Conduction and Switching Loss Comparison Between an IGBT/Si-PiN Diode Pair and an IGBT/SiC-Schottky Diode Pair

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***Abstract*—Two insulated-gate bipolar-transistors (IGBTs) inverter leg modules of identical power rating have been manufactured and tested. One module has silicon-carbide (SiC) Schottky diodes as anti-parallel diodes and the other silicon PiN diodes. The power modules have been tested in an inductive switching circuit and curve tracer at a range of temperatures. Static and dynamic characteristics of both IGBTs and diodes have been used in loss comparisons between the two power modules. The results demonstrate the superior electrothermal performance of the SiC Schottky diode over the Si PiN diode leading to a reduction in the power module switching and conduction losses.**

***Index Terms*—Conduction losses, power converter, Si PiN diode, SiC Schottky diode, silicon carbide, switching losses.**

I. Introduction

ONE of the reasons for the slow adoption of electric vehicles (EV) is their limited driving range compared to conventional vehicles. Electric vehicle powertrains consist of three key components; energy sources, power converters and electric machines. With batteries accounting for a large percentage of the energy sources used in EVs, most research into increasing driving range is on developing battery chemistries that will have high energy densities to provide the driving range required. However, further gains can be made by increasing the efficiency of the power converters used to transmit the energy source power to the electric machines. The power converters process the electrical energy from the energy source into a suitable form for the electric motor. When regenerative braking is employed, it transmits energy from the wheels of the vehicle back to the energy source. Although typical power converters have efficiencies close to 90% [1], a 10% loss of transmitted power represents a significant loss of potential driving miles. The bulk of the losses in the converter are switching and conduction losses in the power electronic devices.

The drive to increase power converter efficiencies is pushing power semiconductor technology down the path of advanced devices and wide bandgap materials. Silicon carbide has been identified as an alternative to silicon for improvements in power devices due to its material properties [2]–[4]. Its high electric field breakdown means high breakdown voltages can be achieved using highly doped and thin epitaxial layers thereby significantly reducing conduction losses compared to silicon devices. Its wider bandgap means that higher barrier heights can be formed at metal-semiconductor Schottky junctions thereby minimizing leakage currents in Schottky rectifiers. The wider bandgap also means better electro-thermal performance since significantly higher temperatures compared to silicon, are required to make the material intrinsic. This better thermal conductivity also means that SiC devices have lower thermal resistances and enable more efficient heat management.

SiC Schottky barrier diodes (SBDs) have shown good promise due to their small reverse recovery charge, low forward voltage drop and high temperature operability [5]. Current high voltage applications use Si PiN diodes which suffer from high reverse recovery charge and therefore reduce the usable switching speed and exhibit high switching losses. Previous studies have shown improvements in conduction and switching loss performance of SiC SBDs over Si pin diodes [6]. One particular advantage of the SiC SBD is the fact that it is a majority carrier device, hence, suffers less from reverse recovery charge of minority carriers.

In this study, a 1200 V/400 A IGBT/SiC SBD inverter leg module is compared to an IGBT/Si-PiN diode inverter leg module of the power rating. The IGBTs and device layouts in both power modules are identical and thus the only variables in the tests carried out are the diodes used. Results are presented comparing the switching performance of the two modules in an inductive switching rig over a range of temperatures (-40°C, 0°C, 25°C, 75°C and 125°C). Forward voltage measurements of both diodes are also presented and conclusions are drawn with regards to the efficiency improvements that can be achieved by using SiC SBDs instead of Si PiN diodes.

II. Static Characteristics

The transfer characteristics are shown in figs. 1 and 2 for the Si PiN and the SiC SB diodes respectively. The zero-temperature coefficient (ZTC) of a semiconductor device is an indicator of electrothermal stability because it demarcates the region of thermal stability (negative current temperature coefficient) from that of thermal instability (positive current temperature coefficient). The device is electrothermally stable if current flowing through it reduces as its temperature

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increases due to mobility reduction from phonon scattering and because hot-spots are evenly distributed. However, if the current flowing through it increases with temperature, as hot-spots are self-amplifying, the device becomes electrothermally unstable because it is prone to thermal runaway. The ZTC points, which are labelled in figs. 1 and 2, are the points where the current is independent of temperature. At regions below this point, the device current increases with temperature (electrothermally unstable) and at the regions above this point, the device current decreases with temperature (electrothermally stable). It can be seen from figs. 1 and 2 that the ZTC point occurs at approximately 150 A and 60 A for the Si PiN and SiC SB diodes respectively.

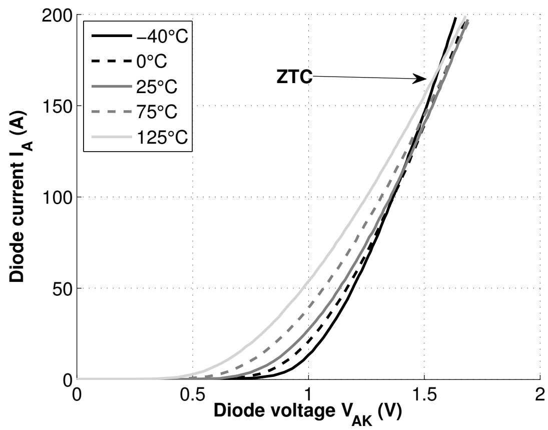


Fig. 1. Transfer curve of the Si-PiN diode.

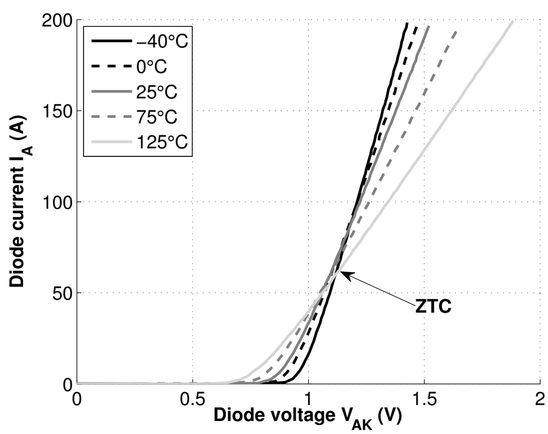


Fig. 2. Transfer curve of the SiC Schottky diode.

III. Dynamic Characteristics

A chopper circuit is used to emulate a single phase of an EV inverter power module. The circuit comprises of a DC power supply, DC-link capacitor, the IGBTs and the anti-parallel diodes as freewheeling diodes (FWDs). An environmental chamber was used to vary the ambient temperature of the power module and a data-logging oscilloscope was used to capture the switching waveforms. The schematic is shown in fig. 3 and the actual lab set up is shown in fig. 4. The switching losses of the devices under test are obtained from their dynamic characteristics (turn-on and turn-off waveforms). Double pulse inductive switching tests were carried out on the power modules with the first pulse used to set the current through the inductor and a second pulse used to switch the devices to obtain their dynamic characteristics. Considering only device behaviour at the second pulse, when the IGBT is switched on, the inductor current starts flowing through it. Only when the entire inductor current flows through this device can the diode become reverse-biased and the IGBT voltage fall to its on-state value. At the moment the IGBT is switched off, it still conducts the entire current until the diode becomes forward biased and begins to conduct. Gradually the entirety of the current is conducted by the diode and the IGBT becomes blocking. The transition characteristics of the devices are a result of their device-physics and determine their switching losses. An in-depth analysis of the interaction between the IGBT and diode during turn-on and turn-off are given in [7] and [8].

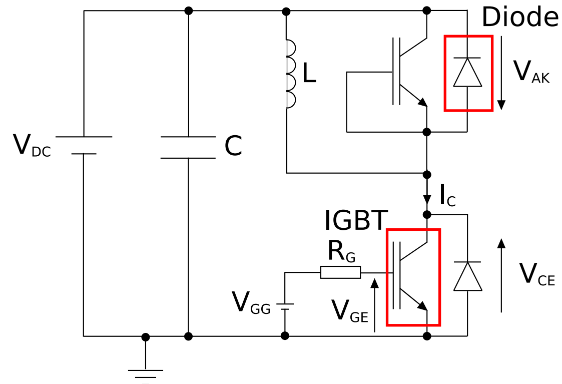


Fig. 3. Schematic of the inductive switching rig with devices under test highlighted.

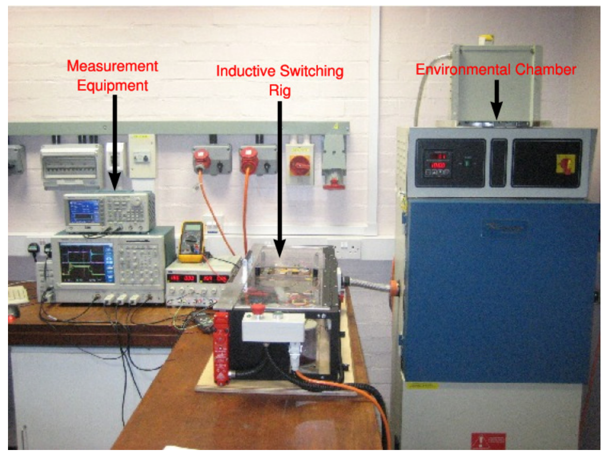


Fig. 4. Inductive switching test set up.

Figs. 5 and 6 show the voltage and current switching transients of the diodes and IGBTs at turn-on and turn-off. The advantage of the SiC SBD can be seen when comparing the reverse recovery characteristics of the diodes in fig. 5c and fig. 6c. The peak reverse current in the Si PiN and SiC SBD is 50 A and 10 A respectively. Also, the reverse recovery current increases with temperature for the PiN diode while it is temperature invariant for the SiC SBD. This is an important advantage for operation in high temperature automotive environments like the engine bay of a hybrid EV. Comparing the I_C overshoot in the Si PiN diode module fig. 5g and the SiC SBD module fig. 6g reveals that peak current overshoot is less (30 A) in the SiC SBD module. This is due to the improved recovery charge in the SiC SBD since the recovery charge adds to the IGBT current. Again, the I_C overshoot increases with temperature for the PiN diode module while it is temperature invariant for the SiC SBD module.

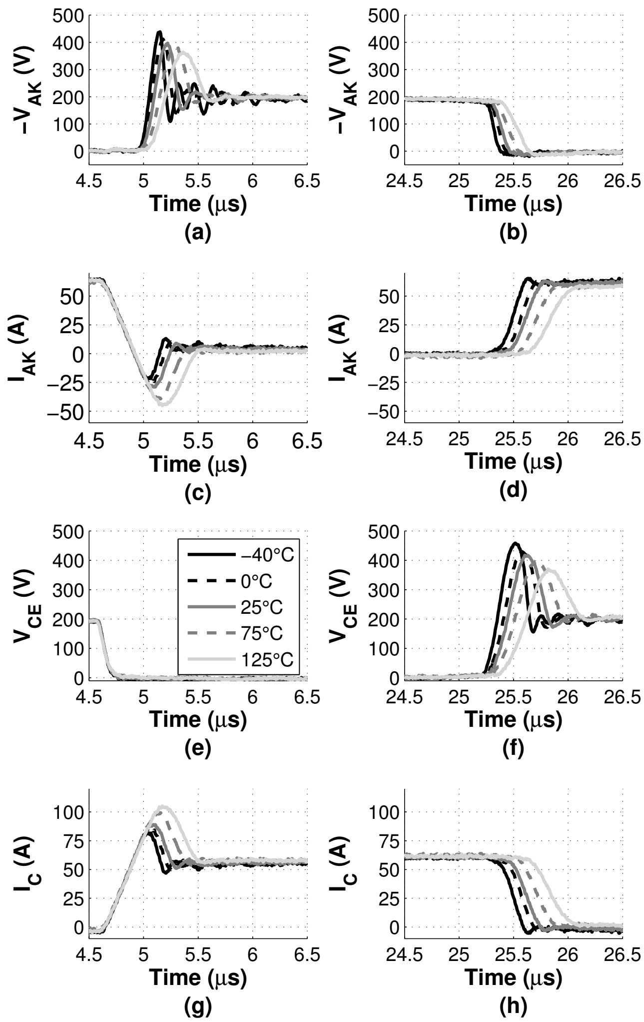


Fig. 5. Switching plots of the IGBT/Si-PiN diode pair at turn-on and turn-off.

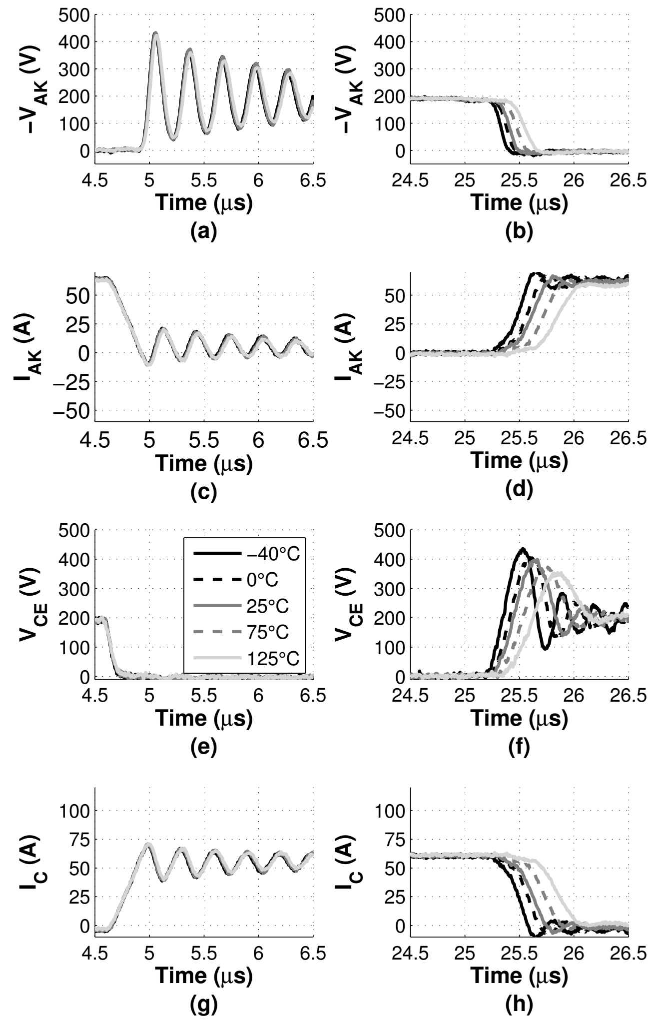


Fig. 6. Switching plots of the IGBT/SiC Schottky diode pair at turn-on and turn-off.

IV. Discussion

The ZTC points shown in figs. 1 and 2 being lower for the SiC SBD indicates a higher degree of electrothermal stability compared to Si-PiN diode. The wide bandgap of the SiC SBD accounts for this electrothermal stability. Current flow in semiconductors is largely due to drift of majority carriers and diffusion of minority carriers. Diffusion currents usually increase with temperature (due to the thermal voltage and increased carrier concentration) and drift currents reduce with temperature (due to increased phonon scattering). The wider bandgap in SiC means there are less thermally generated carriers, hence, less diffusion currents. This feature enables much higher temperature operation of SiC SBD than Si PiN diodes.

As evident in the dynamic characteristics of both the Si-PiN diode and SiC SBD in figs. 5 and 6 the SiC SBD exhibits lower reverse recovery current at diode turn-off. As expected, due to the silicon carbide material properties in the SBD, the diode dynamic characteristics are temperature invariant. However, the turn-off oscillations are greater than for the Si-PiN diode. In [6], diode voltage and reverse recovery current oscillations at turn-off in an inductive switching circuit are attributed to the resonance between the test circuit stray inductance and the output capacitance of the IGBT switch used. It is also stated that a portion of the observed oscillations are due to the magnetic coupling between the measurement circuit and the test circuit. These factors might play a role in the cause in the oscillations but cannot be used to explain the difference between the oscillatory behaviour of the two different diodes as the circuit and measurement equipment used in both tests are the same. This can best be explained by considering the representative circuit components of the diodes when they are forward and reverse biased.

In the forward biased configuration, the test diode is on and has virtually zero capacitance as it's depletion region is none existent. It however has an on-state resistances as shown in fig. 7(a) due to it's drift region and parasitic ohmic resistance as it freewheels and discharges the inductor. In the reverse biased configuration, the depletion region of the diode reappears and forms a capacitance in series with it's on-state resistance as shown in fig. 7(b).

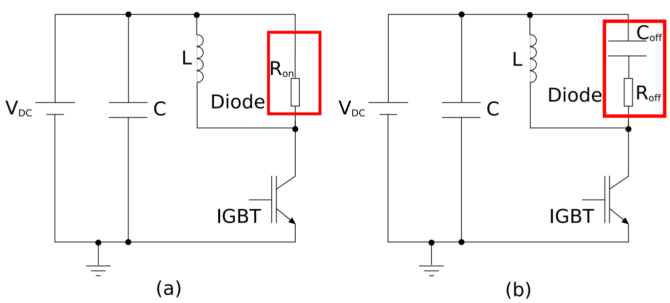


Fig. 7. Diode representation in the inductive switching circuit when the diode is (a) on and (b) off.

Due to the higher critical field in SiC, thinner and more highly doped epitaxial drift layers can be used to deliver very low on-state losses without sacrificing the breakdown voltage rating. As a result, the depletion capacitance in the SiC SBD is higher than that in the Si PiN diode because its highly doped drift region reduces its depletion width. Off-state leakage in the SiC SBD will be higher compared with the Si PiN diode because the leakage current due to Schottky barrier lowering at high reverse fields is greater than the space-charge generation current within the expanding depletion region [4], [9]. The result is an RLC circuit that can generate oscillations in the absence of sufficient resistive damping. In the case of the SiC SBD, higher reverse leakage (or lower off-state resistance) exacerbates the oscillations as observed in the turn-off characteristics of the SiC SBD.

The switching losses for both diodes have been calculated for all the temperatures. Fig. 8 shows the switching power losses calculated at different temperatures for the Si PiN and the SiC SBD where the temperature stability of the SiC SBD can be seen; the peak switching loss increases from 6 mW at -40°C to 12 mW at 125°C for the Si PiN diode whereas it remains stable at just below 6 mW at all temperatures for the SiC SBD.

Fig. 9 shows the calculated switching energy losses of the IGBT/Si-PiN diode pair and IGBT/SiC SBD pair at IGBT turn-on and diode turn-off. The Si-PiN diode has lower turn-off switching losses at the low temperature -40°C and 0°C compared to the SiC SBD. At 25°C, they both exhibit the same losses, 1.85mJ. Over this temperature range (-40°C to 25°C), the Si-PiN diode turn-off losses increase slightly from 1.65mJ to 1.85mJ as the SiC SBD turn-off losses decrease very slightly from 1.9mJ to 1.85mJ. With a further increase in temperature the turn-off losses of the Si-PiN diode starts to increase significantly rising to 3mJ at 125°C. The SiC SBD however shows a very slight decrease in losses to 1.75mJ at 125°C. The IGBTs of both diodes have similar turn-on switching loss values. These are approximately 1.9mJ at -40°C and decrease to 1.6mJ at 125°C. There is a discrepancy in the reading taken for the IGBT in the IGBT/Si-PiN pair switching test at 75°C. This is mostly likely due to an error during the logging of the IGBT switching waveforms at this temperature as it clearly does not follow the trend at the other temperatures.

Fig. 10 shows their switching energy losses at IGBT turn-off and diode turn-on. The Si-PiN diode and SiC SBD have very similar losses at turn-on. Their losses decrease marginally from 0.6mJ to 0.45mJ from -40°C to 125°C. The IGBTs of the diodes have a similar loss value of 4.25mJ at turn-on at -40°C. With increasing temperature both IGBTs in the power modules exhibit higher turn-off losses. However the IGBT in the power module with the Si-PiN diode has higher turn-off losses resulting in a value of 5.85mJ at 125°C. The IGBT of the SiC SBD has a turn-off losses of approximately 5.5mJ at 125°C.

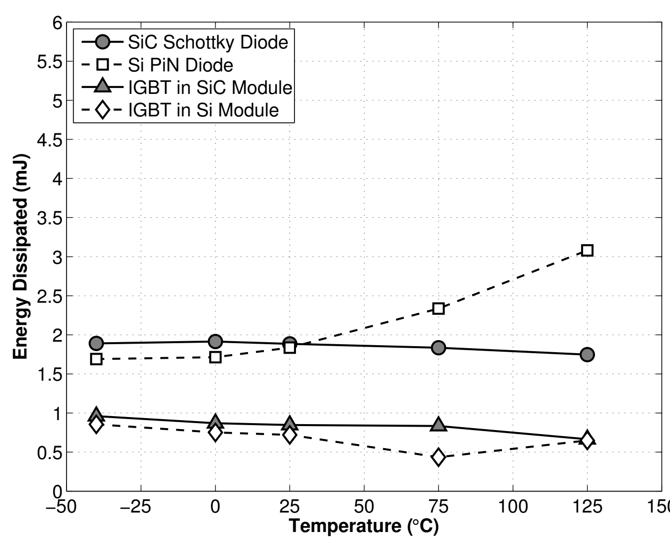
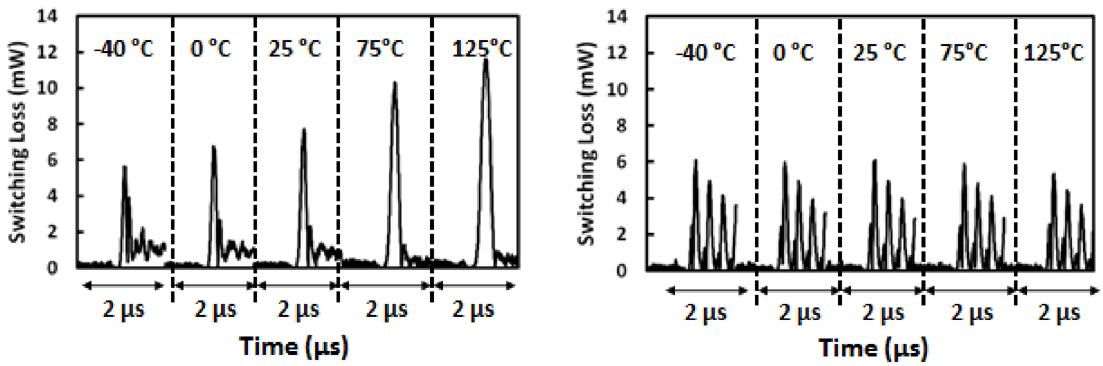


Fig. 9. Energy dissipation at IGBT turn-on and diode turn-off vs temperature comparison of the two power modules.



(a) (b)

Fig. 8. Diode switching power losses at different temperatures for the (a) Si PiN diode and (b) SiC Schottky diode.

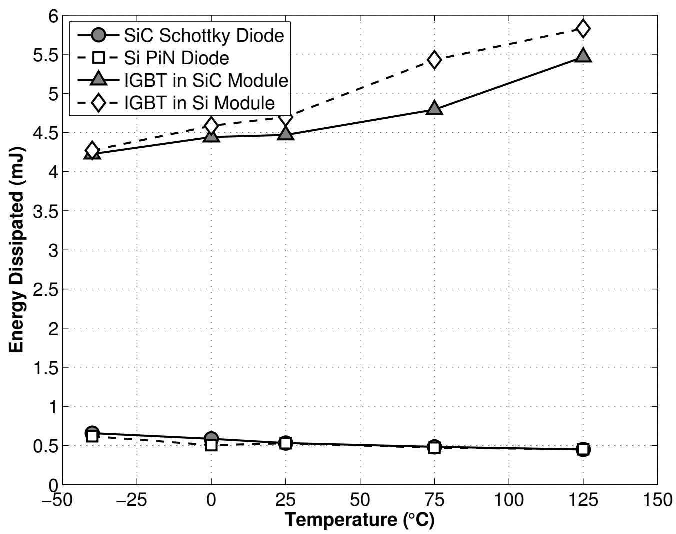


Fig. 10. Energy dissipation at IGBT turn-off and diode turn-on vs temperature comparison of the two power modules.

V. Summary

The switching characteristics of the diodes and IGBTs have been measured as functions of temperature and comparisons of switching losses have been made between the SiC SBD and the Si PiN diode. The SiC SBD has demonstrated improved electrothermal stability compared to the Si PiN diode due to its lower ZTC point.

The improved reverse recovery characteristics of the SiC SBD translates to lower turn-off switching losses at all temperatures compared to the Si PiN diode. This also affects the turn-on switching losses in the IGBT since the reverse current contributes to the IGBT collector overshoot current during switching. At IGBT turn-off and diode turn-on when the IGBT dynamic characteristics dominate in the power module, the turn-on losses of both diodes are similar. The IGBT losses are worse for the one in the Si PiN diode pair than the one in the SiC SBD pair. It can be summarised that the total power dissipation in the module is reduced when the Si PiN diode is replaced with a SiC SBD.

VI. Key Contributions

- Demonstration of improved switching of SiC SBDs at different temperatures.
- Demonstration of improved IGBT switching performance due to SiC SBD integration.
- The diode turn-off power losses in the Si PiN and the SiC SB diode increase by 83% and -7% as the temperature increases from -40°C to 125°C thereby demonstrating the superior electro-thermal performance of SiC.
- The IGBT turn-on loss is 121% (at -40°C) and 11% (at 125°C) lower in the module with the SiC SBD compared with that of the Si PiN diode. This is due to the improved recovery characteristics in the SiC SBD compared with the Si PiN diodes.

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