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Increasing Power Density In Three-Phase Inverters With Direct-Cooled SiC Power Modules

by Matthew Feurtado, Matt Reeves, Daniel Martin, and Ty McNutt, Wolfspeed, Fayetteville, Ark. and Wieland Microcool, Bend, Ore.

Current trends in electrification are placing increasing demands on the power electronics for improved efficiency, higher power capability and higher power density. Since these demands apply to systems, the requirements extend down to the component level. Silicon carbide (SiC) is poised to rapidly replace silicon (Si) in many applications due to the higher performance characteristics SiC enables. SiC devices offer faster switching speeds, lower dynamic loss and lower conduction loss in a smaller die area compared to Si devices. To translate these semiconductor advantages into usable solutions, new power module designs are necessary to take full advantages of SiC.

Wolfspeed has developed a next-generation module that has been highly optimized to achieve the maximum performance out of Wolfspeed Generation 3 SiC MOSFETs. The XM3 half-bridge power modules offer the capability to carry high currents (300 to >600 A) in a small footprint (53 mm x 80 mm) with a terminal arrangement that allows for straight-forward bussing and interconnection.

A low-inductance, evenly matched layout results in high-quality switching behavior, minimizing oscillations internal and external to the module. The module has a stray inductance of 6.7 nH and occupies approximately 60% of the area of a 62-mm module as can be seen in Fig. 1. Due to the high current density of SiC power devices the thermal performance of the module and cold plate is critical to maximizing heat flux and reducing system size and cost.

The XM3 modules are offered in both a conventional flat baseplate version, which mounts to a liquid-cooled heatsink, and a direct-cooled baseplate which essentially integrates liquid cooling within the baseplate. In this article, the characteristics of both module types are described and the performance and manufacturing benefits of the direct-cooled modules are explained and demonstrated.

The improved thermal performance of the direct-cooled module will be verified with an experiment that measures the thermal resistance (junction to liquid) of the two module types, with power and cooling applied to the modules, and SiC MOSFET junction temperatures driven to 175°C. The different methods of measuring the junction temperature are noted. The system-level advantages of the direct-cooled module are then demonstrated in a three-phase inverter design example. This example uses an 800-V bus, which is becoming increasingly popular in electric vehicle applications.

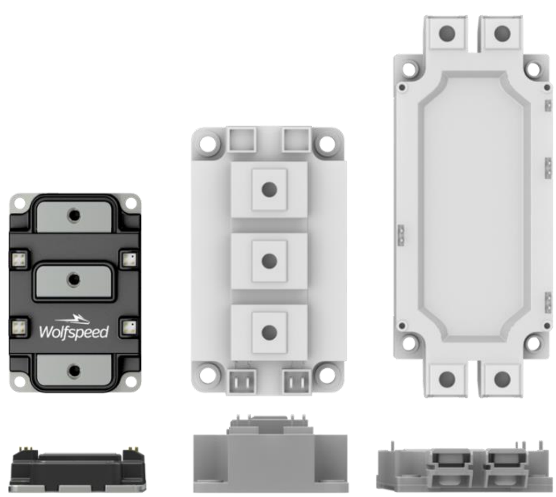

Fig. 1. Size comparison of flat baseplate XM3 power module with existing packages.

Flat Baseplate

The CAB450M12XM3 is a 1200-V half-bridge power module with a current rating of 450 A. The drain-source on-state resistance is 4.6 mΩ at the max junction temperature of 175°C. The part uses a flat copper baseplate which acts as a heat spreader to transfer heat away from the SiC die and as the mechanical mounting surface (Fig. 2).

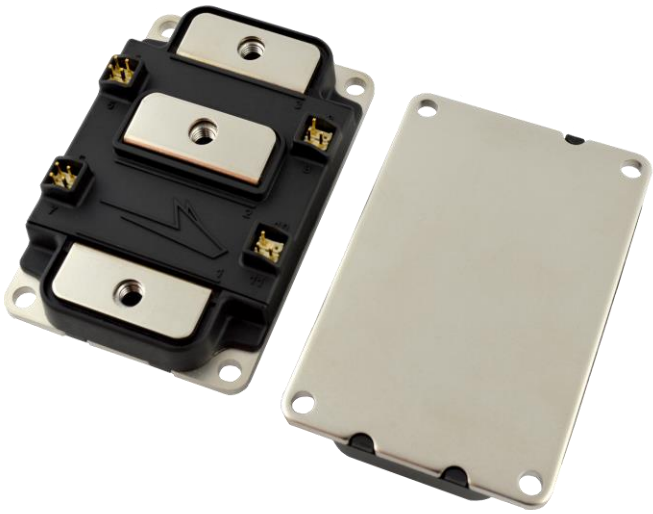

Fig. 2. Top and bottom views of an XM3 module with flat baseplate.

The temperature rise across the package structure per unit of power dissipated by the semiconductor junction is the thermal resistance, R_{Θ}, of the package given in units of °C/W. The total thermal resistance from junction to coolant is the sum of the series resistances in the thermal path. For a flat baseplate module on a liquid-cooled heatsink this will be the resistance from junction to case, $R_{\Theta JC}$, resistance from case to heatsink, $R_{\Theta CS}$, and the resistance from heatsink to liquid, $R_{\Theta SL}$,

$$R_{\Theta JL} = R_{\Theta JC} + R_{\Theta CS} + R_{\Theta SL} \quad (1)$$

Any imperfection in the surface finish of the baseplate or the heatsink it is mounted to will result in air gaps at the interface with higher thermal impedance than the base metals. Therefore, a thermal interface material (TIM) is required to be applied between the module and a heatsink or cold plate to fill any voids in the thermal path with a thermal resistance lower than air.

The effect of this TIM is a non-zero thermal impedance between module case and cold plate, $R_{\Theta CS}$. The value for the $R_{\Theta CS}$ will vary based on thickness after mounting and material composition with typical thermal conductivity between 3 and 10 W/mK.

Direct-Cooled Baseplate

The XAB525M12XM3 utilizes the same SiC devices and exchanges the flat copper baseplate for a direct-cooled, copper pin-fin baseplate. This simple change enables a current rating of 525 A (Fig. 3). The pins of the baseplate are designed to be in direct contact with a coolant, negating the need for a TIM and have a profile that is optimized to balance performance, pressure drop, and anti-clogging characteristics.

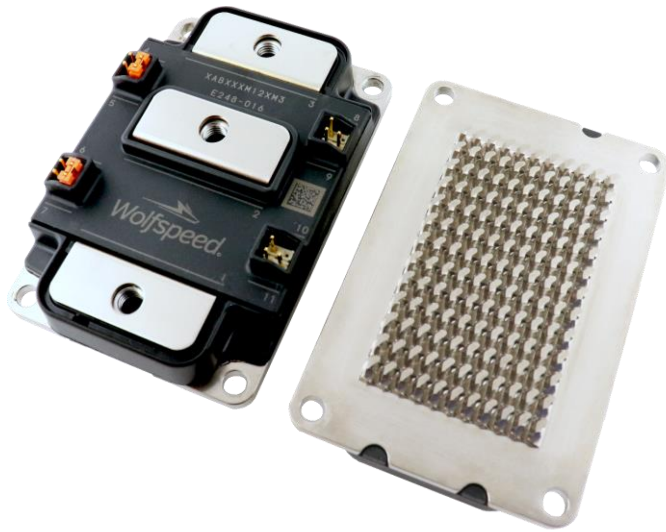

Fig. 3. Top and bottom views of a direct-cooled XM3 module showing its pin-fin structure.

Fig. 4 shows the heat transferred from the module to the coolant liquid as it flows across the pin fins. The surface which conducts the heat to the coolant is incorporated as part of the power module itself, therefore, the case surface temperature and the coolant temperature are equal and $R_{\Theta CS}$ becomes zero, simplifying equation (1) to a single term. This means the full thermal resistance to coolant, $R_{\Theta JL}$, will be specified in the datasheet for a direct-cooled power module.

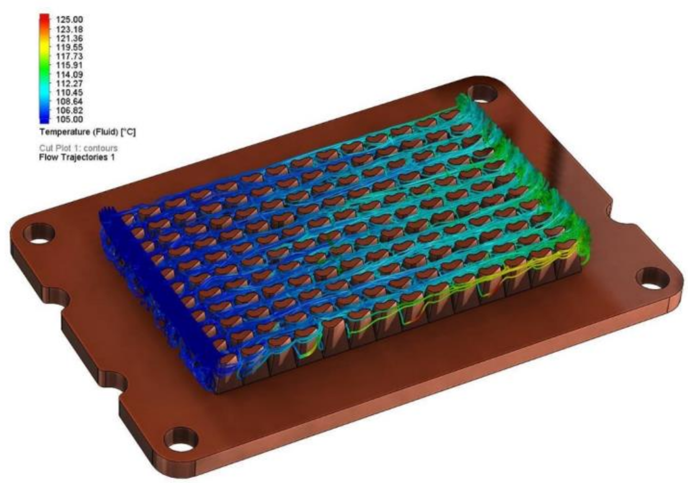

Fig. 4. Temperature gradient in the coolant as it traverses cooling fins in a direct-cooled XM3 module.

A common pitfall when interpreting thermal performance metrics in datasheets is comparing the $R_{\Theta JL}$ of a direct-cooled module with the $R_{\Theta JC}$ of a flat baseplate module. The $R_{\Theta JL}$ will appear to be worse, however the $R_{\Theta JC}$ does not include the full thermal path from heat source to coolant medium (air, water, etc.). Designers must add the additional thermal impedance of the cold plate as well as the TIM for an equivalent comparison.

For the flat baseplate XM3, the suggested cold plate is the CP3012-XP, a custom micro deformation liquid-cooled cold plate developed by Wieland MicroCool. This cold plate offers a very low thermal resistance of

0.008°C/W at 12 L/min while maintaining a balanced flow across all module positions and a low pressure drop. The CAB450M12XM3 weighs 175 g and the total assembled mass of three modules, TIM, cold plate, and fasteners is 1258 g.

As for the direct-cooled XM3, there is a matching Wieland MicroCool CP3012-DIRECT coldplate with interior coolant channels and machined cavities that the baseplate sits inside, allowing the coolant to pass through the pins and an o-ring seal to prevent leaks. Fig. 5 shows the balanced coolant flow across all three module baseplates in the cold plate manifold.

The XAB525M12XM3 weighs 208 g and the total assembled mass of three XAB525M12XM3 modules, o-rings, cold plate, and fasteners is 1314 g. This cold plate can be a drop-in replacement for the flat baseplate XM3 and mounting is even easier. Simply place the o-ring seals into the groove in the cold plate, place the XM3 module into position with the pin fins in the machined cavity, and tighten mounting bolts to the specified torque as shown in Fig. 6. No need for stencils, spatulas, or messy paste.

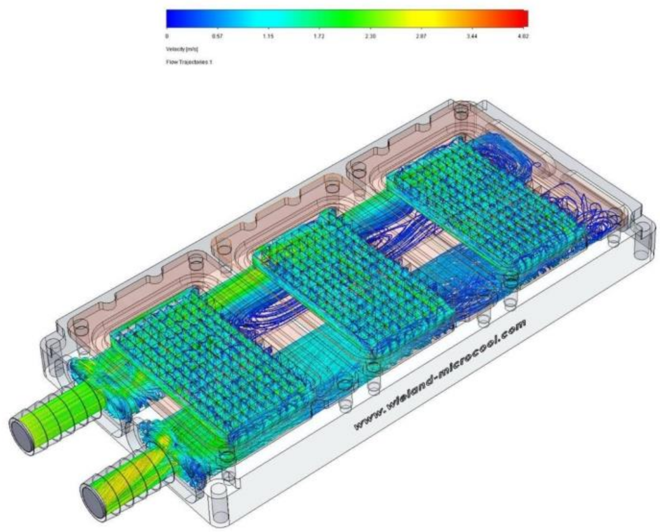

Fig. 5. Coolant flow trajectories for 3x direct-cooled XM3 modules at 12 L/min.

Fig. 6. Assembly of direct-cooled XM3 modules mounted on a cold plate as used in the test setup with one position removed to show the coolant chamber and gasket.

Thermal Validation

One of the challenges of characterizing the thermal performance of a power module is obtaining an accurate measurement of the junction temperature. One way is to modify the module by opening the lid and either attaching temperature probes directly to the die or by applying matte black paint and using a thermal camera to measure die temperature as shown in Fig. 7. Then apply a dc current to the module and divide the measured temperature delta by power dissipated.

Another method is to perform a characterization sweep of each switch position to determine an on-state resistance versus temperature profile. Then apply a dc current to the module, measure the on-resistance and correlated junction temperature, and divide by the power dissipation. This method does not require any permanent modification to the power module. Any of the above methods can also be used to characterize the NTC temperature sensor in the module to the junction temperature.

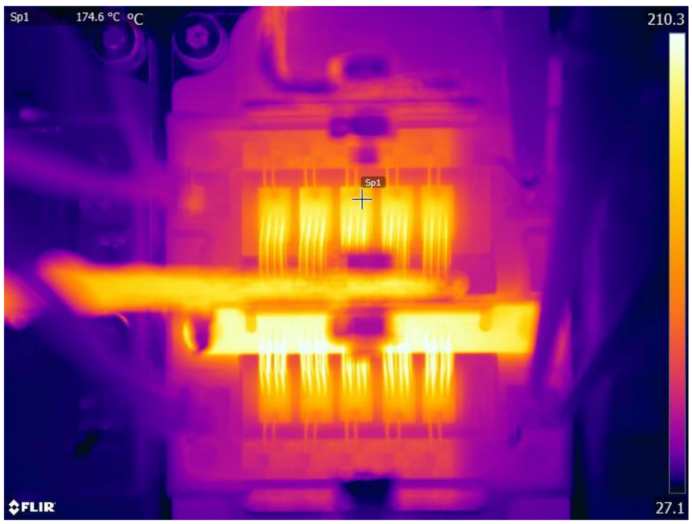

Fig. 7. Thermal image of an open module painted black.

Using a 50/50 water-ethylene-glycol coolant with a flowrate of 12 L/min and a temperature of 25°C, the maximum power dissipation for the flat baseplate CAB450M12XM3 is measured at 750 W per position at a junction temperature of 175°C for a thermal resistance of 0.2°C/W for $R_{\Theta JL}$. For the same coolant conditions, the direct-cooled XAB525M12XM3 has a maximum power dissipation of 1070 W at a junction temperature of 175°C for a thermal resistance of 0.14°C/W for $R_{\Theta JL}$.

We can see from these results that while the 0.13°C/W $R_{\Theta JC}$ specified for the CAB450M12XM3 is lower than the $R_{\Theta JL}$ of the XAB525M12XM3, when you factor in the thermal resistance of the TIM and cold plate, the actual $R_{\Theta JL}$ for the flat baseplate module is 43% higher than the direct-cooled module. For the designer this means that using the direct-cooled solution leads to a lower junction temperature for the same power level, resulting in better reliability. Alternatively, the output power can be increased with the additional thermal overhead.

Inverter Results

To demonstrate the performance advantage of direct-cooled power modules at the system level both versions of the XM3 module were installed in a three-phase inverter as shown in Fig. 8 and tested under application conditions. The XM3 three-phase inverter reference design is a complete inverter system for evaluation of Wolfspeed's SiC XM3 power module and includes power modules, cold plate, bussing, dc link capacitor, current sensors, gate drivers, controller and enclosure.

The reference design operates with an 800-V dc bus, a switching frequency of 20 kHz, a three-phase load, and a constant coolant temperature of 25°C and 12 L/min. After applying the dc bus voltage to the inverter, the output current of the inverter is slowly increased while monitoring the temperature sensor built into the module and the power dissipation measured by the power analyzer.

As shown in Fig. 9, the flat baseplate version of the inverter can process a maximum of 395 Arms while the direct-cooled version can process 480 Arms. This corresponds to an 85 A or 21% increase in output current capability. Since the direct-cooled inverter has a lower junction temperature for a given output current it also has a higher efficiency as shown in Fig. 10. Nominal output power for the flat baseplate inverter is 300 kW for a power density of 32.25 kW/L and the direct-cooled inverter can achieve 360 kW for a power density of 38.7 kW/L.

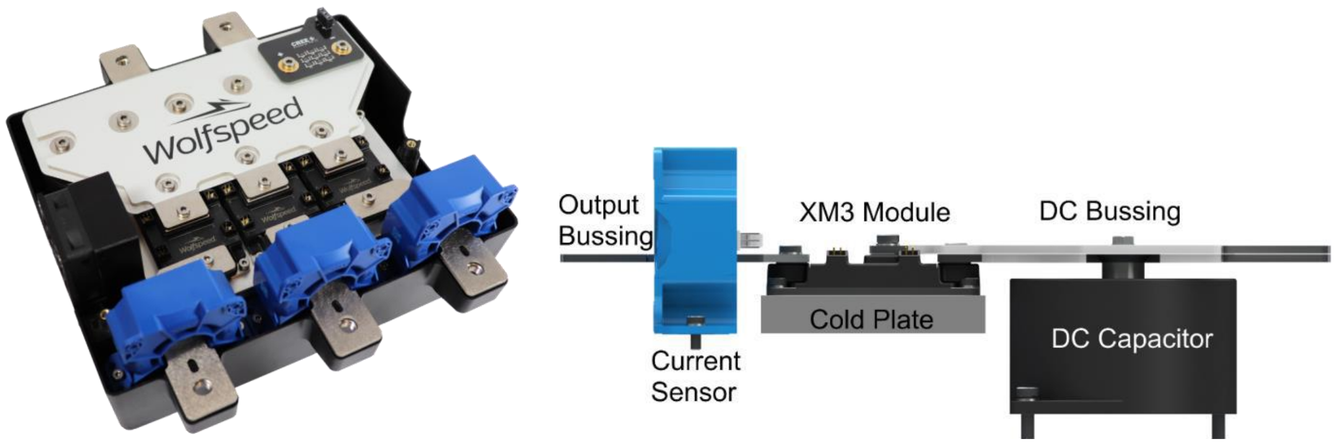

Fig. 8. Interior view (a) of an XM3 three-phase inverter reference design kit and a cross-sectional view (b) of its major components.

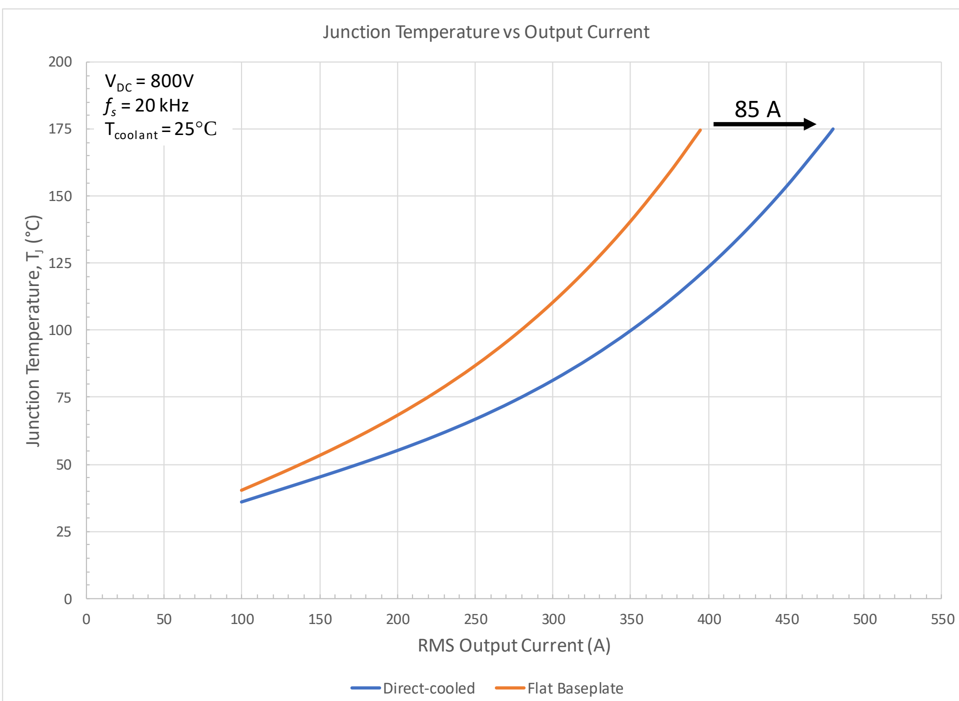

Fig. 9. Junction temperature vs. three-phase output current for direct-cooled and flat baseplate XM3 modules operating in an XM3 three-phase inverter reference design running off an 800-V dc bus and switching at 20 kHz.

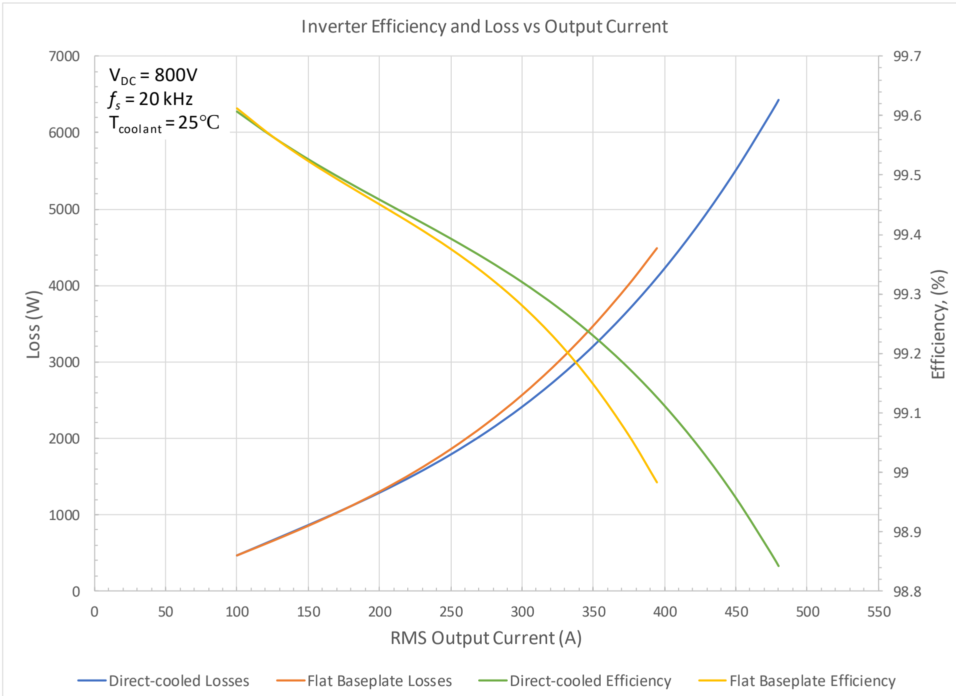

Fig. 10. Three-phase inverter power loss and efficiency vs. RMS output current for the direct-cooled and flat baseplate XM3 modules operating in the inverter reference design.

Conclusion

Direct-cooled power modules are rapidly gaining popularity in liquid-cooled applications due to the superior performance and numerous advantages over traditional flat baseplate power modules. The direct-cooled XM3 power modules have 30% lower thermal resistance compared to the same module equipped with a flat baseplate. Lower thermal resistance enables designers to deliver higher output currents, greater power density and better efficiency.

Lower junction temperatures as a result of improved thermal performance improve device reliability. A 21% increase in output current for the direct-cooled three-phase inverter comes with less than 4.5% increase in weight. Finally removing the thermal interface material from the system eliminates the messy handling and application of pastes as well as long term performance degradation due to TIM aging and pump-out.

Systems based on direct-cooled power modules have lower assembly cost, cheaper thermal management and higher power, making them ideal for designers looking to optimize price-performance of high power-density systems. Flat baseplate XM3 power modules are available now worldwide and direct-cooled XM3 power modules will be available shortly.

About The Authors

Matthew Feurtado is an application engineer for the power modules business unit at Wolfspeed. He has over five years of experience in SiC applications with a focus on power module analysis, gate drivers, and inverters. In addition, he has authored several papers, application notes, and patents. Matthew received his BSEE from the University of Arkansas.

Matt Reeves is a principal engineer & business development lead at Wieland Microcool with 20 years' experience in the design of cooling solutions, specializing in heat transfer and liquid coldplate design for power electronics.

Daniel Martin is the manager for Power Module Applications at Wolfspeed where his team supports power module integration through the development of application notes, gate drivers, and evaluation kits. He has been utilizing high-speed SiC and GaN devices in power electronic systems for over eight years. Daniel's experience utilizing SiC in a variety of applications has enabled insight into device behavior, optimized power module packaging, optimal gate driver control/design, and system-level optimization to fully enable the utilization of SiC devices.

Ty McNutt currently serves as director of Business Development & Marketing for Wolfspeed Power Modules. He works closely with customers and their applications teams to integrate SiC device and packaging technologies into power electronic systems. He is an inventor on eight issued patents on SiC materials, devices, packaging, and applications, as well as author or co-author of over 70 publications on wide-bandgap devices. Ty has been working in the field of silicon carbide for 20 years.

For further reading on designing with power modules, see the How2Power Design Guide, locate the Component category and select "Modules." For more about SiC power devices see How2Power's special section on Silicon Carbide and Gallium Nitride Power Technology.