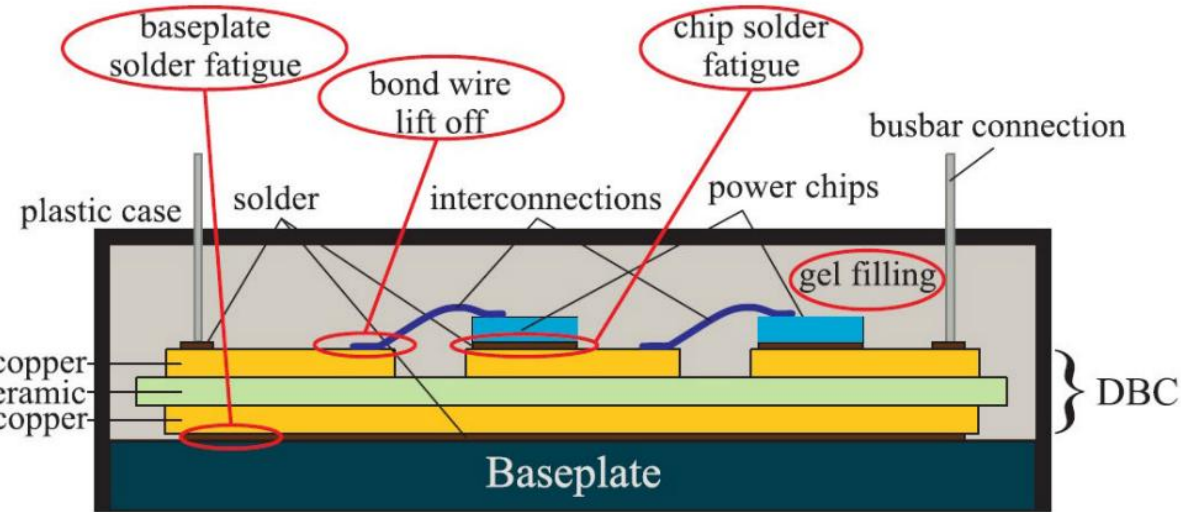


TPG BASED THERMAL MANAGEMENT TECHNOLOGIES TO REMOVE CRITICAL HEAT IN POWER ELECTRONICS



Thermal failure sites, causes, stresses, modes, and mechanisms of IGBT packages⁺



Structure of power semiconductor device*

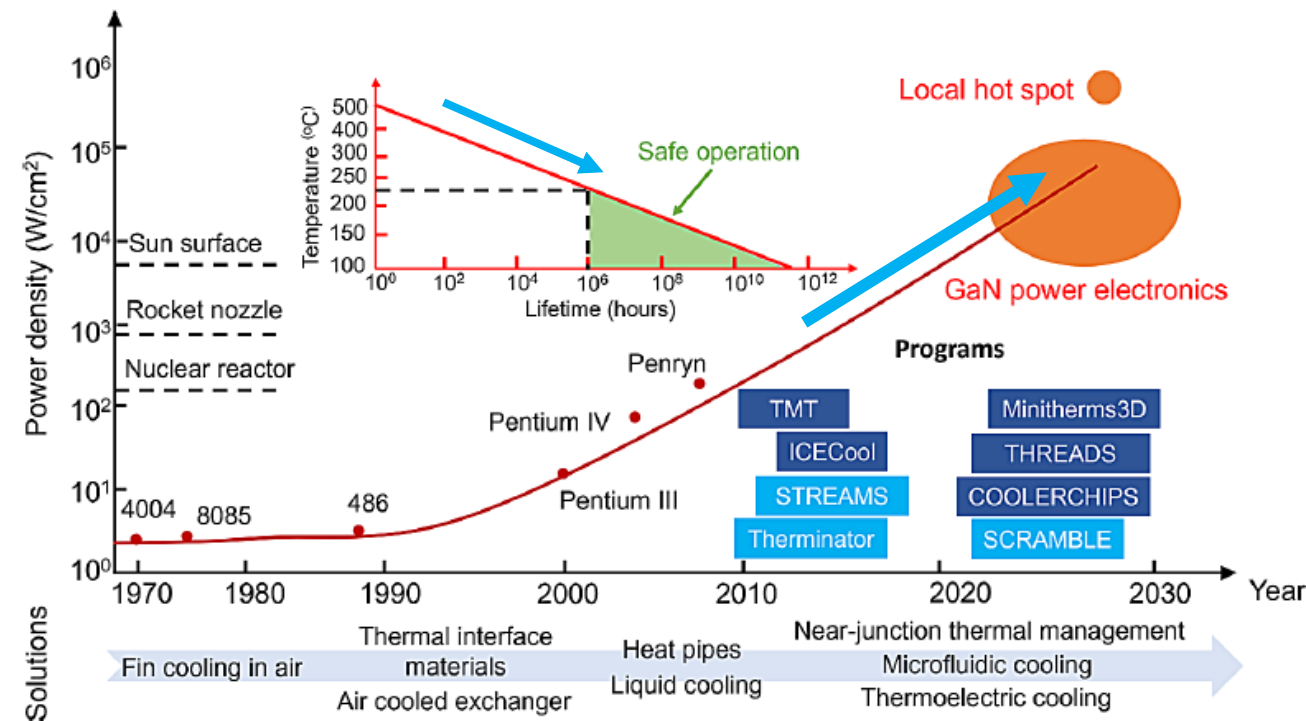
Common Issues in Power Electronics Devices

- CTE mismatch leads to thermomechanical stress
- High power dissipation leads to hotspots
- Interconnection failure due to thermal cycling
- Fatigue related failures of bond wires

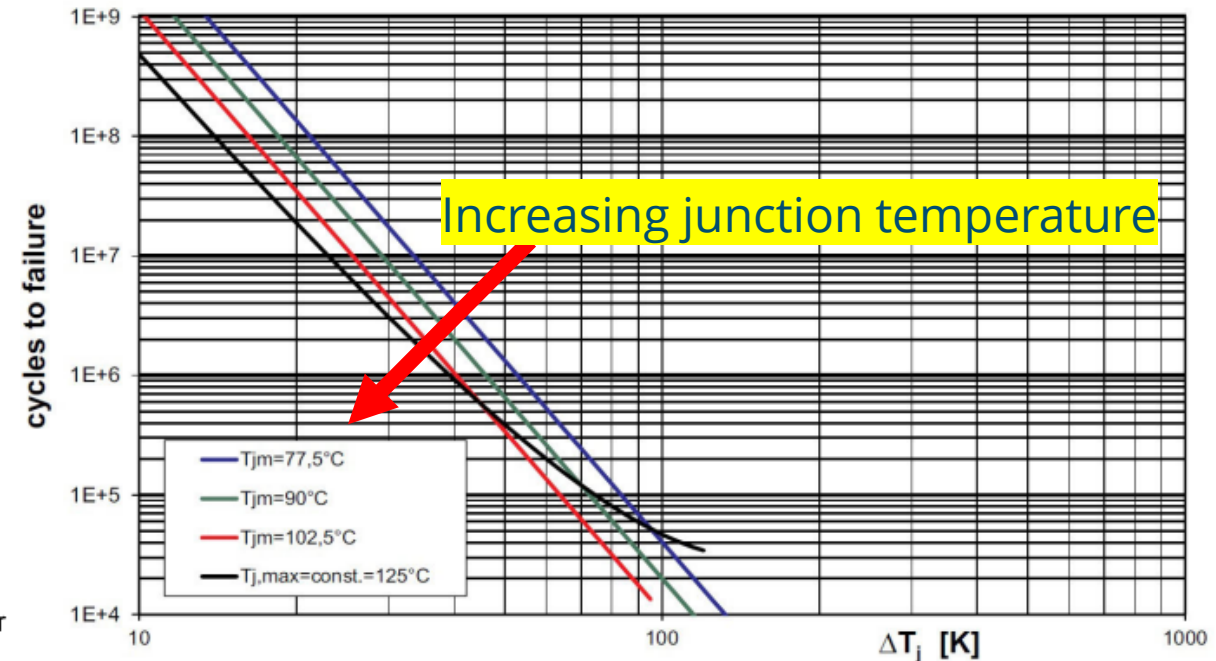
Failure Site	Primary Causes	Dominant Stresses	Failure Modes	Underlying Mechanisms
Bond Pad	High temperature exposure	Thermal overstress	Open circuit	Metallization degradation and reconstruction
Bonding Wire (Bond)	Coefficient of thermal expansion (CTE) mismatch between die and wire during temperature cycling	Thermomechanical stress	Bond lift-off	Fatigue-induced interfacial degradation
Bonding Wire (Heel)	Cyclic expansion and contraction due to temperature variation	Thermomechanical stress	Heel cracking	Fatigue crack initiation and propagation
Bonding Wire (Body)	High temperature and corrosive environment	Thermoelectrical stress Thermomechanical stress under corrosion	Open wire Wire burnout	Electromigration; Stress corrosion; Joule heating
Solder Joint	CTE mismatch during thermal cycling Microstructural evolution at elevated temperature	Thermomechanical stress	Solder joint cracking	Fatigue damage and grain coarsening
Ceramic Substrate	Rapid temperature changes (thermal shock)	Thermomechanical stress	Delamination	Interface degradation and metallization delamination

*Taken from Emerging Trends and Challenges in Thermal Management of Power Electronic Converters: A State-of-the-Art Review (2024)

⁺Adapted from Thermal Management on IGBT Power Electronic Devices and Modules (2017)



From "Advancing Thermal Management Technology for Power Semiconductors through Materials and Interface Engineering (2025)"

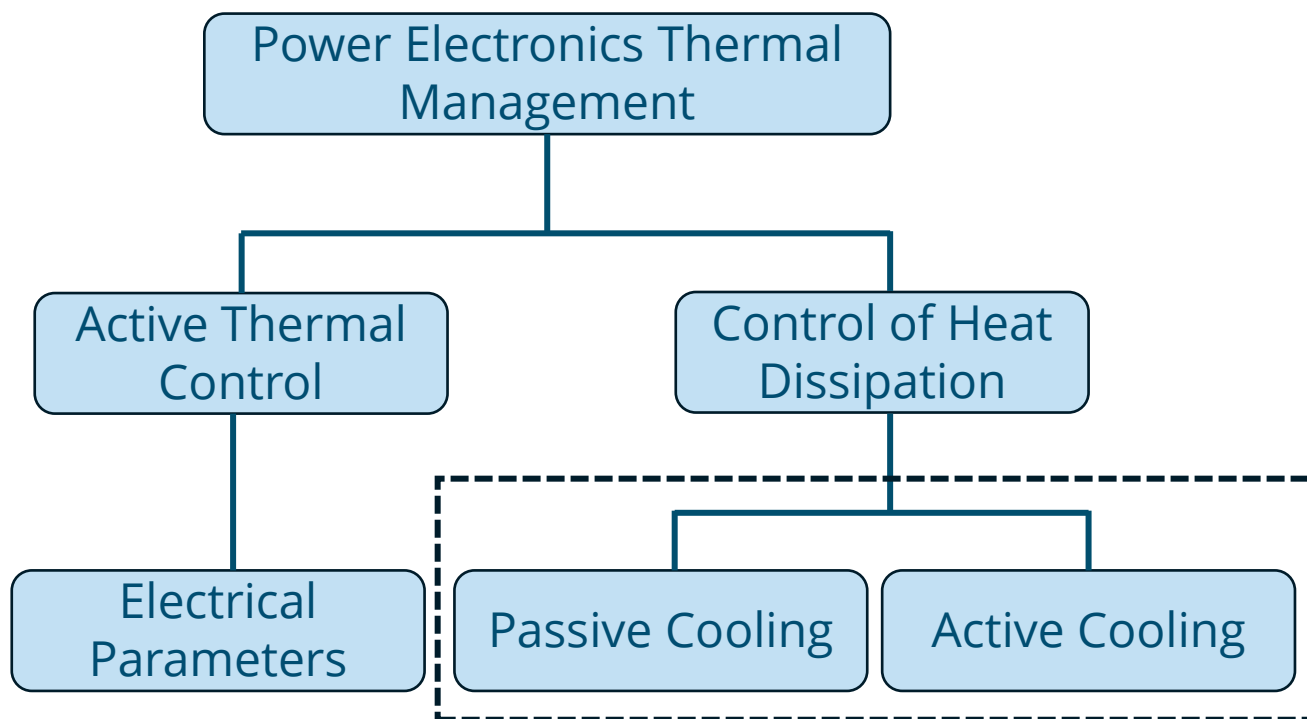


Standard IGBT modules Power cycling lifetime as a function of ΔT_j and T_{jm}^*

- Junction temperature critically impacts the device lifetime, reliability, and efficiency
- Every 10K rise in temperature diminishes device lifetime by 50%

*Emerging Trends and Challenges in Thermal Management of Power Electronic Converters: A State-of-the-Art Review (2024)

Maintaining lower junction temperature is crucial to extend reliability and device life

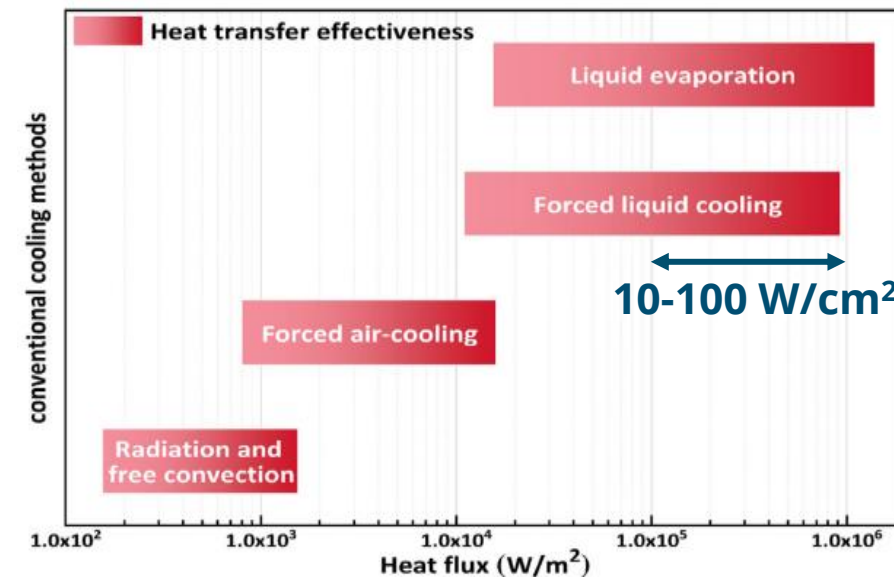


Passive Cooling Techniques

- Heat Sinks
- Heat Pipes
- Natural Convection
- Radiation

Active Cooling Techniques

- Liquid Cooling
- Fans/Blowers
- Thermoelectric coolers



Graphite based materials can enhance performance of both Passive and Active Cooling Techniques

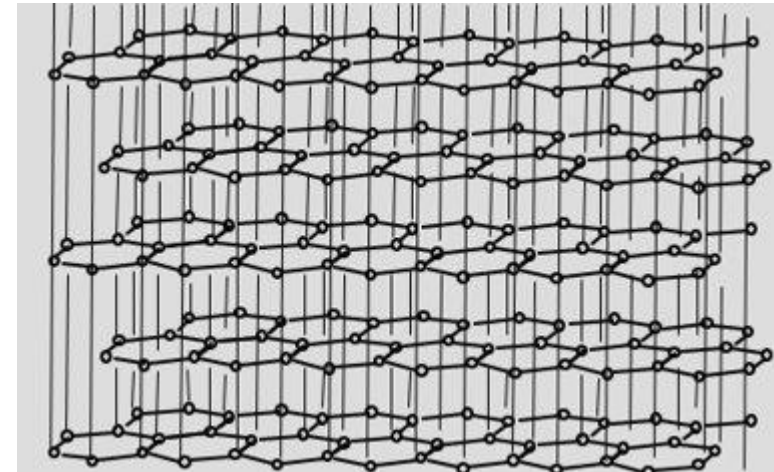
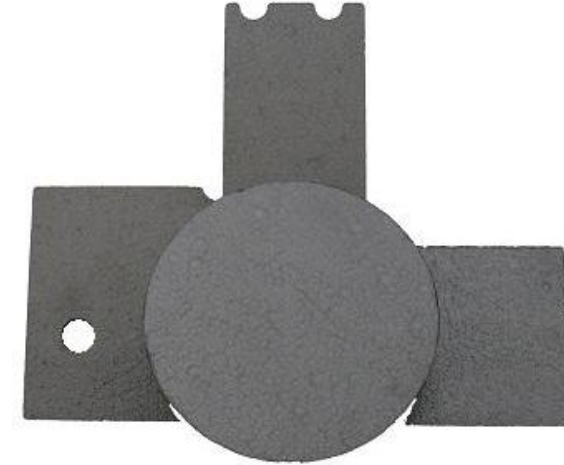
TPG®: Layers of highly oriented stacked graphene planes exhibiting excellent in-plane thermal conductivity

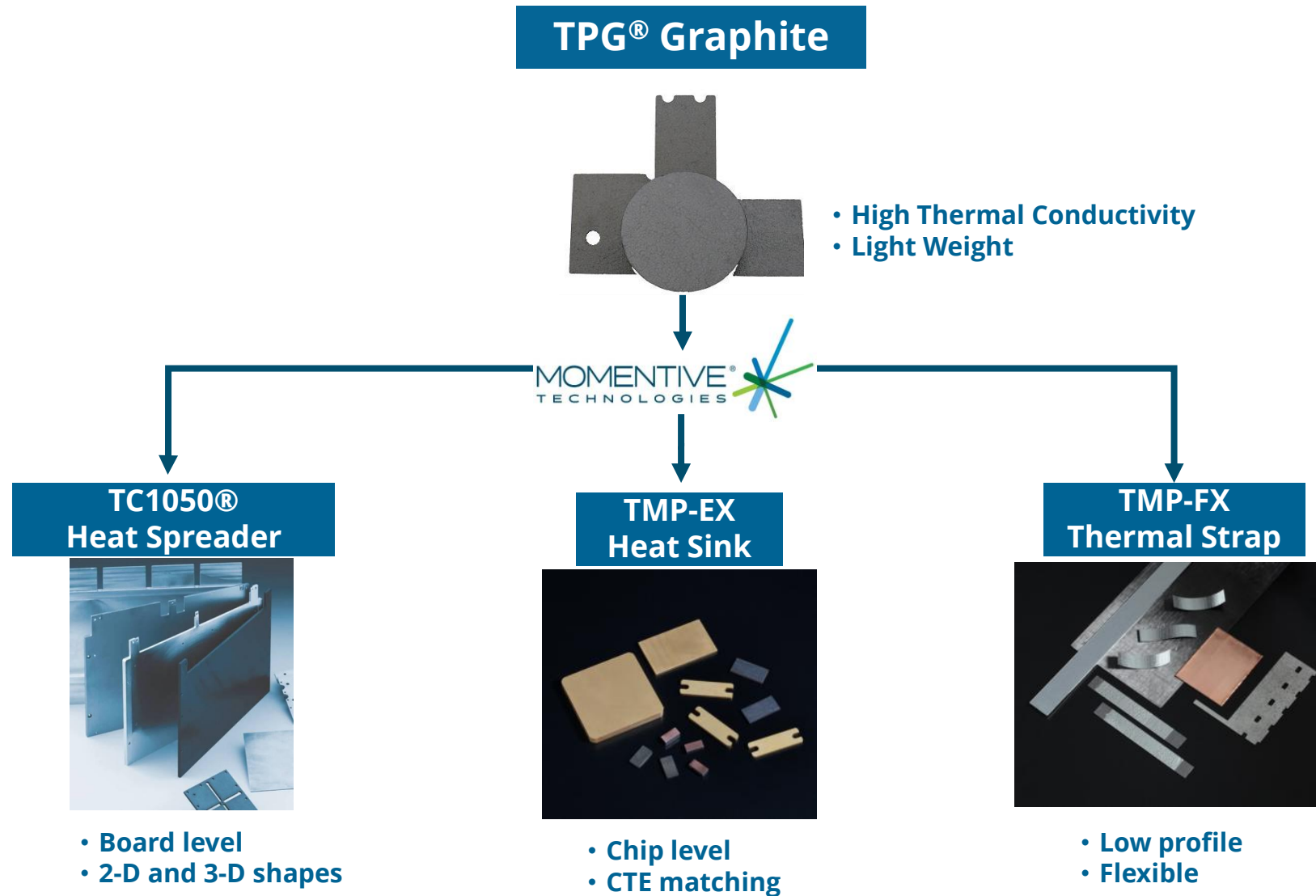
Thermal

- Temperature stable to 3000°C
- In-plane thermal conductivity $>1,500 \frac{W}{mK}$
- Excellent thermal uniformity

Mechanical

- Compatible with ultra high vacuum
- Light weight
- Low coefficient of thermal expansion
- Resistant to shock





Material*	In-Plane TC (W/m-K)	Thru-Plane TC** (W/m-K)	Density (gm/cm ³)
Aluminum	210	210	2.7
TPG + Aluminum	1073	507	2.4
Copper	400	400	8.9
TPG + Copper	1133	783	4.5
AlSiC12	180	180	3.0
TPG + AlSiC12	1060	435	2.5
W85Cu	190	190	15.6
TPG + W85Cu	1063	455	6.7
Mo70Cu	170	170	9.8
TPG + Mo70Cu	1057	416	4.8

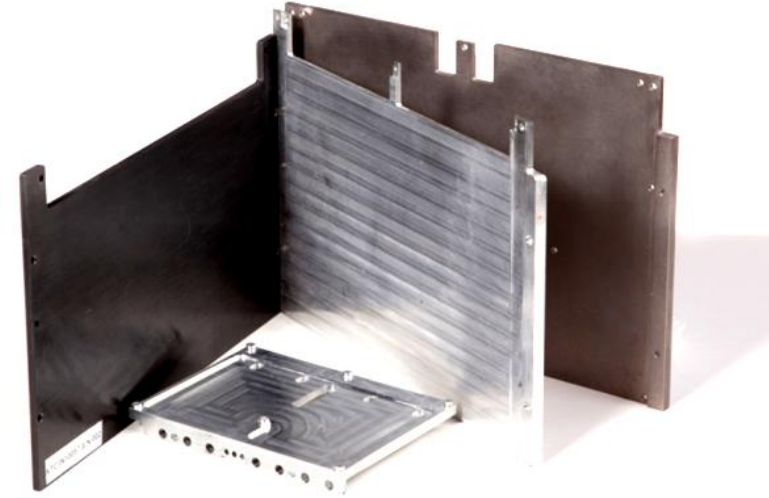
* Estimated values based upon calculation using published information and should not be used as or to develop specifications. Actual values may vary.

** TPG graphene plane is perpendicular to the metal surface for this calculation.

Features

- Thermal conductivity
 - 5x of aluminum
 - 2.5x of copper
- Lighter than aluminum
- Wide operating temperature range
- Mechanical load bearing
- Size up to 4 ft² (0.37 m²)
- Machinable, Platable, Heat treated T4 and T6

Examples of TC1050 Heat Spreaders

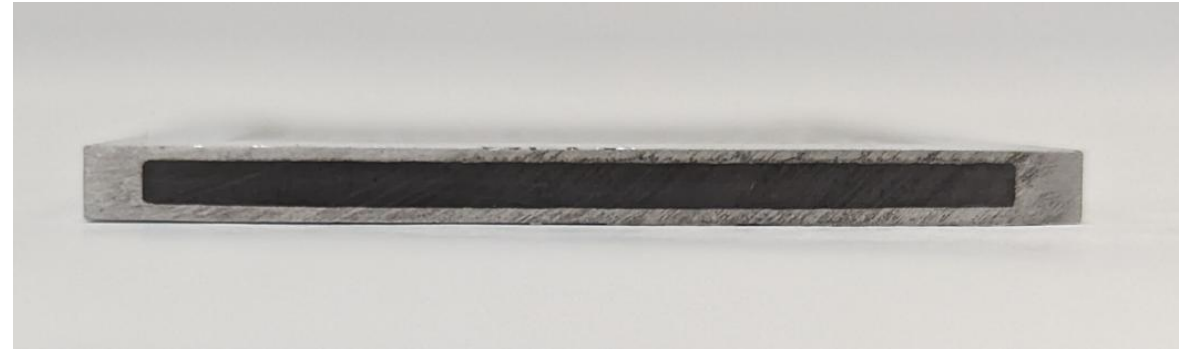


Exposure View of TC1050 Heat Spreader



Potential Applications

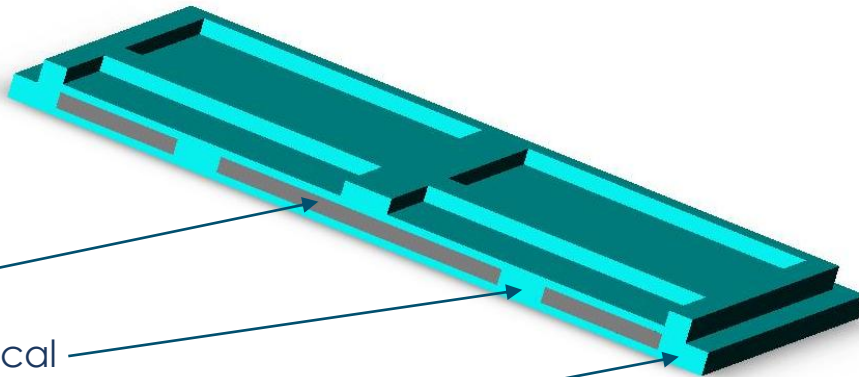
- Heat spreader in electronic packaging
- Thermal cores for PWB's
- Avionic thermal cores
- Satellite traveling wave tube mounts
- Electronic chassis
- Cold plates in radar systems



Cutaway View



AL-TPG® interface



TPG graphite tile

Thermal/mechanical
vias

Metal shell/rail

- MIL-STD-883H testing for microcircuits
 - Thermal Shock Method 1010.8
 - 150°C to -65°C, 10 cycles
- Mechanical Shock Method 2002.5
 - 500G, 1.0mS, 1 shock per axis (total of 6 shocks)
- Mechanical Vibration Method 2005.2
 - 60Hz, 20G, 32 hours per axis (3 axis total – x, y, z)
- All tests done at DLA certified laboratories

Thermal shock



Mechanical shock



Vibration



No change, cracks, or delamination after environmental testing

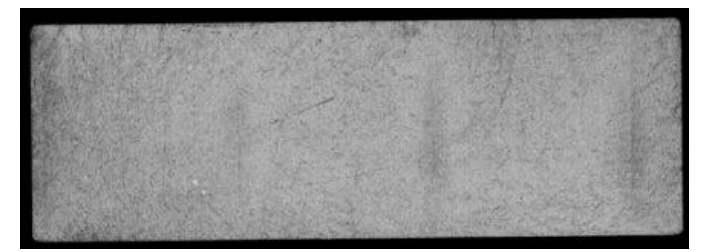
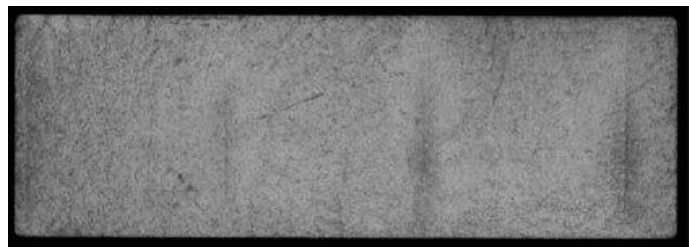
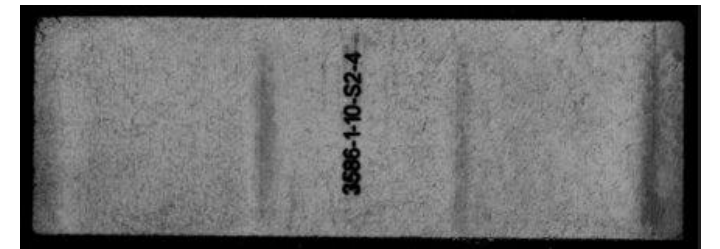
As Machined



After mechanical
shock and vibration



After mech shock, vibration,
and thermal shock



Features

- High thermal conductivity
- CTE matching to semiconductors
- Light weight

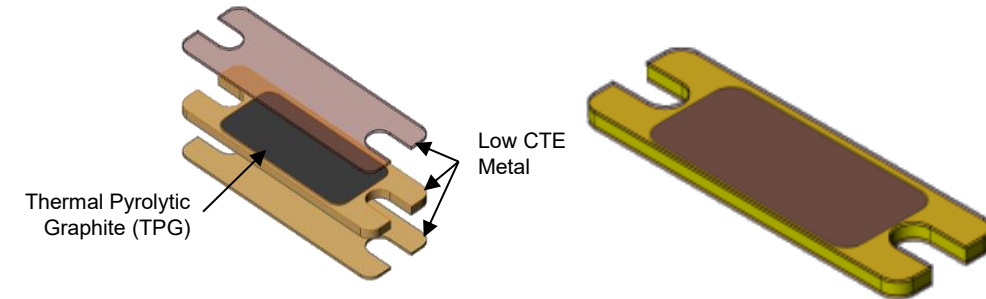
Potential Applications

- CTE-matched flange
- Air-cooled heat sink base

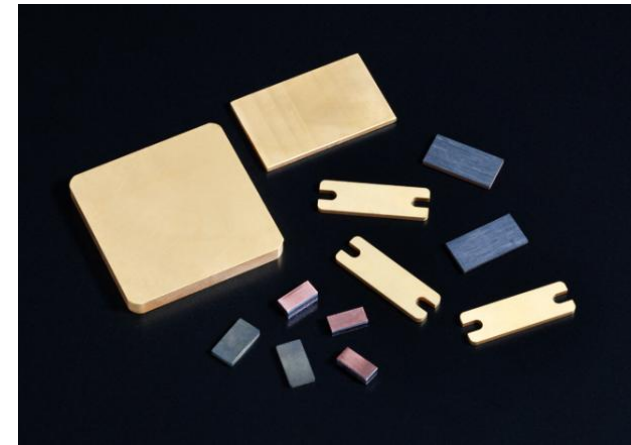
Typical Physical Properties

- Parallelism: 0.0005" (0.01mm)
- Flatness: 0.001"/1" (1 μ m/1mm)
- Surface Finish: Ra 16 μ in (0.4 μ m)
- Plating: Ni 160-250 μ in (4-6 μ m) / Au 40-80 μ in (1-2 μ m)

Schematic of TPG-EX Heat Sink



Examples of TPG-EX Heat Sinks



Features

- High thermal conductivity
- Low profile
- Light weight
- Flexibility
- Formability
- Durability
- Solderability

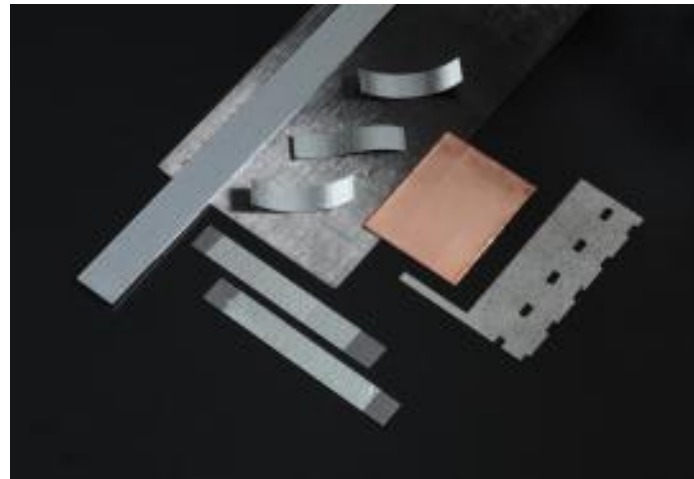
Potential Applications

- Heat spreader
- Thermal strap
- Heat sink fin

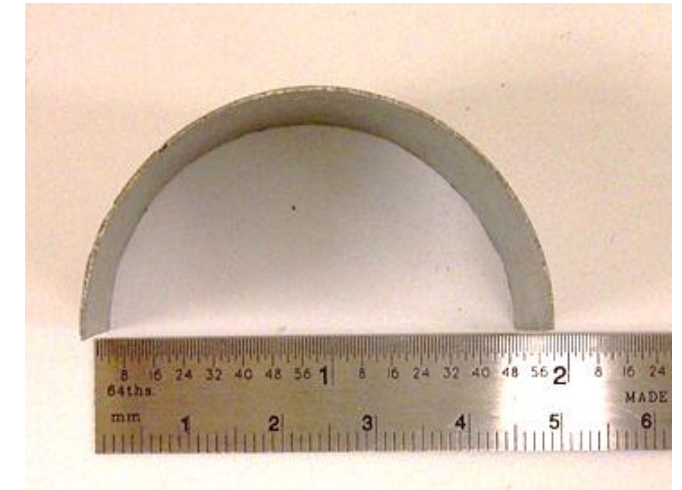
Typical Properties

- Laminate TC > 1200 W/m-K
- Surface Finish: Ra 24 μin (0.4 μm)
- Operating Temp: -55 to +125°C

Examples of TPG-FX Laminates



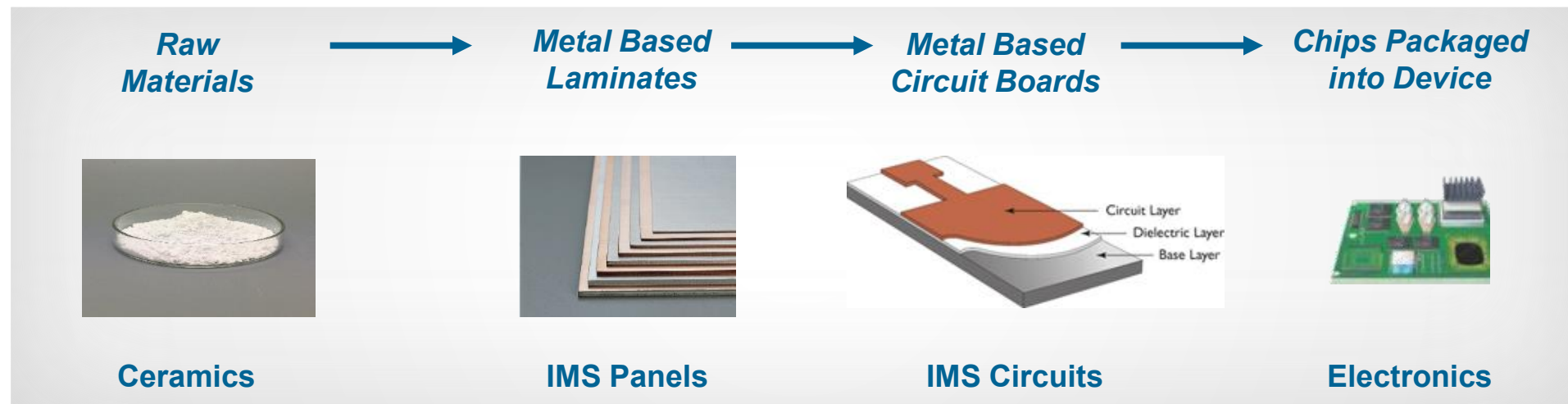
Thermal Strap Forming



APPLICATION EXAMPLES

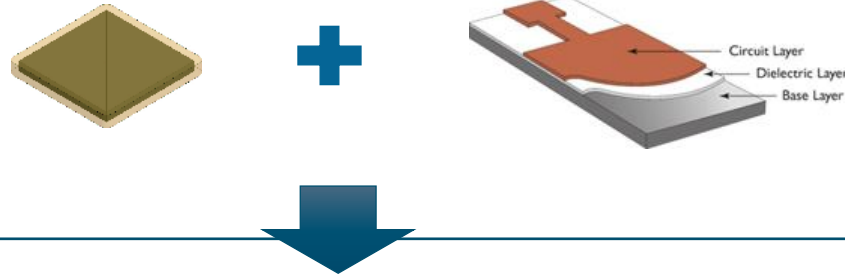


- 20+ year experience providing reliable IMS thermal solutions
- Fully integrated IMS solution also aligns with entire value chain



TMS-CORE IMS CONCEPT

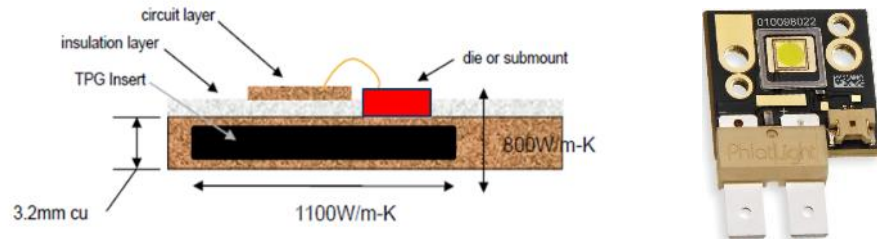
Traditional Assembly



Challenges:

- Complex design
- Many interfaces
- High assembling cost

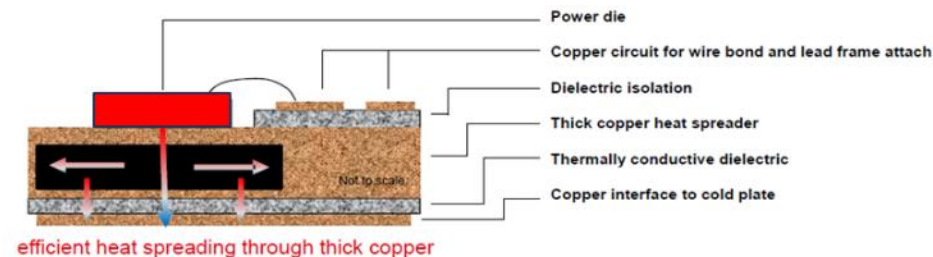
GEN I – Single Side Insulation (Low Voltage)



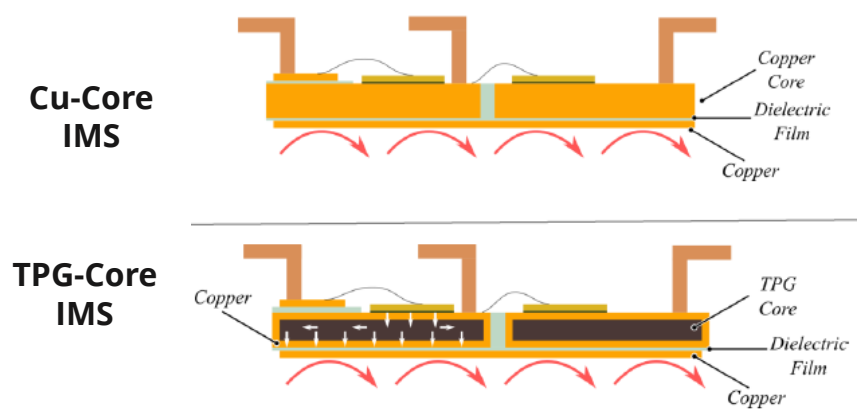
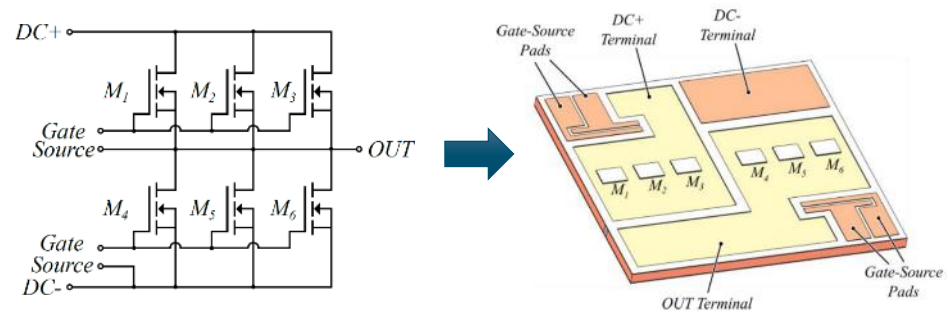
Advantages:

- Integrate TPG and IMS solutions
- Improve thermal performance
- Improve reliability
- Maximize device capacity
- Reduce module complexity
- Reduce weight

GEN II – Double Side Insulation (High Voltage)



SIC POWER MODULE DESIGN FOR DEMONSTRATION



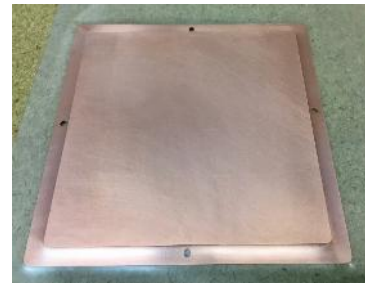
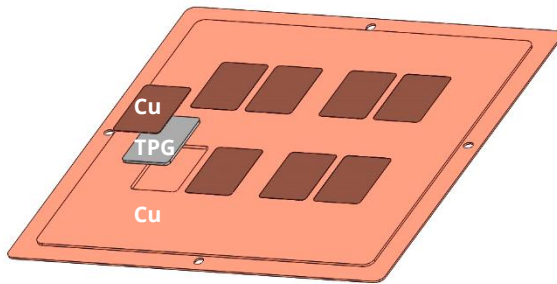
	Specifications
Die Size	4.08 mm x 3.1 mm
Die Spec	900V, 30mΩ
Module Size	42.7 mm x 45.1 mm
Module Power Loss	45 W per chip
Dielectric Thickness	152 μm
Dielectric Strength	11 kVAC
Max Junction Temperature	140 °C
Copper Thickness	71 μm (2 oz.)
Center Core Thickness	1.60 mm

*TC1050 and TPG are trademarks of Momentive Performance Materials Inc.
*TCLAD and IMS are trademarks of TCLAD.

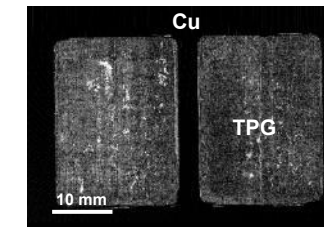
MOMENTIVE TPG-CORE SUBSTRATE PROVIDES HEAT CONDUCTION

- Momentive proprietary bonding technology ensured structure integrity and thermal excellence.
- Solid and intimate bonding was revealed at TPG-Cu and Cu-Cu interfaces.
- Through-plane thermal conductivity of 760 W/m-K was achieved.
- 31% weight reduction was also observed.

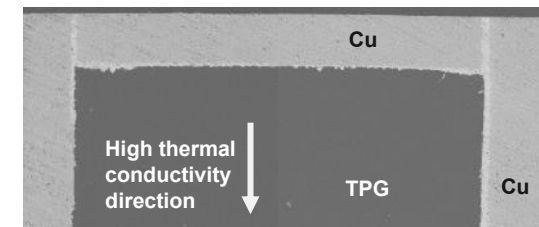
TMP-EX Substrate Design and Production



Interface Top View (Sonoscan)

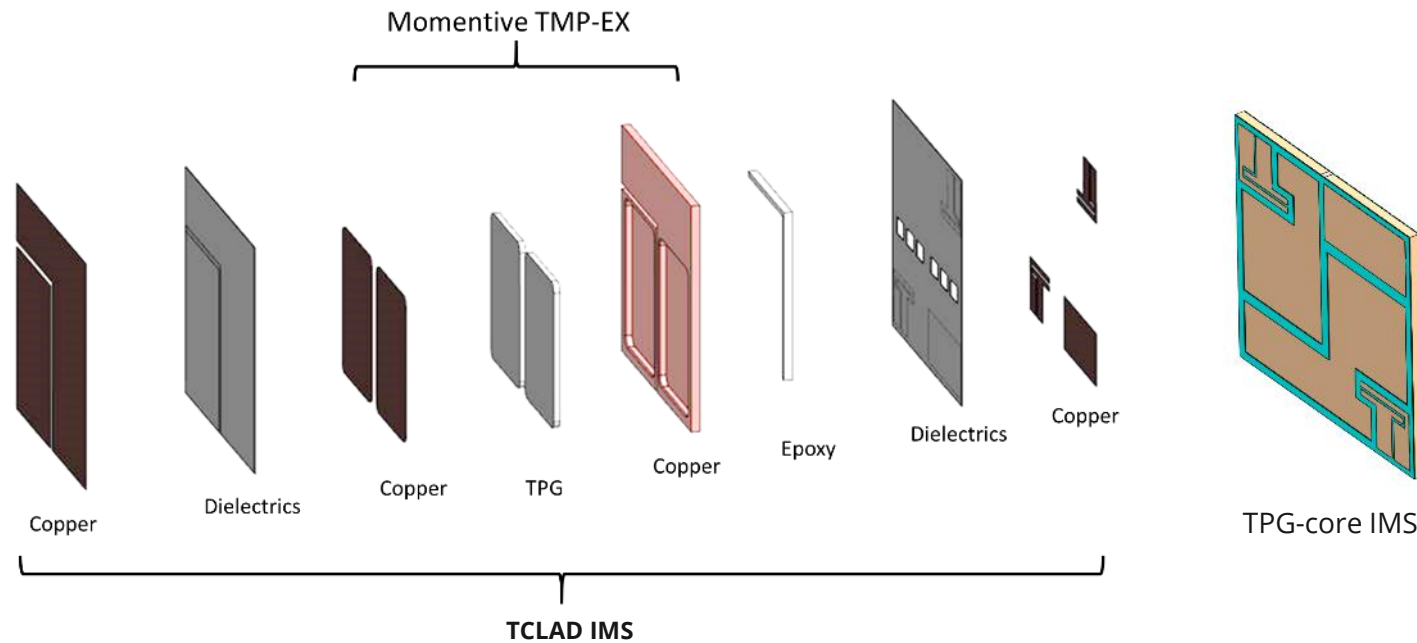


Interface Cross Section View (SEM)

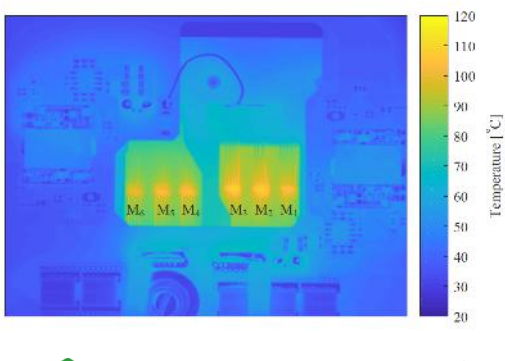
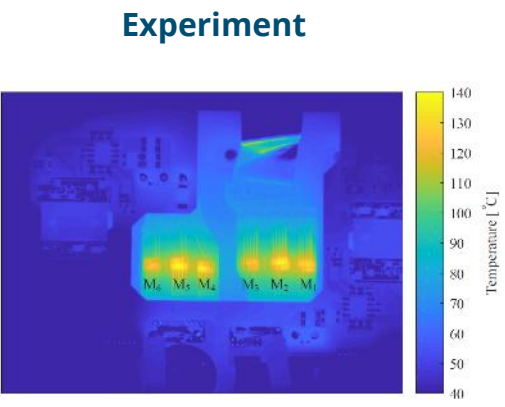
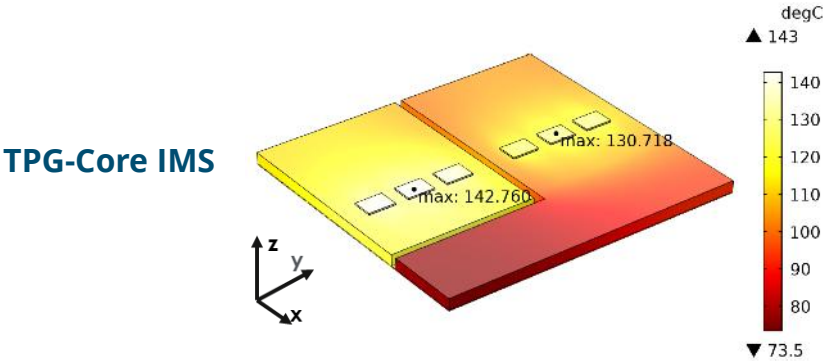
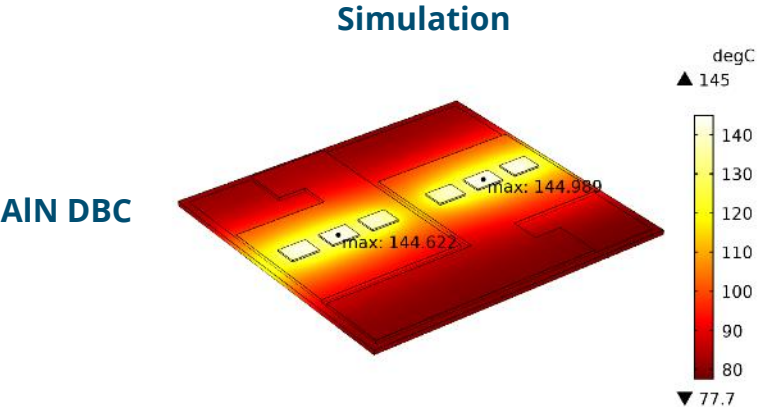
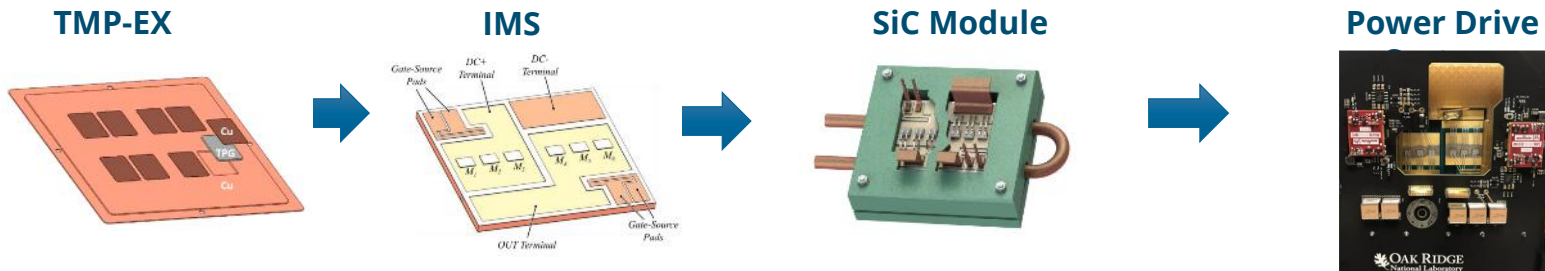


*TPG is trademarks of Momentive Technologies

IMS PROVIDES ELECTRICAL FUNCTIONALITY AND PROTECTION



- TCLAD produced laminate panels and piece cut individual circuits using both copper and TPG substrate cores.
- TCLAD HT-07006 dielectric layers were applied per proprietary coating technology to ensure good wet-out to the metal layers and the required 6 kVAC breakdown protection.
- The two TPG inserts were isolated from each other using San-Ei Kagaku epoxy (PHP-900 IR-10F).

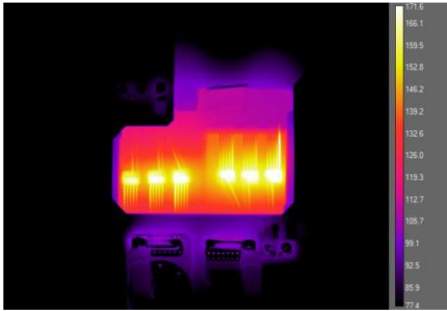


PERFORMANCE SUMMARY

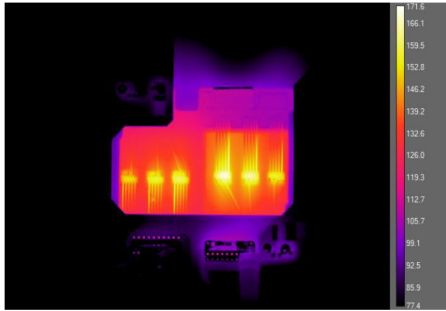
	Weight (gm)	Thermal Conductivity (W/m-K)			Max T _{Junction}		T _{Junction} Variation
		x	y	z	@ steady state	@ power cycle	@ power cycle
Cu-core IMS	26.5	395	395	395	152°C	113°C	8.6°C
TPG-core IMS	18.3	1155	130	760*	141°C	104°C	6.8°C

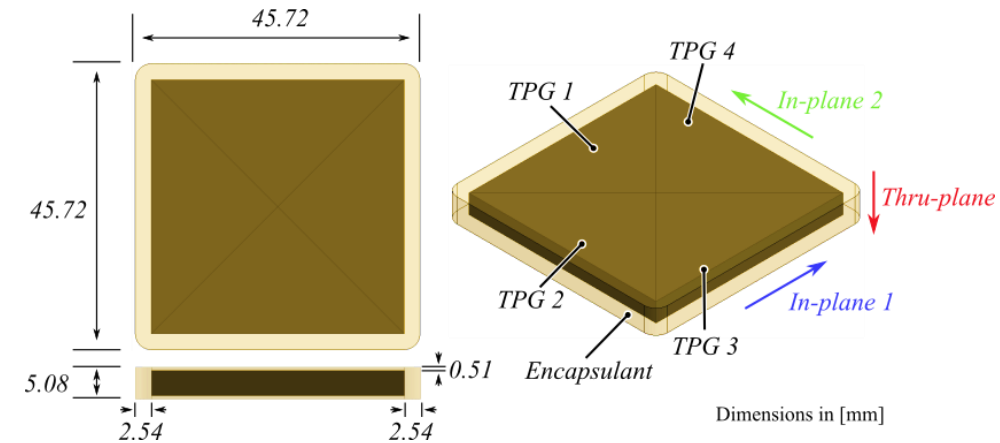
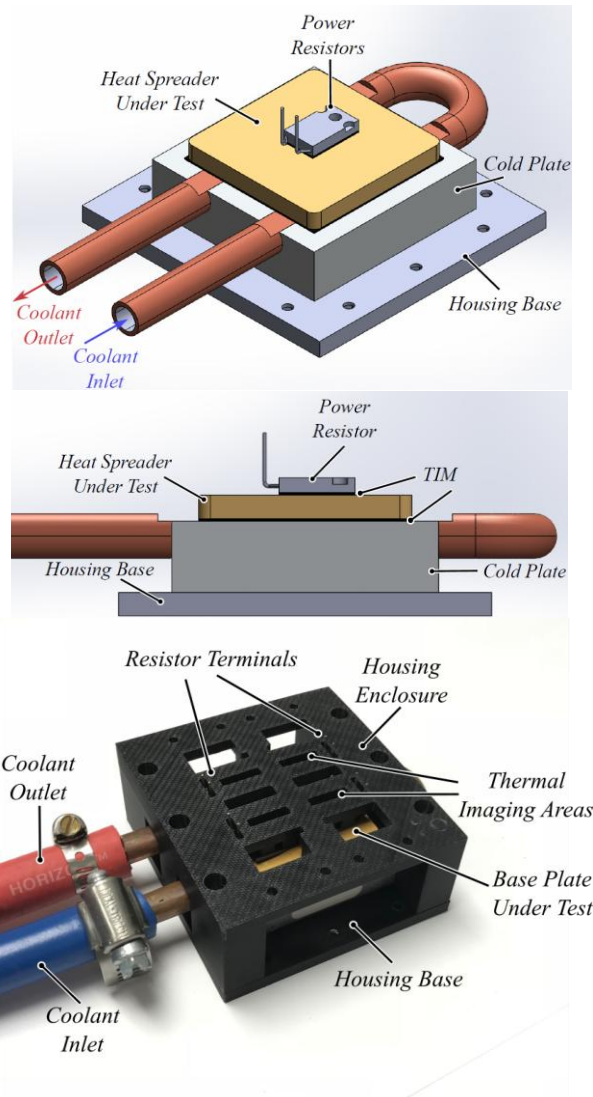
- TPG-core IMS
 - Increased in-plane TC by 3x
 - Increased through-plane TC by 2x
 - Reduced T_{junction} by 9~11°C
 - Reduced T_{junction} range by 1.8°C
 - Reduced weight by 31%
- TPG-core substrate panel is compatible with standard IMS production.
- TPG-core IMS is compatible with SiC power module packaging process.

Cu-Core IMS

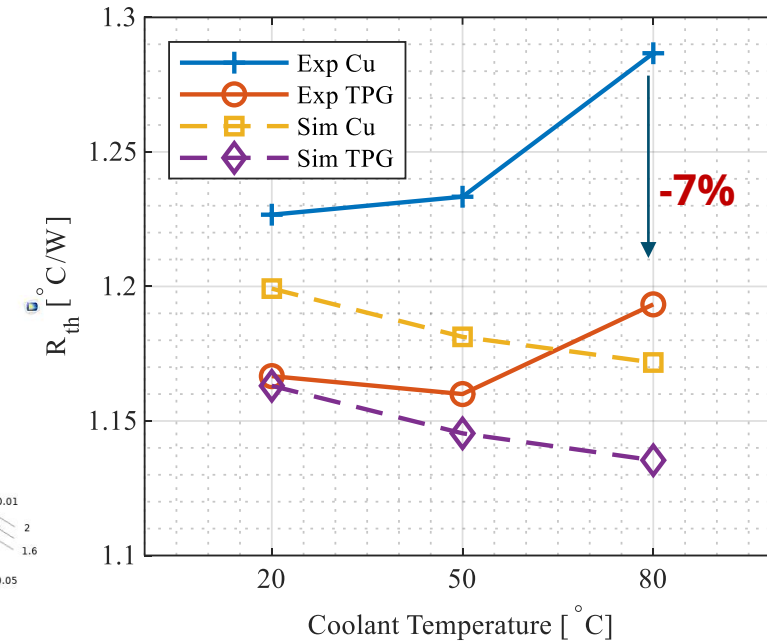
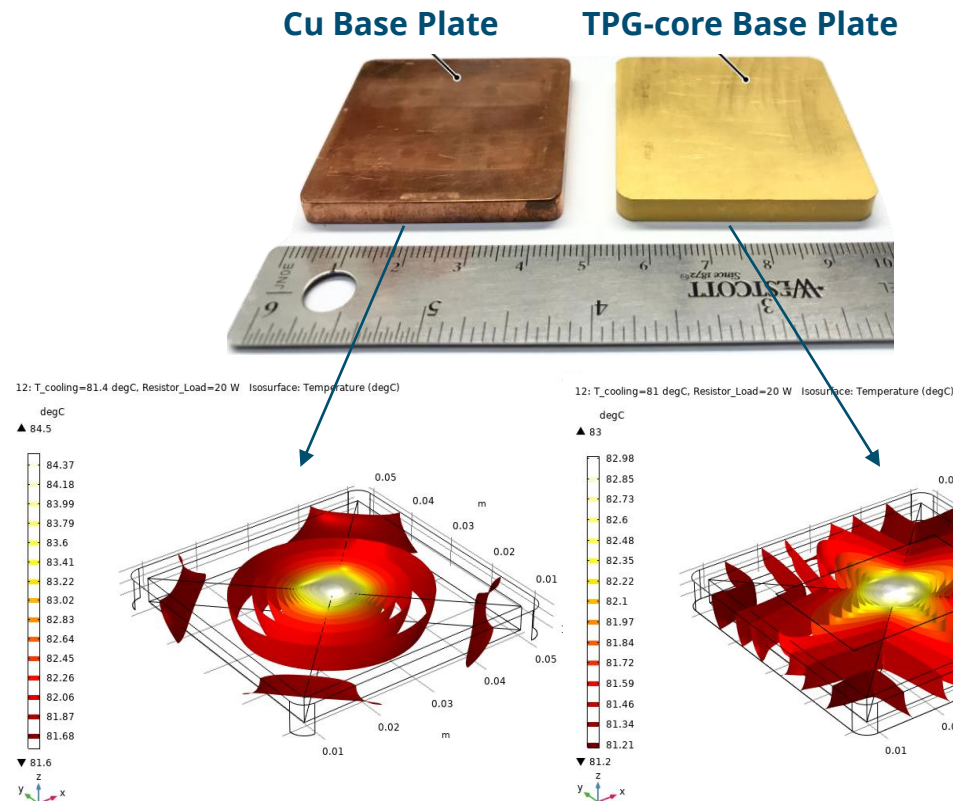


TPG-Core IMS

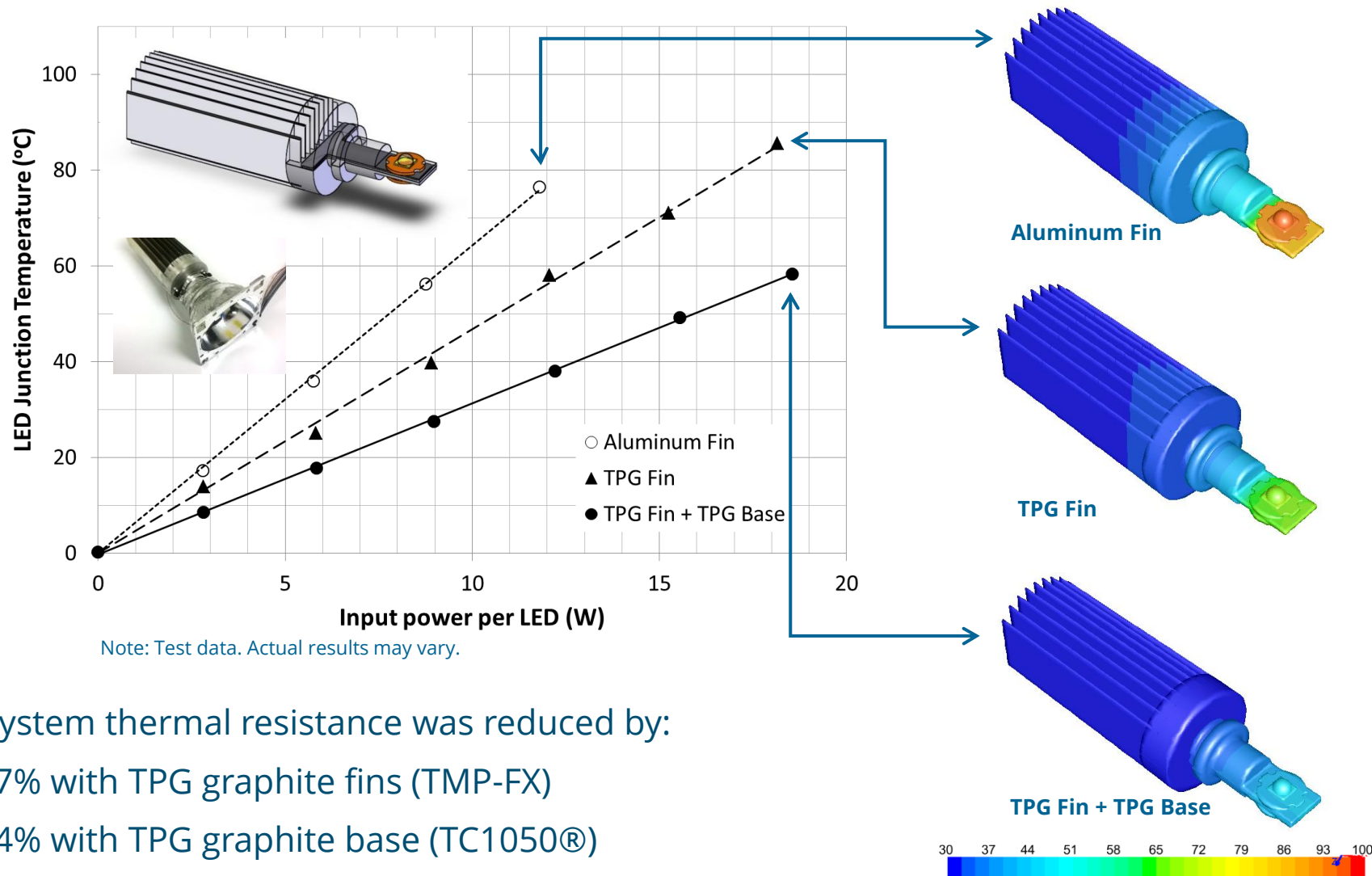




- Four TPG tiles with vertical graphene basal planes were bonded inside copper base plate.
- Power module was constructed to compare performance of TPG-core base plate and incumbent copper base plate.

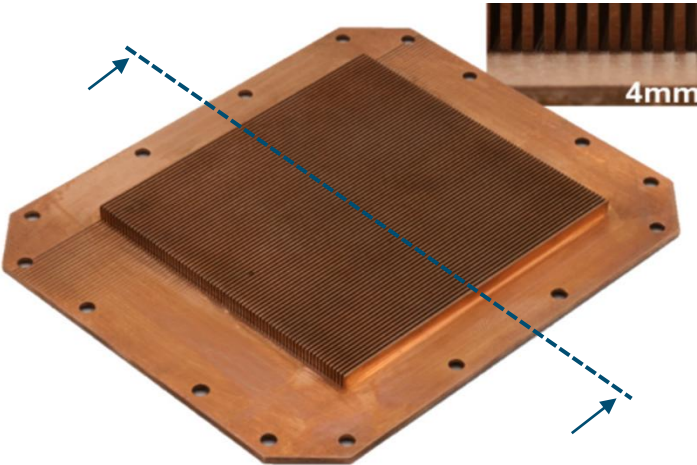


- TPG core reduced 50% thermal resistance of the base plate.
- TPG core reduced 48% weight of the base plate.
- As the result, system thermal resistance R_{th} decreased by 5~7%.

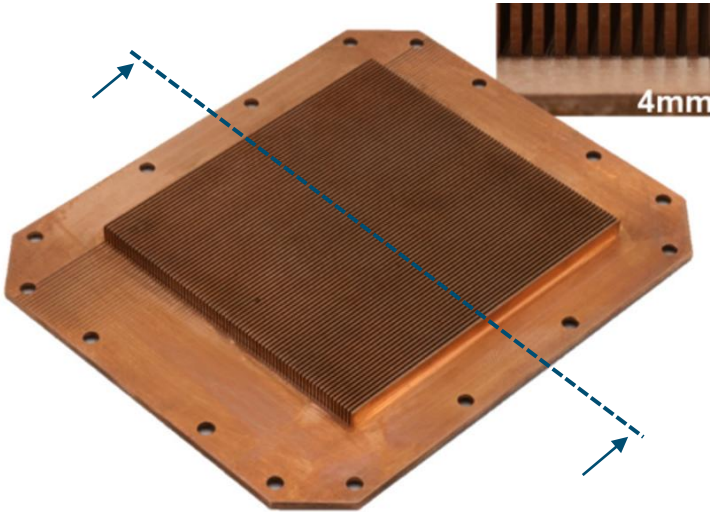


Total system thermal resistance was reduced by:

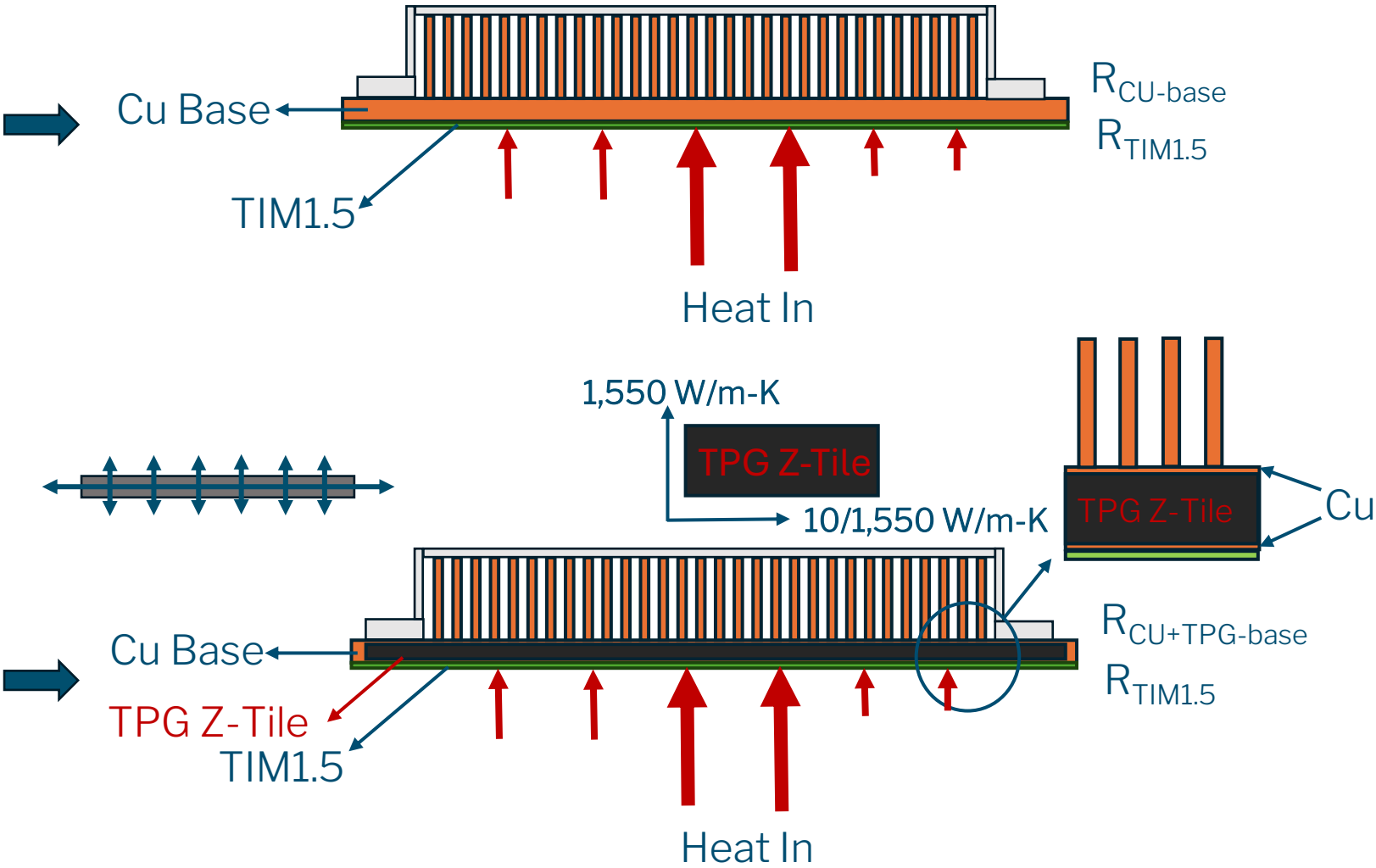
1. 27% with TPG graphite fins (TMP-FX)
2. 24% with TPG graphite base (TC1050®)



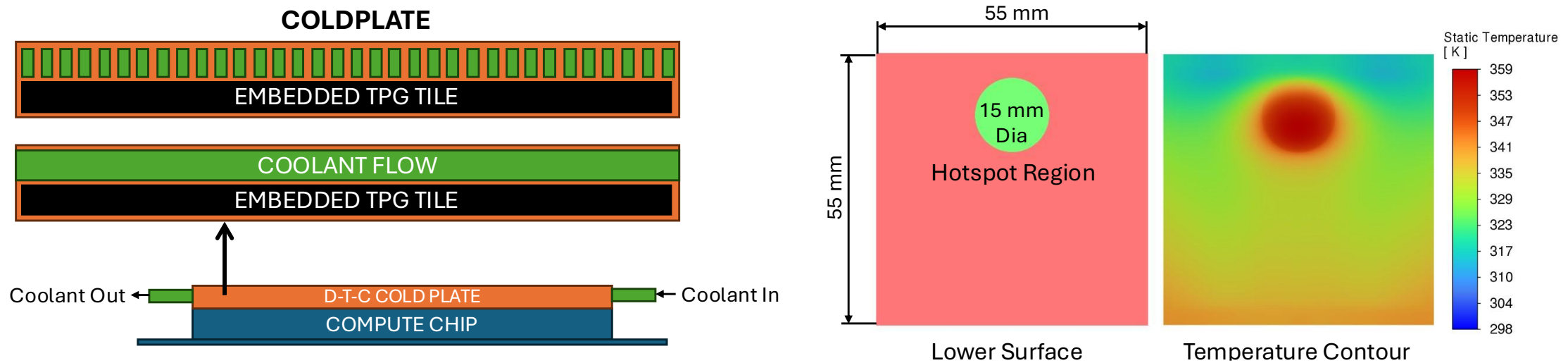
Regular Cold Plate*



MT Cold Plate w TPG*



$$R_{Cu+TPG-base} = R_{Cu} + R_{TPG} \qquad R = L/kA$$

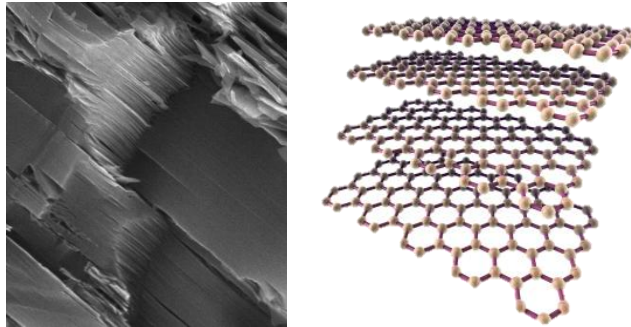


Maximum Hotspot Temperature Reduction (K)

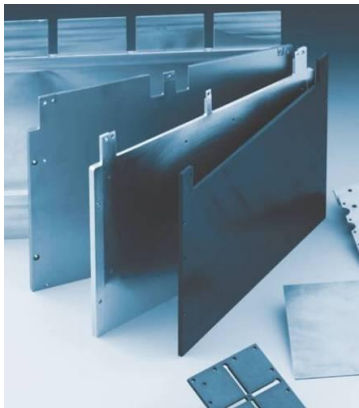
Case	Material	Coolant Flowrate		
		0.5 LPM	1.0 LPM	2.0 LPM
1	Copper-0.0 mm	Reference	-15.2	-25.6
2	TMP-0.5 mm	-17.0	-28.0	-35.9
3	TMP-1.0 mm	-23.1	-32.9	-39.8
4	TMP-1.5 mm	-26.5	-35.8	-42.2
5	TMP-2.0 mm	-28.7	-37.7	-43.8

- TPG® core enables hot spot temperature reduction at significantly lower coolant flow rates
- Improved channel and manifold design can further enhance cold plate performance

TPG® Graphite



TC1050® Heat Spreader



TMP-EX Heat Sink



TMP-FX Laminate

