Switching Performance of a 3.3-kV SiC Hybrid Power Module for Railcar Converters

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ABSTRACT The unique properties of a SiC hybrid 3.3-kV/450-A half-bridge IGBT power module which is designed for enhanced reliability of railcar converters are presented in this paper. The hybrid technique enabled by utilizing the state-of-the-art 3.3-kV SiC SBDs has shown impressive electrical performances during switching. The switching waveforms, switching time lengths, voltage overshooting, current overshooting and information contained therein have been exploited in detail, in comparison with the corresponding fully Si-based IGBT module as a control sample. The potential of reliability enhancement by this SiC hybrid concept at the rated voltage and current levels will provide essential benchmark for railcar converter designs.

INDEX TERMS Power semiconductor devices, insulated gate bipolar transistors, silicon carbide, Schottky diodes, converters.

I. INTRODUCTION
The optimization of silicon-based (Si-based) semiconductor power devices is reaching the upper limit based on their physical characteristics. Alternatives have been sought after to replace the commonly used Si-based devices, such as the insulated-gate bipolar transistors (IGBTs) [1]–[3] and fast recovery diodes (FRDs) [4]–[6]. The main target is to further improve the performance of power converters such as AC/DC rectifiers and DC/AC inverters. Currently, the full substitution of the IGBTs by the wide bandgap devices such as the silicon carbide (SiC) metal oxide semiconductor field effect transistors (MOSFETs) [7] is an efficient but expensive approach. Thus the idea of replacing only the anti-parallel FRDs in the conventional power modules with the SiC Schottky barrier diodes (SBDs) to provide hybrid integrations, is also becoming more and more popular. Compared with the full substitution solution, the latter idea describes features such as lower cost, better manufacturability due to the simple chip structure and less modifications to the existing application system.

Over the years, such hybrid idea of combining the low-cost, robust and mature Si-based IGBTs with the SiC SBDs has been applied extensively in low-voltage IGBT power modules [8]–[12], for wind power conversion and electric vehicle applications. The development of medium-to-high voltage hybrid IGBT modules has also been enabled in recent years [13]–[15], as a result of the development of high-voltage SiC SBDs, being a low-cost member compared with the other SiC families. A number of 3.3 kV hybrid IGBT power modules have been introduced for the application of the rolling stock converters, as one of the key components of power conversion. The suspension AC line voltage of 25 kV with alternating frequency of 50 Hz is transformed to lower voltage and rectified before being supplied to the traction motor inverter. The traction inverter converts the DC line voltage by switching the IGBT module under power width modulation strategies and generates three-phase AC output to drive the motor. The previous published work mainly focuses on the low power loss feature of the modules, while the transient switching behavior has not been exploited fully. In high-speed train application where the power modules are usually switched with high frequency, not only the power loss feature of the modules matters, but also the transient switching performance is
ers, such as Infineon [16], Mitsubishi [17], Hitachi [18] and Dynex [19]. The detailed layout and characteristics of the Si-based module can be found in [16]–[19]. In general, this shared module packaging layout is designed for the voltage level up to 6.5 kV, with minimum terminal-terminal clearance and creepage distance of about 22 and 44 mm, respectively. The terminal-baseplate isolation voltage is designed to be more than 10.2 kV.

While similar module designs have been reported frequently in the past 6 years, the incorporation of the SiC SBDs in this type of module is new. Since such module is designed as the next-generation industrial standard with great potential for traction converter applications, continuous performance improvement is a hot topic for both industry and academia. This paper will focus on the SiC hybrid version of such module, with the aim of benchmarking the advantages of the hybrid technology on enhancing the module switching performance.

The internal layout design varies for different designers considering the required current rating, chip technology, parasitic inductance and thermal characteristics. The module internal design utilized in this study is shown in Fig. 2. Fig. 2 (a) shows the top view of a module sample without the frame, the busbars and inter-substrate wire bondings. The two symmetrical substrates to the left belong to the low-side switch while those on the right form the high-side switch. On top of each substrate, a 4.7 Ω resistor chip is allocated for gate control terminal. The chips are soldered on the top metallization layer of the substrates, which are in turn soldered on the baseplate. Such vertical structure is typical for high-voltage IGBT modules [20] and will not be elaborated here. Fig. 2 (b) shows the module prototype without the top lid. The modules in Fig. 2 (a) and (b) belong to the same batch. The busbars are inserted in the module frame with their feet bonded to the substrates via ultrasound welding. The major terminals are annotated, while the circuitry topology will be introduced later in the next section. The DC+ and DC- busbars are designed to have a large overlapping area such that the module stray inductance can be reduced considerably by cancelling the magnetic field during current commutation. A detailed view of the DC busbars design can be seen in Fig. 2 (c). The module stray inductance is simulated as around 24 nH.

The SiC SBD is fabricated in-house on a 4-inch 4H-SiC wafer. The chip size is designed as 6.2 × 6.4 mm². Larger area design is also achievable at the cost of reduced yield due to the known SiC wafer defects. The cross-section view of the SBD with the junction barrier Schottky (JBS) structure [21] is shown in Fig. 3. Unlike the traditional Si FRD process where the drifting layer is formed by ion implantation, the epitaxial layer of around 33 µm thickness for the SBD die is grown on the n-type SiC substrate by chemical vapor deposition process. A floating field ring (FFR) structure towards the edge is adopted for the chip termination, such that the implant process can be considerably simplified. The designed P+ region and FFR structure are formed by an ion implantation and anneal process, after which the Schottky contact is deposited.
The backside of the wafer is then grinded to make the chip as thin as 380 µm, being 20 µm thinner than the Si FRDs used in the Si-based module. After the grinding process, the cathode electrode is deposited to form ohmic contact. Each SBD die is designed to carry 37.5 A current, while single Si FRD chip in the original Si-based module is rated at 75 A. Thus each of the original Si FRDs is replaced by two SiC SBDs for the fabrication of the hybrid module, as shown in Fig. 4 for single substrate.

### III. EXPERIMENTAL RESULTS

In this section, a detailed comparison between the transient switching characteristics of the two types of module by the dynamic double-pulse test will be carried out, to show the beneficial factors of reliability enhancement by incorporating the SiC SBDs in the high-voltage module for locomotive applications. The module layout, the processing technology, the test configuration and the test equipment are identical for the two types of modules to ensure trustworthy comparison result. The half-bridge module circuitry layout and the dynamic test circuit topology in this study are shown in Fig. 5 (a). In the test, the IGBTs of one switch are tested with the diodes of the other switch being utilized for the current free-wheeling during the turn-off process. The IGBTs are turned off and then turned on at the rated voltage and current levels. From the recorded turn-off and turn-on waveforms, essential parameters of both the IGBTs in one switch and the corresponding free-wheeling diodes in the other switch can be extracted, such as the switching losses, turn-on and turn-off time lengths, IGBT turn-on current overshooting and diode reverse recovery characteristics. As shown in the test setup, a DC power supply is utilized to provide the request line voltage \(V_{dc}\) to perform the test. The high-voltage capacitance is used to store and discharge energy at a stable DC line voltage level during the short transience of IGBT switching. For testing the switching performance of the low-side IGBTs, the gate and emitter terminals of the high-side IGBTs are shorted to avoid false turn-on. In the gate driver of the low-side IGBTs, the turn-on and turn-off resistors are applied to adjust the switching speed and protect the device. The experimental setup for the test is shown in Fig. 5 (b). The module is connected to the capacitance via the laminated busbars with low stray inductance. A coil inductor is used
as the inductive load. A high-voltage differential probe and Rogowski coil are utilized for testing the device voltage and current, respectively.

A. IGBT TURN-OFF

The IGBT turn-off waveforms of the hybrid module and its Si-based counterpart are shown in Fig. 6, where the collector current ($I_C$) and collector-emitter voltage ($V_{ce}$) variation during the transience are plotted. The turn-off waveforms as can be seen in Fig. 6 are triggered when the gate driver voltage ($V_{ge}$) is switched from around +15 to -15 V. The IGBTs in the low-side switch are turned off, with its $I_C$ gradually decreasing to zero while $V_{ce}$ ramping up to $V_{dc}$. At the same time, the diodes in the high-side switch are turned on as the inductive load becomes a source that provides forward voltage bias. The current is commutated in the loop formed by the inductive load and the diodes. The nominal test condition with DC line voltage ($V_{dc}$) of 1800 V, switching current ($I_s$) of 450 A, turn-on gate resistance ($R_{gon}$) of 3.3 Ω and turn-off gate resistance ($R_{goff}$) of 3.3 Ω has been used.

It can be seen that one key feature of the hybrid module is that its $V_{ce}$ overshooting ($\Delta V$) during the turn-off event is lower than the Si-based module, where $\Delta V$ is defined as the difference between $V_{dc}$ and the maximum $V_{ce}$ during the turn-off process. This is because the SiC SBDs in the former module are unipolar devices while the Si FRDs in the latter are bipolar devices, which describe a transient turn-on voltage drop [20] during the forward recovery process. Such a turn-on voltage drop adds on to the existing voltage overshooting induced by the commutation path parasitic inductance, and causes even higher peak voltage on the IGBTs of the Si-based module. The hybrid module, by eliminating the transient turn-on voltage of the diodes, reduces the peak $V_{ce}$ of the switching IGBTs and enhances the reliability of the device.

The variations of $\Delta V$ with $V_{dc}$ and $I_s$ for the two types of module are shown in Fig. 7. Across the tested $V_{dc}$ and $I_s$...
ranges, $\Delta V$ of the hybrid module is lower than its Si-based counterpart, due to the aforementioned reason. It can be seen that at the nominal test condition, $\Delta V$ of the hybrid module is about 50 V lower than the Si-based counterpart. Across the tested $V_{dc}$ range, $\Delta V$ varies irregularly within a small range, which is due to the limited accuracy of the differential probe used for the test. Also, $\Delta V$ increases with $I_s$ for the two types of modules, due to the impact of the parasitic inductance. In modern high-speed electrified rolling stock traction inverter, the line voltage is often chosen to be as high as possible for the semiconductor switches, to produce enough torque for the drive while limiting the required phase current level [22]. It is thus important to limit the $\Delta V$ level during the turn-off process, to ensure the device health and the system reliability.

Since the transient turn-on voltage drop in the hybrid module is eliminated, the forward recovery process of the diodes is faster. This in turn leads to faster turn-off process of the IGBTs in the hybrid module. Fig. 8 shows the turn-off $\frac{di}{dt}$ value variations with $V_{dc}$ and $I_s$. The $\frac{di}{dt}$ is extracted as the transient $I_c$ variation rate when $V_{ce}$ reaches the peak value, as shown in Fig. 6. Since $\frac{di}{dt}$ varies considerably fast with time, a time window of 32 ns (with 80 data points) is chosen for the calculation of the transient value to enable fair comparison of the two modules. Such narrow time window and the limited resolution of the Rogowski current probe ($\sim 8$ A) inevitably lead to inaccuracies in the $\frac{di}{dt}$ calculation. This also explains the sudden increase of $\frac{di}{dt}$ in Fig. 8 (a). Across the tested $V_{dc}$ and $I_s$ range, the $\frac{di}{dt}$ of the IGBT current drop in the hybrid module is higher. The $\frac{di}{dt}$ of both modules are higher with larger $I_s$, due to higher levels of charge carrier concentration. The $\frac{di}{dt}$ rate is however confined in an acceptable level to avoid excessive voltage overshooting. Both the higher level of $\frac{di}{dt}$ and lower level of $\Delta V$ contribute to the reduction of the turn-off energy loss ($E_{off}$) of the hybrid module, which is about 3% lower than the Si-based one at the nominal test conditions. Although the loss energy reduction is trivial, the limited $\Delta V$ level in the hybrid module lowers the risk of overvoltage failure and enables simpler driver circuit design [23].

**B. IGBT TURN-ON**

The turn-on transient waveforms of the two types of modules with the nominal test conditions are shown in Fig. 9. The gate control signals for the two modules show similar waveforms and are not plotted. The turn-on process is triggered a few microseconds after the turn-off event. To turn on the low-side IGBTs, the $V_{ge}$ is increased from -15 to 15 V within a short transience. Then the commutation current in the high-side diodes is redirected to go through the low-side IGBTs. The high-side diodes, being switched from on to off state, need certain amount of reverse recovery time before their reverse blocking capability is regained. Such reverse recovery process induces current overshooting to the low-side IGBTs.

Three major observations should be noted here. Firstly, it can be seen that the current overshooting during the turn-on process of the hybrid module is much lower than the Si-based counterpart, since the adoption of the SiC SBDs can substantially remove the reverse recovery phenomenon which is inevitable for the Si-based FRDs. The reduction in the current overshooting for the switching IGBTs can...
considerably reduce the risk of overcurrent failure during the turn-on process and improve the long-term reliability for application with high switching frequency. The second observation is that it takes a rather long time for the current of the switching IGBT to revert to the normal level, which will cause excessive transient heating effect for the Si-based module. Such adverse effect has been considerably removed from the hybrid module. Thirdly, although \( I_c \) of the switching IGBTs ramps up almost simultaneously, the \( V_{ce} \) of the IGBTs in the hybrid module starts to drop at an earlier time than the Si-based one. This can be explained by the fact that the reverse blocking capability of the SBDs in the hybrid module recovers within a short transience after the low-side IGBTs being turned on. Such feature can help to shorten the time length during which the switching IGBT is exposed to both high current and voltage, hence reduce the electrical and thermal stresses added on the module. The \( V_{ce} \) waveform of the Si-based module exhibits a dip followed by a small peak at around 28.8 \( \mu \)s. This is caused by the stray inductance of the testing circuit and the fast variation of the turn-on \( di/dt \) [20]. At the time point where the dip is found, the turn-on \( di/dt \) reaches its maximum value and causes the maximum \( V_{ce} \) drop. After this point, \( di/dt \) gradually decreases until \( I_c \) reaches its maximum value. The decreasing \( di/dt \) causes smaller \( V_{ce} \) drop, which in turn induces the slight increase of \( V_{ce} \) at around 28.8 \( \mu \)s.

The \( di/dt \) level variations with the \( V_{dc} \) and \( I_s \) are shown in Fig. 10 for the two types of modules. It can be seen that across the tested \( V_{dc} \) and \( I_s \) range, turn-on \( di/dt \) of the hybrid module is higher than the Si-based one, since the reverse recovery process of the SBDs takes shorter time than the FRDs. The comparison of the \( I_c \) variation with different \( R_{gon} \) values for the two types of modules is shown in Fig. 11. The turn-on current overshooting (\( \Delta I \)) level of the hybrid module remains at reasonable low level with different \( R_{gon} \), where \( \Delta I \) is defined as the difference between \( I_s \) and peak value of \( I_c \) during the turn-on process. It is thus possible to increase the \( di/dt \) by decreasing the turn-on resistance value to further reduce the IGBT turn-on loss (\( E_{on} \)) without risking the overcurrent failure of the hybrid module, since modern IGBT chips are designed to sustain at least twice of their rated currents for a short transience. In the Si-based module, such approach is risky since the \( \Delta I \) already amounts to about 500 A, as can be seen in Fig. 11. In fact, in field application of the Si-based module, it would be recommended to increase the \( R_{gon} \) value to suppress the turn-on current overshooting. It should be noted that the increased \( di/dt \) in the hybrid module could potentially add the electromagnetic interference (EMI) noise, as has been reported in [24].

### C. DIODE SWITCHING

The diode voltage (\( V_{fd} \)) and IGBT \( V_{ce} \) waveforms during the IGBT turn-off transience are shown in Fig. 12, for the two types of modules, under the nominal test condition. During this transience, \( V_{ce} \) rises to the line voltage \( V_{dc} \) while \( V_{fd} \) gradually falls to zero. The transient on-state voltage drop of the FRDs in the Si-based module is evident at about 13.3 \( \mu \)s, where \( V_{fd} \) clearly goes to negative value. Such voltage drop also adds to the \( V_{ce} \) of the IGBT and causes higher voltage overshooting for the Si-based module. The transient on-state
voltage drop of the SiC SBDs is much smaller than the Si FRDs. The diode $V_{fd}$ and IGBT $V_{ce}$ waveforms during the IGBT turn-on transience are plotted in Fig. 13, for both types of modules. At this transience, $V_{ce}$ decreases to zero while $V_{fd}$ goes through the reverse recovery process with its voltage gradually increasing to $V_{dc}$. It can be seen that $V_{fd}$ of the hybrid module starts to increase at an earlier time than the Si-based module. Consequently, $V_{ce}$ of the former drops faster than the latter. This is an advantage of the SBDs to share the line voltage and avoid the switching IGBTs being exposed to high current and high voltage simultaneously for a long time. Such feature is essential for the high-speed train traction inverter reliability where the devices are exposed to repeated voltage and current stress under high switching frequency during the operation. The different reverse recovery behaviors of the two types of diodes also cause the distinguished IGBT turn-on $I_c$ waveforms in Fig. 9, which is plotted with the same time scale as Fig. 13.

The reverse recovery time ($t_{rr}$) of the two types of diodes are plotted in Fig. 14 for different $V_{dc}$ and $I_s$ values. Here $t_{rr}$ is defined as the time taken for $V_{fd}$ to rise from 5% to 95% of $V_{dc}$. It can be seen that in the tested $V_{dc}$ and $I_s$ ranges, the $t_{rr}$ values of the SiC SBDs are shorter than the Si FRDs. The shortening of the $t_{rr}$ values can not only reduce the reverse recovery loss ($E_{rr}$), but also enhance the robustness of the half-bridge topology as a branch of the three-phase inverter. The reverse recovery charge ($Q_{rr}$) of the two types of diodes are shown comparatively in Fig. 15, for different values of $V_{dc}$ and $I_s$. It is calculated by integration of the reverse recovery current within the defined $t_{rr}$ range. While the reverse recovery charge of the Si FRDs per switch typically amounts to about 200 µC, that of the SiC SBDs is negligible, showing the advantage of the majority carrier device. It can also be interpreted that the $E_{rr}$ is trivial for the SiC SBDs.

As a summary of the above characterization results, a few key beneficial factors for enhancing the reliability of railcar converters are listed in TABLE 1, under the test condition with $V_{dc}$ of 1500 V, $I_s$ of 450 A, $R_{gon}$ of 3.3 Ω and $R_{goff}$
of 3.3 kV. It can be seen that the hybrid module has reduced switching energy losses, shortened characteristic switching time lengths and lower current as well as voltage overshooting levels. $E_{on}$, $E_{off}$ and $E_{rr}$ are calculated by integrating the products of the corresponding voltage and current waveform data sets in the time ranges specified by $t_{on}$, $t_{off}$ and $t_{rr}$, respectively.

**IV. CONCLUSION**

In this paper, comprehensive analysis of a 3.3-kV/450-A SiC hybrid IGBT module has been carried out, in comparison with the Si-based counterpart. The 3.3 kV SiC SBDs used in the hybrid module have shown superior properties not only in its own switching process, but also in enhancing the switching performances of the corresponding IGBTs. Apart from reducing the switching losses and the IGBT turn-on current overshooting, the advanced features, such as lowering of the turn-off voltage overshooting of the IGBTs, allowing higher $di/dt$ values during IGBT turn-on process and a faster diode reverse recovery process to take on the line voltage, are important for module robustness and avoiding spontaneous failures. These features, being capable of improving the traction converter performance, are essential beneficial factors for the device reliability during application.

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