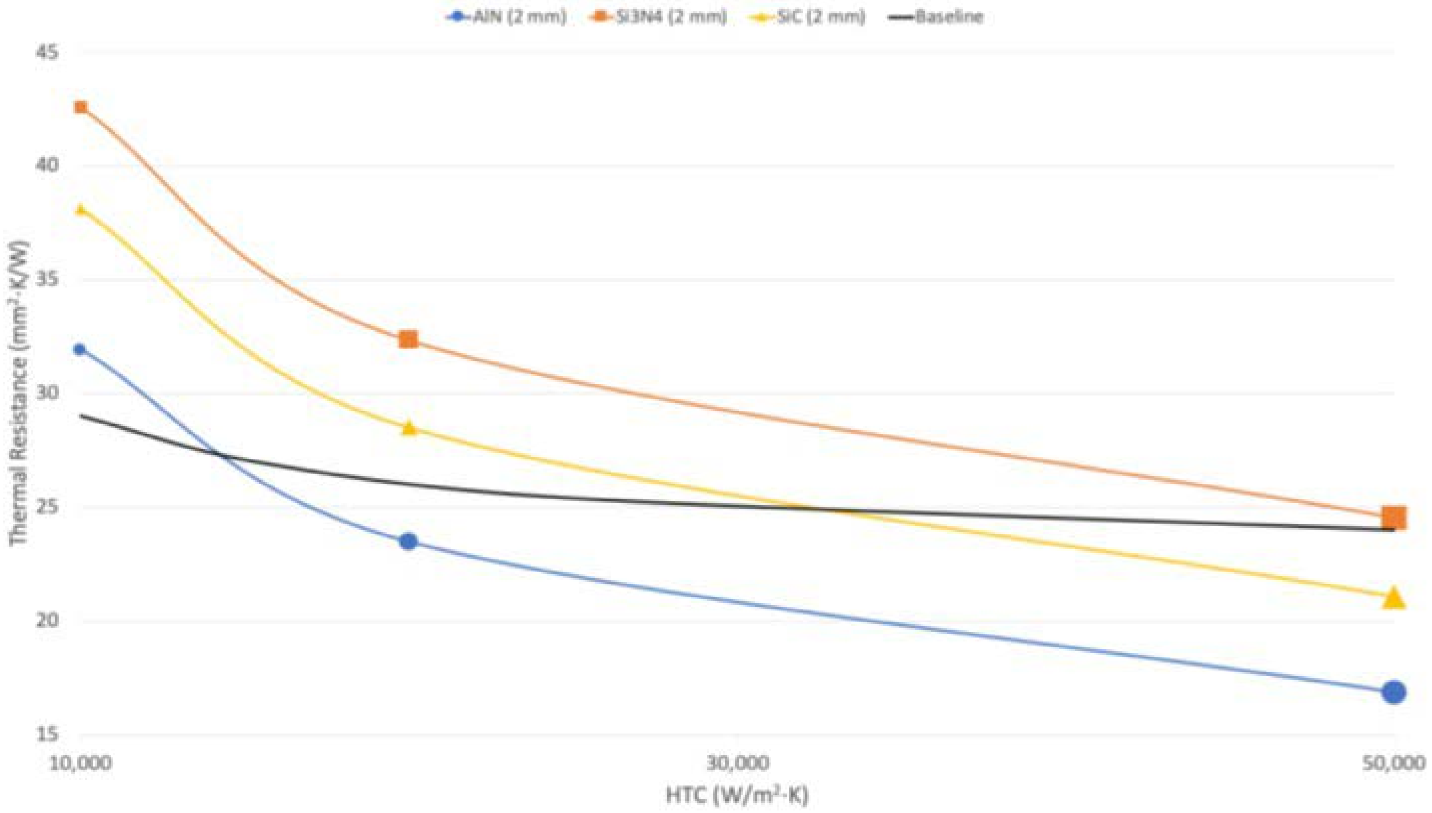




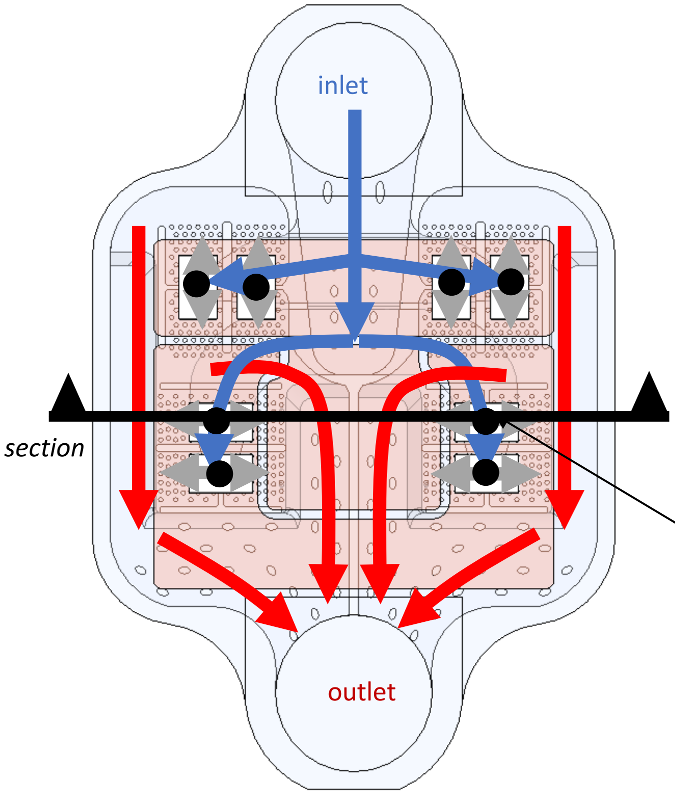
Maintain electrical conductor layout from CREE module

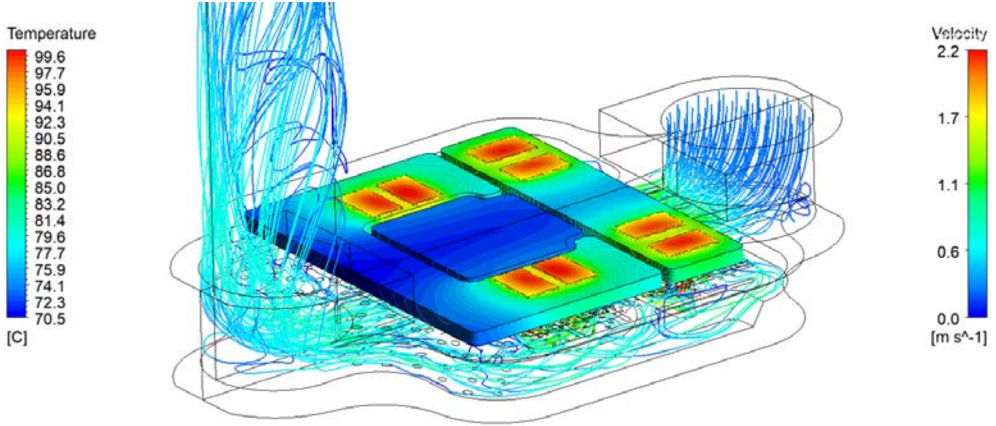


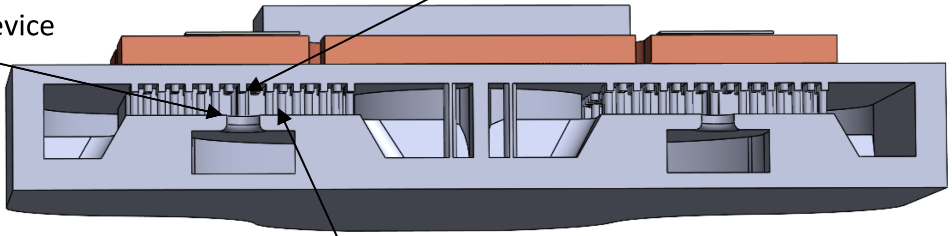
Package Thermal Performance



Package Thermal Performance

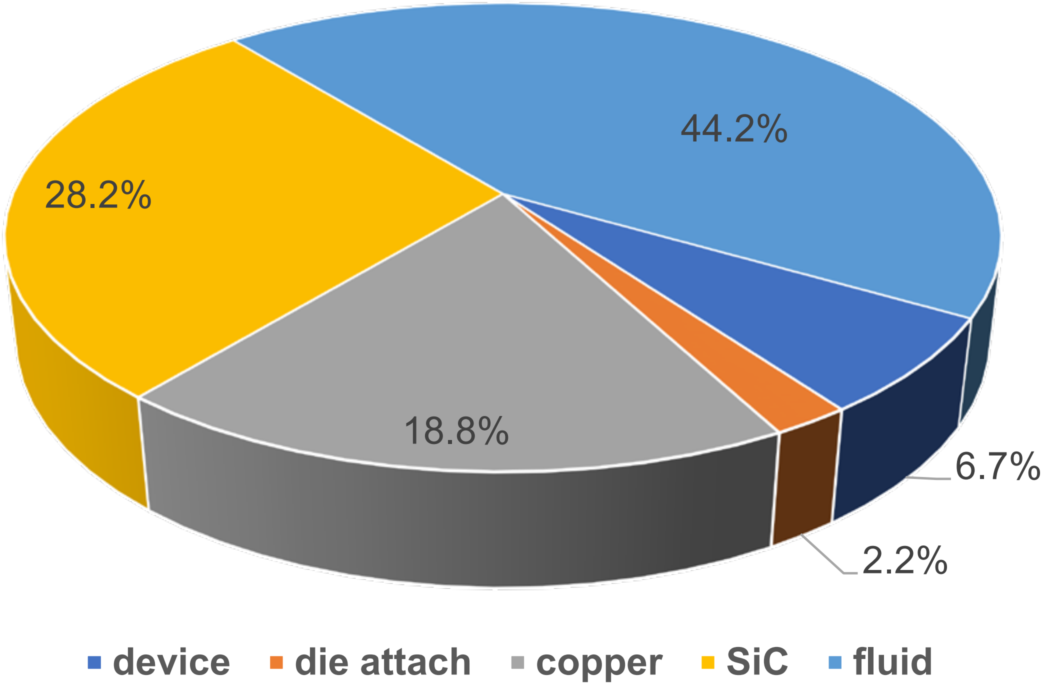




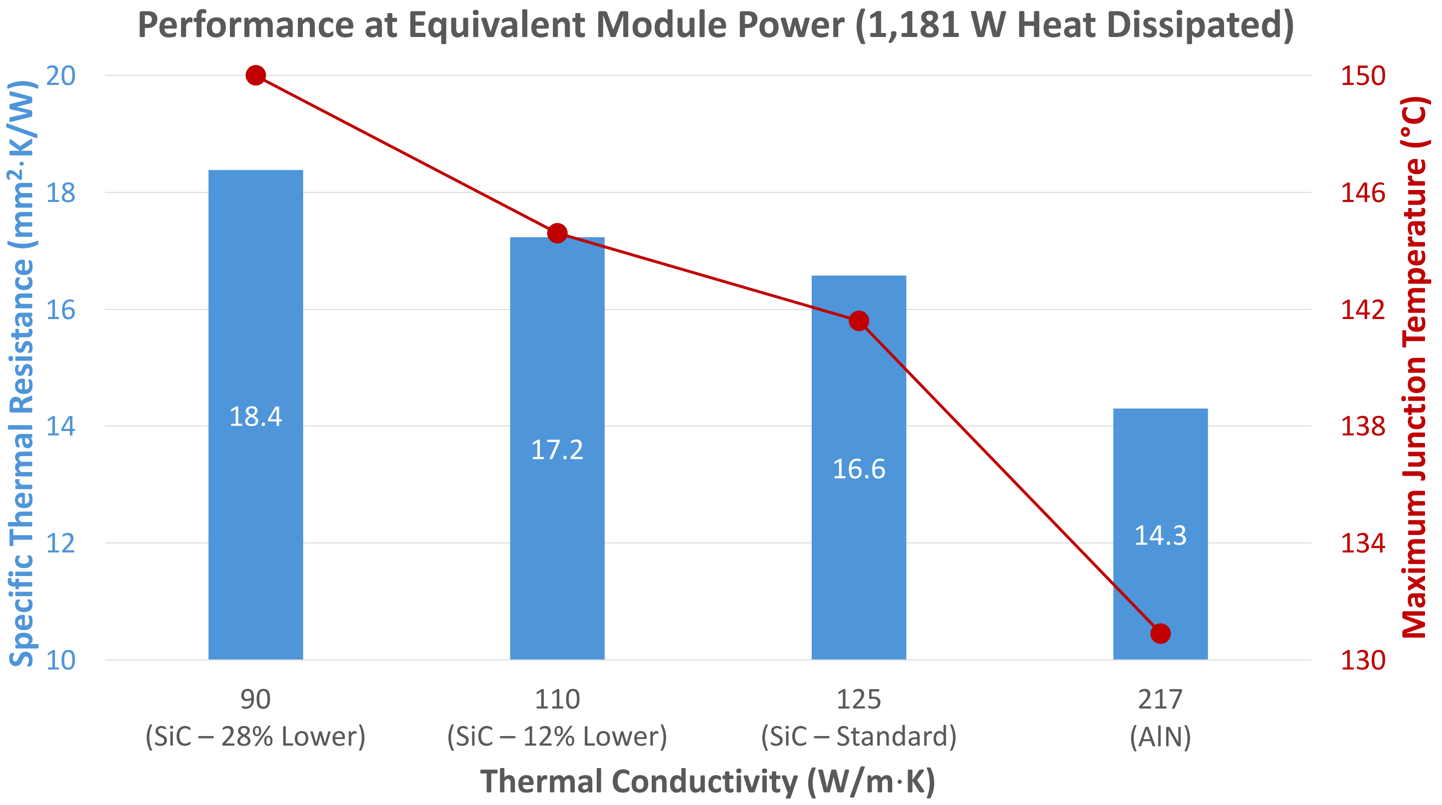


Package Thermal Performance

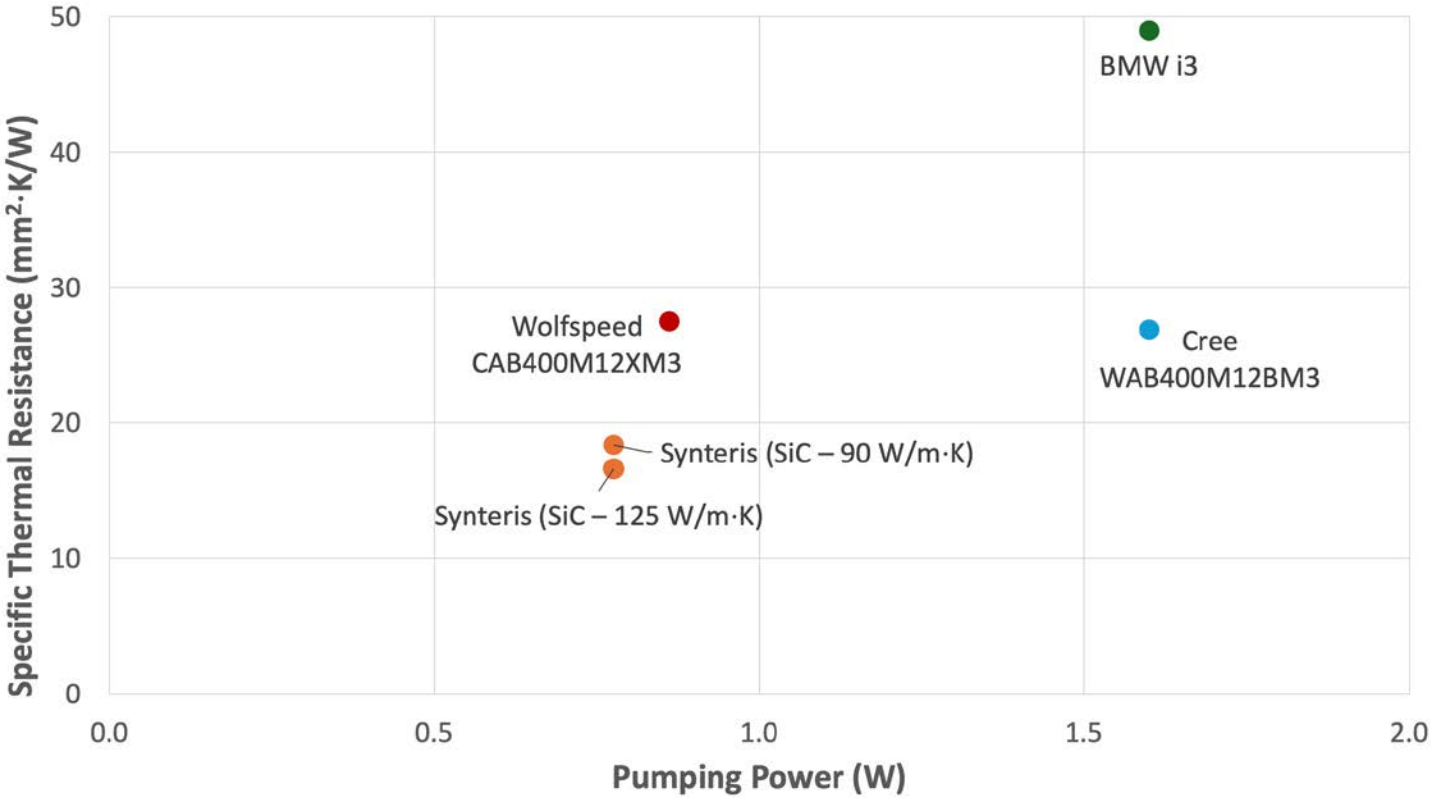
- Estimate of the thermal resistance percentage for each layer.



Package Thermal Performance



Package Thermal Performance



Cree WAB400M12BM3 on Wieland MicroCool CP 3009 cold plate
Wolfspeed CAB400M12XM3 on Advanced Cooling Technologies cold plate

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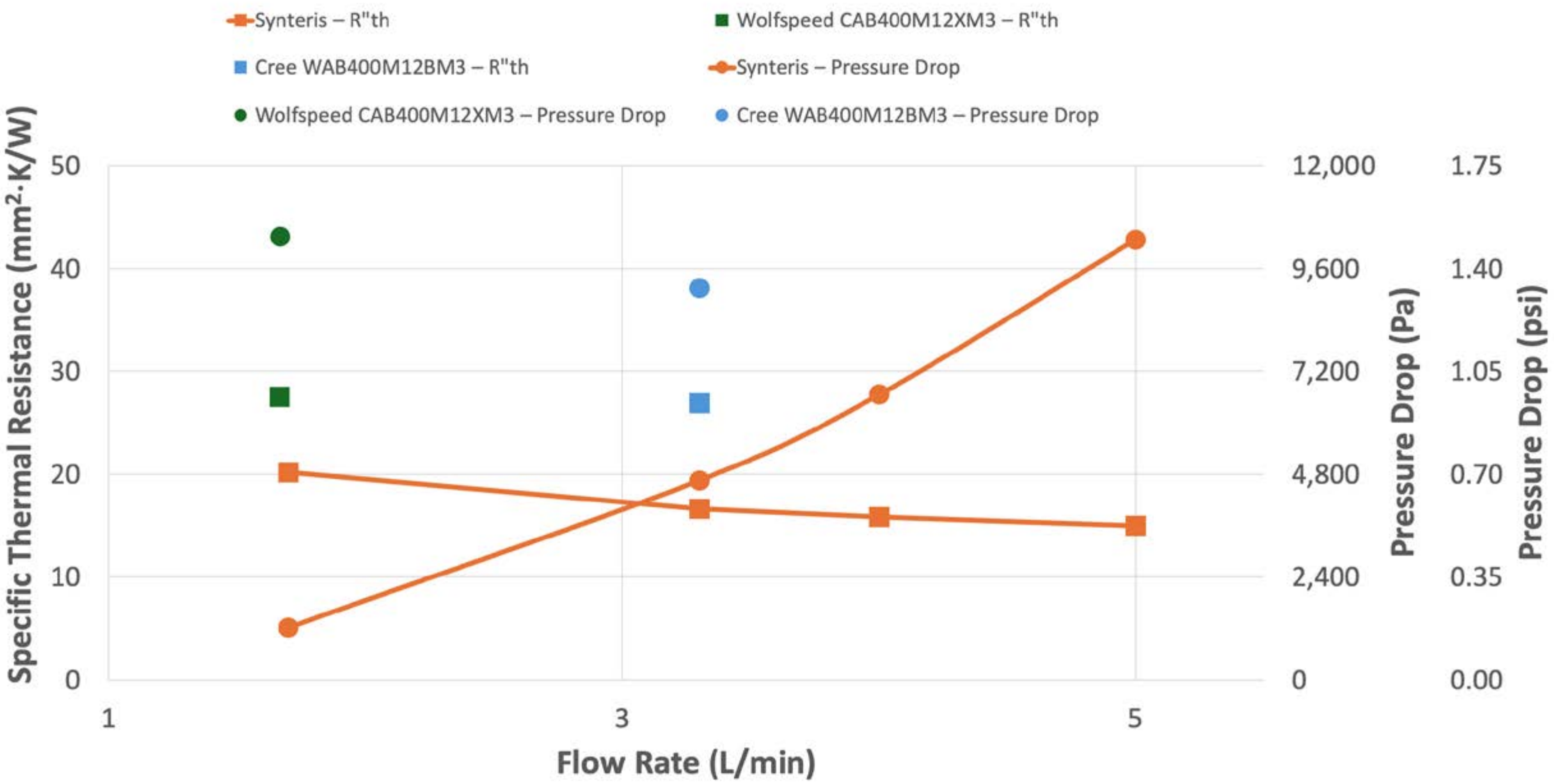
NREL

Package Thermal Performance

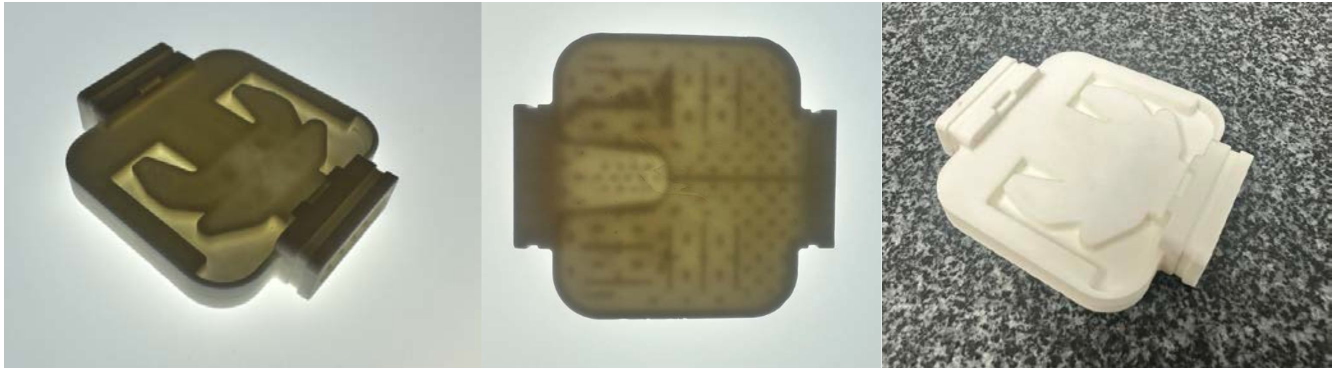


125 W/m·K used for Synteris case

3.3 L/min flow rate at module level corresponds with 10 L/min flow rate at inverter level

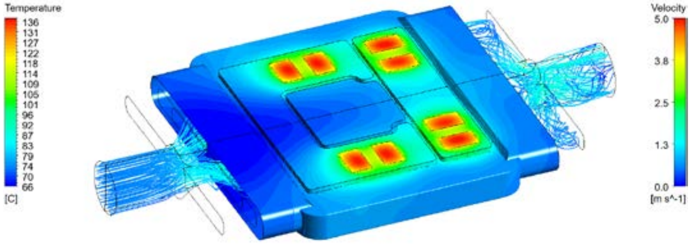
Pivot to Canopy Aerospace

- SiC SLRS conversion efficiency was not sufficient to meet minimum electrical and thermal properties needs.
- While SLRS process continues to be improved, the team pivoted to Canopy Aerospace for lithography-based ceramic manufacturing (LCM) for parallel development of aluminum oxide (Al_2O_3) and aluminum nitride (AlN) samples.
  - Modifications of design (wall thickness, minimum pin diameters, additional fillets) allowed for crack-free Al_2O_3 parts, but the thermal performance was greatly reduced.

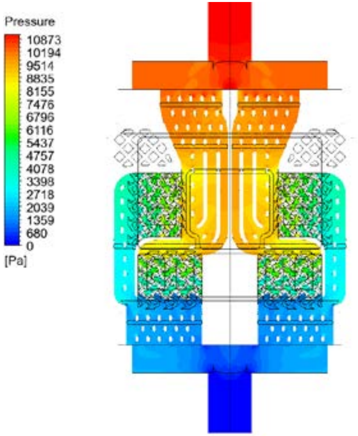


SLRS vs LCM

- A new design was created that incorporated constraints of the LCM process.
  - Switched from a jet impingement design to flow-through design with integrated gyroids under devices.



R''_{th}: 15.4 $mm^2 \cdot K/W$
Pressure Drop: 1.6 psi
(used 170 W/m·K for AlN)



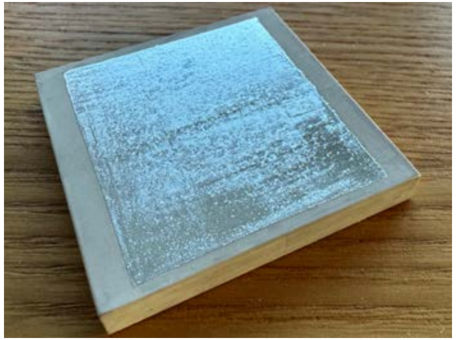
Design Parameter	SLRS	LCM
Self-supporting features?	Yes	No
Varying wall thicknesses?	Yes	No
Fillets	Minimal	Mandatory
Volume constraints	Printer build volume	Printer, crucibles, furnaces
Cleaning	Excess powder removal	Excess slurry removal
Post Processing	Build plate removal	Debinding and sintering
Tolerance to CAD	Good	Poor (~20% shrinkage)

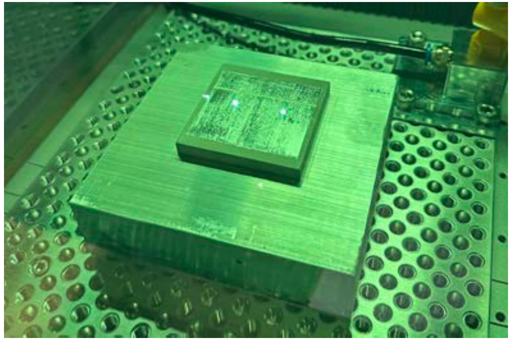
Fabrication Steps – Metallization

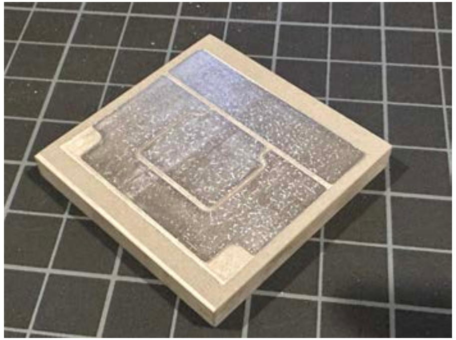
- It is desirable to bond a metallization layer to the SiC component at a low temperature to minimize cracking from CTE mismatch. A copper thickness of around 1.6 mm is ideal from a thermal perspective but may cause thermomechanical concerns.
- Several techniques were explored:
  - Thick-film metallization screen printing with **CMS Circuits** was not successful at greater thicknesses (> 500 µm). Poor adhesion between metal and ceramic interface has been the cause. Thinner samples would be promising.
  - **Shenqiang Ren at UMD** metallized copper with his process. Metallization was a little green but processing temperate could be increased to 200°C. Collaboration was paused to focus on thick metallization methods.
  - Held initial discussions with **Fabric8 Labs**, who have developed an electrochemical additive manufacturing technique. They have already demonstrated copper printing on silicon, Al_2O_3, and AlN. Design would need to be modified to add a temporary electrical path from the bottom of the SiC part to the top, where the metallization pattern would be grown.
  - **S-Bond Technologies** applies an initial metallization layer that will be compatible with their metal/ceramic solder. Patterning of the seed layer and soldering will occur at NREL.

Fabrication Steps – S-Bond Metallization

- S-Bond applies an initial (~12 µm Ti/Sn/Ag) metallization layer to the ceramic component.
- A fiber laser etches away excess metal to create the three separate metallization pads.
- Solder mask is applied between pads.
- A low-temperature solder (Sn42/Bi58) bonds a copper layer to the ceramic component.

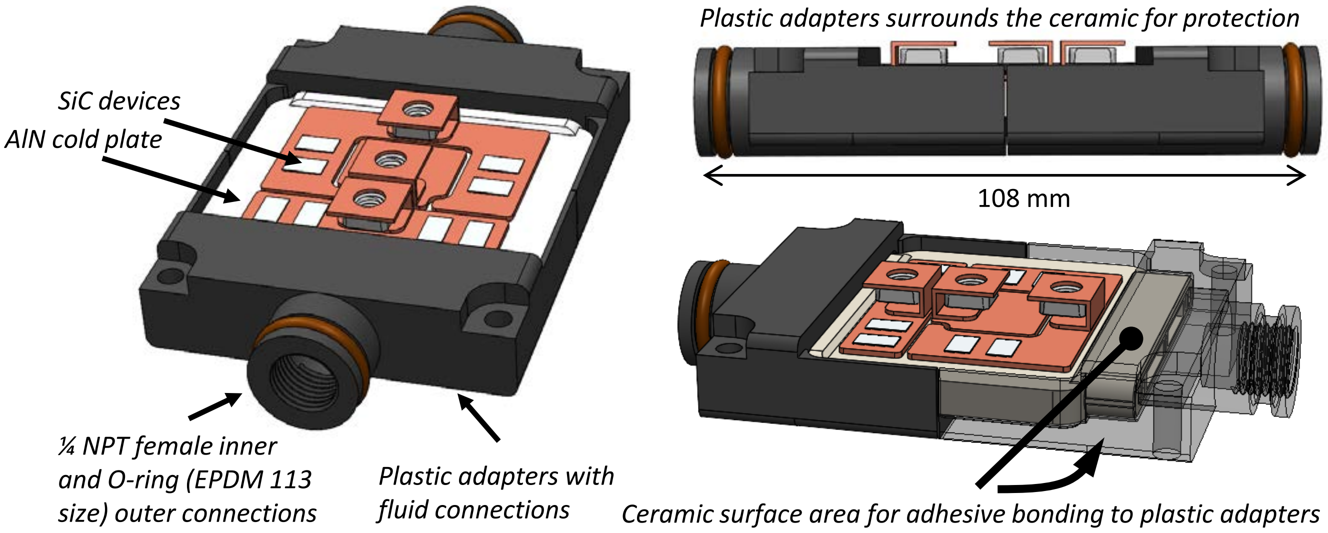


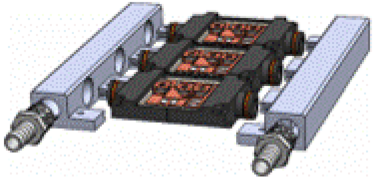




Metallization Patterning

Fabrication Steps – Manifolds



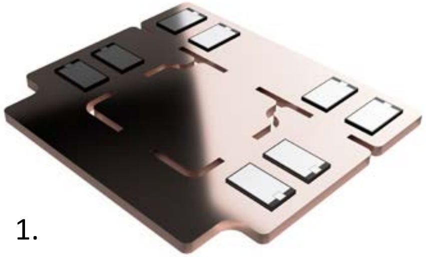


Air Pressure Test

- Mass production would rely on injection molded manifolds.
- For prototyping, several methods were explored:
  - SLA (Rigid 10K) parts met heat deflection requirements but were very brittle.
  - Post processing of FDM/SLS/MJF parts with Diamant Dichtol AM Hydro or vapor smoothing creates fully sealed parts.

Fabrication Steps – Overview

1. Attach MOSFETs to Cu metallization with SAC 305 solder.
2. Cold plates from Canopy Aerospace will be sent to S-Bond for metallization (Ti/Sn/Ag), then patterned at NREL with fiber laser.
3. Attach Cu metallization to AlN cold plate with Sn42/Bi58 solder that has lower reflow temperature than SAC 305.
4. Remove Cu tabs.
5. Epoxy manifolds to AlN cold plate.
6. Secure PCB to manifolds.
7. Bond source, gate, and Kelvin wires.
8. Solder terminals to Cu metallization layer (note that tops will be unbent).
9. Fill cavity with silicone encapsulant and snap lid in place.


1.


2.


3.


4.


5.


6.


7.


8.


9.

Final Design Concepts

Modular

Unified

Benchmark

Inverter	Length (mm)	Width (mm)	Height (mm)	Volume (L)	Volume Reduction	Power (kW)	Power Density (kW/L)	Power Density Increase	R_{th} ($mm^2 \cdot K/W$)
Benchmark	195	130	54	1.37	–	49	35.6	–	26.9
SynPack (Unified)	210	93	21	0.41	70%	85.4	208.2	485%	15.4
SynPack (Modular)	205	141	26	0.75	45%	85.4	113.6	219%	15.4

Next Steps

With future funding:

- Design reliant on successful print of either SiC (Synteris) or AlN (Canopy Aerospace) ceramic component.
- Full assembly for functional module.
- Thermal and thermomechanical characterizations of assembled prototype module.

Additional thoughts:

- Current designs focus on electrical, thermal, and reliability performance.
- Electronic waste is a growing problem and circularity concepts (design for repair, repurpose, and recycling) should be equally considered.

Questions?

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http://www.nrel.gov/transportation/peem.html

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