Comparison of Hybrid 3.3kV Si-IGBT/SiC-Schottky and 3.3kV Si-IGBT/Si technologies

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Keywords

«Silicon carbide», «Schottky diode», «IGBT», «Hybrid SiC», «Power semiconductor device», «Reverse recovery»

Abstract

In this paper the electrical test results of 3.3kV Si-IGBT/4HSiC-Schottky hybrid substrates (Hybrid SiC substrates) and modules are presented. Comparison with 3.3kV Si-IGBT/Si-diode substrates (Si substrates) at 20ºC (RT) and 125ºC (HT) have shown that the losses in Hybrid SiC substrates/modules are miniscule as compared to Si devices. Finally the benefits of this technology are shown by building some hybrid 3.3kV, 1100 A modules.

Introduction

Due to the low band gap of Si, the intrinsic carrier concentration n_i of Si increases rapidly with increasing temperature. If n_i becomes equal to the doping concentration, a material loses its semiconductor characteristics and behaves as a simple resistor. The intrinsic carrier concentration of a semiconductor is given by [1,2]

$$n_i = \sqrt{N_C\, N_V}\, e^{(-Eg/2kT)}$$

where

N_C = effective density of states in conduction band;

N_v = effective density of states in valance band;

E_g = band gap energy;

k = Boltzmann's constant;

T = absolute temperature If we want to use a Si device at temperatures >100ºC, then we have to increase the doping. But there is a problem with this approach. Increased doping results in a higher internal electric field in the device and which leads to electrical breakdown.

Silicon carbide (SiC) is a wide bandgap semiconductor material. The much larger band gap of SiC (x3 Si) leads to lower intrinsic carrier concentration and a theoretical operating temperature of up to 500 ºC.Because of its unique properties such as high electric field of breakdown, E_c , (~7× Si) , large thermal conductivity (~3× Si) and capability to operate at higher switching frequencies as compared with Si (Si only in kHz range) it has the potential to replace Si devices in high power applications (devices rated at voltages > 1kV) [3-5]. There are SiC devices in 650V-1000V voltage range, but the cost/performance competition is very fierce in this range from Si devices as well as some of the GaN devices. Although in recent times the cost of SiC devices is coming down. There is already a plethora of applications where SiC devices have made a promising impact. One of the interesting applications is the use of SiC Schottky diodes in hybrid modules, where a conventional Si diode is replaced by a 4H-SiC Schottky diode. The unipolar nature of Schottky diodes lead to significantly reduced losses as compared with Si diodes. It has already been demonstrated with 1.2 kV and 1.7 kV SiC diodes, that the hybrid approach can reduce the power loss of the modules drastically [6-8]. In this study we have observed similar behaviour for 3.3 kV SiC Hybrid substrates/modules at RT and HT. Hybrid substrates are built using two types of SiC didoes, one is rated at 3.3 kV, 50 A and the second SiC is rated at 1.7 kV, 50 A. In order to obtain the required blocking voltage from 1.7 kV SiC didoes they are packaged serially. In the following section the results obtained from these substrates are discussed.

Results and Discussion

This section is divided in to three parts. In the first part we will discuss the electrical characteristics of hybrid substrates manufactured using 3.3 kV SiC diodes. In the second part we will discuss the results obtained from hybrid substrates built using 1.7 kV SiC diodes. Finally, we discuss the electrical performance of hybrid 3.3 kV, 1100 A hybrid modules. In each case we have a Si reference, (either Si substrate or Si module) to compare the performance of Si and hybrid SiC technologies.

Hybrid 3.3kV SiC technology using 3.3 kV diodes

SiC Schottky diodes used in this work are from Global Power Technology Ltd. and Wolfspeed. These diodes are rated at 50A, 3.3kV and 1.7 kV, 50 A. Si IGBT is rated at 63A, 3.3kV.

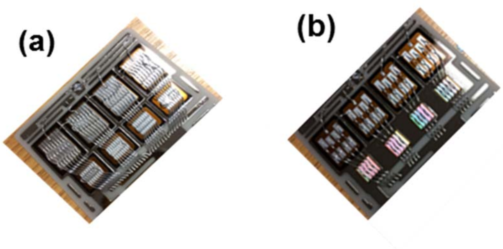

Fig. 1: Two types of substrates used in this study - 3.3 kV, 200A Si (a), and hybrid SiC (b) substrates.

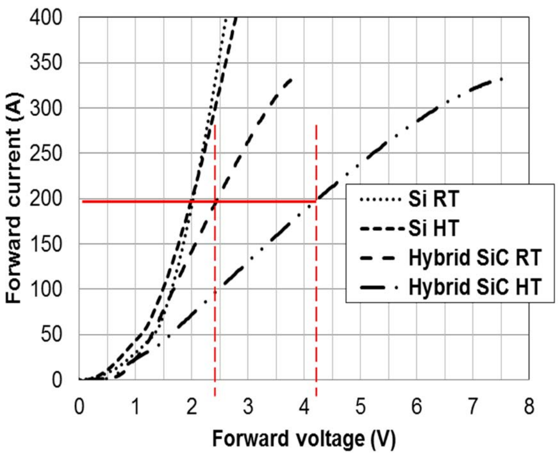

Fig. 2: Forward static characteristics of a Si substrate, and a hybrid SiC substrate, at 20 ºC (RT) and 125 ºC (HT).

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Table I: Comparison of the V_F of Si diode with SiC Schottky diodes at ratted current and 150% of the rated current at 20 °C (RT) and 125 °C (HT).

Substrate type (Current/Sub)	V_F (V), 20 °C	V_F (V), 125 °C	ΔV_F (%)
Full Si substrate (200A)	2.00	2.00	0.0
Full Si substrate (300A)	2.35	2.45	4.2
Hybrid SiC substrate (200A)	2.45	4.20	71.4
Hybrid SiC substrate (300A)	3.40	6.40	88.2

3.3kV substrates employed in this work are shown in Fig. 1, (a) - Si substrate and (b) – hybrid SiC substrate. Conventional static and dynamic electrical tests are done on these substrates, to evaluate their performance. Static test results are shown in Fig. 2. The V_F values for Si and SiC diodes are listed in Table I for RT and HT. As we can see that there is no change in the forward voltage drop (V_F) of Si diode, and it stays constant around 2.0 V at RT (50 A/chip) and 200 A/substrate. In the case of Hybrid SiC substrate the V_F of SiC Schottky diode increases from 2.45 V to 4.20 V which represents a $\Delta V_F = V_F$ (125 °C) - V_F (20 °C) of 71.4%. Also, the V_F and ΔV_F values are listed for the condition when the current flowing through each chip is 150% (75A) of the rated value. Again, we can see that the shift in the V_F with temperature is more for SiC Schottky diode (88.2%). The test set-up used to conduct a double-pulse dynamic test is shown in Fig. 3.

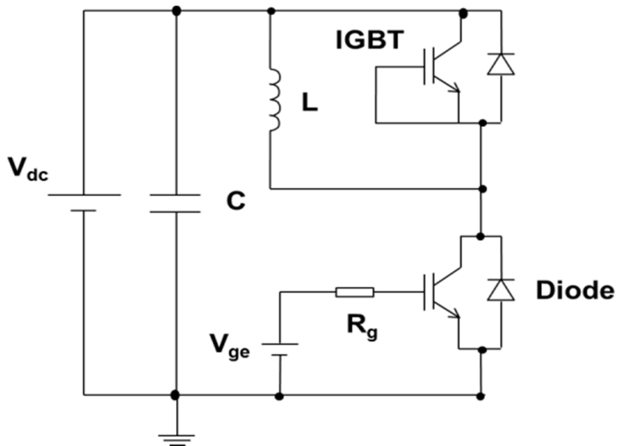

Fig. 3: Schematic of the double-pulse test bench.

The values of the gate resistor ($R_{gon} = R_{goff}$) and the inductor (L) used for substrate testing are 6Ω and 176 µH respectively. The waveforms obtained from these substrates at RT and HT are shown in figures 4 and 5 respectively. At RT for a di/dt = 1415 A/µs, we can see a reverse recovery current

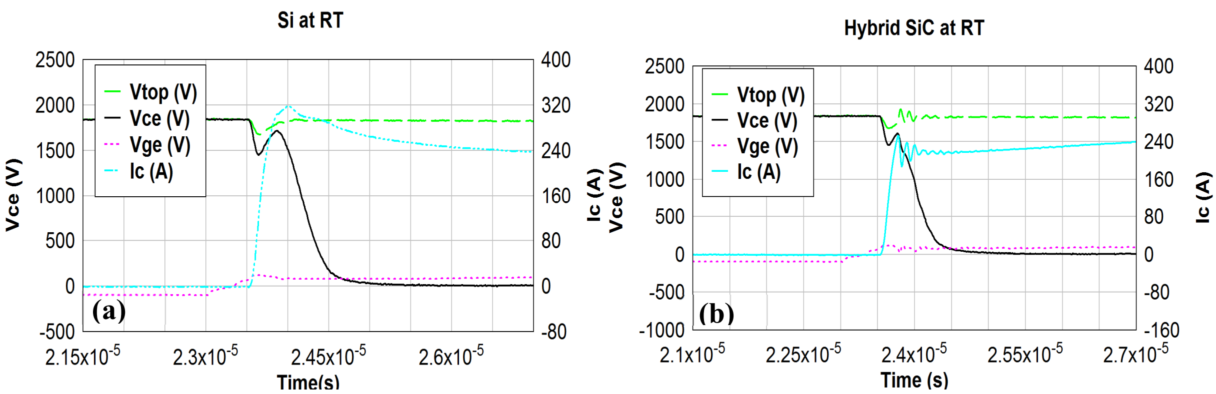

Fig. 4: The switching waveforms of (a) a Si substrate and (b) a hybrid SiC substrate at RT during the second turn-on of the IGBT.

overshoot (equivalent to the stored charge in the diode) of 141 A for Si as compared with Hybrid SiC substrate (12A). The reverse recovery energy loss (E_{rec}) occurred in a substrate during the transient, and the values for $E_{rec/Si}$ and $E_{rec/Hrbrid\ SiC}$ substrates are 0.178 J and 0.013J respectively. This represents a reduction of more than 90% for Hybrid SiC substrate. At HT for the switching rate of 1100 A/µs, the E_{rec} for Si substrate is more than that of the Hybrid SiC substrate. In fact the E_{rec} reduction for the Hybrid SiC substrate is more than 95%. Other electrical parameters for the substrates namely Q_{rr} (µC), E_{on} (J) and E_{off} (J) are also listed in table II, both, at RT and HT. These reductions in switching losses could be translated in to power saving when building systems using Hybrid SiC modules.

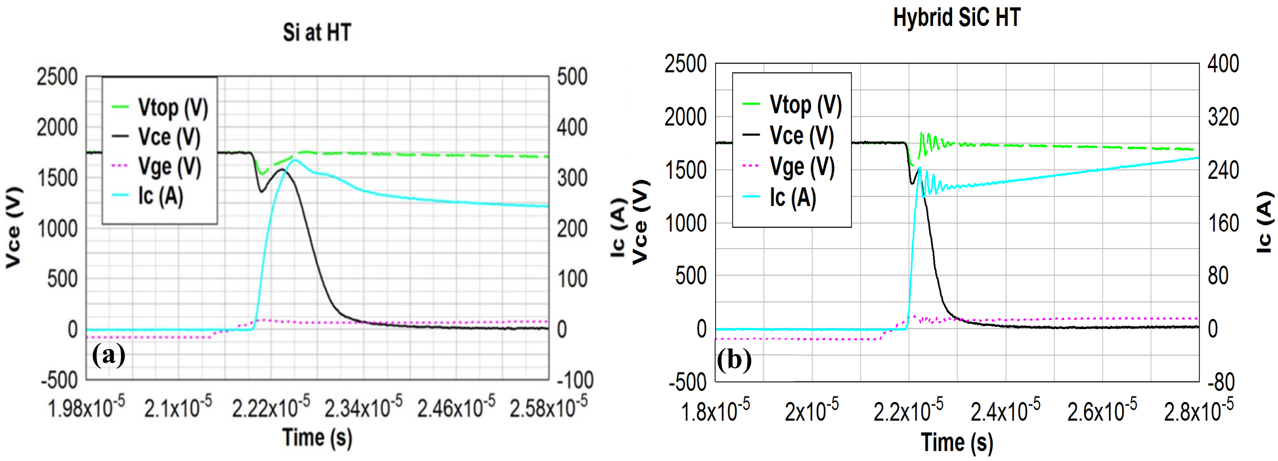

Fig. 5: The switching waveforms of (a) a Si substrate and (b) a hybrid SiC substrate at HT during the second turn-on of the IGBT.

Table II Comparison of different electrical parameters - I_{rr}(A), Q_{rr} (µC), E_{on} (J), E_{rec} (J) and E_{off} (J) calculated for Si and Hybrid SiC substrates at RT and HT .

Substrate type	Temp (^{o}C)	dI/dt (A/µs)	I_{rr} (A)	Q_{rr} (µC)	E_{on} (J)	E_{rec} (J)	E_{off} (J)
3.3 kV Full Si	20 ^{o}C	1415	109	141	0.290	0.178	0.388
3.3 kV Full Si	125 ^{o}C	1100	128	167	0.321	0.199	0.375
3.3 kV Hybrid SiC†	125 ^{o}C	1388	65	13	0.30	0.01	0.68
3.3 kV Hybrid SiC	125 ^{o}C	1103	43	6	0.155	0.004	0.367

†Two 1.7 kV SC diodes put in series

Hybrid 3.3kV SiC technology using 1.7 kV diodes

In this approach two 1.7 kV, 50 A SiC diodes are used to manufacture hybrid SiC substrates. While selecting 1.7 kV diodes to build 3.3 kV substrates, we made sure that the diodes have similar leakage current so that there is no problem in current sharing while they are under operation The substrate used for the electrical tests are shown in Fig. 6. As mentioned previously the IGBTs are rated at 63 A, so three IGBTs/per substrate can sustain 189A, and if increase the current through each IGBT to 69A then it is possible to get an output current of 200 A the substrate. To match the output current of 200 A from diode's side each diode need to support a current of 33.4 A while under operation. This means that SiC diodes are operating in a low current regime (33.33 A) in this design. Static performance of the diode is depicted in Fig. 7. The average value of V_F at 125 °C at 200 A (33A/chip) is 3.36 V which is 0.84 V lower than that of 3.3 kV diode (V_F = 4.20 V at 125 °C) under similar conditions. The V_F for SiC diodes under different conditions for this substrate design is listed in table III. In SiC Schottky diodes, in order to increase the blocking capability (e.g. from 1.7 kV to 3.3 kV) of a chip thickness of the epilayer is increased, while at the same time doping of the drift region is decreased. Also, processes involved in fabricating different voltage rating diodes, like Schottky contacts, implant doses, etc. could be different. All these differences (at the wafer level as well as at the process level) could affect the V_F of Schottky diode. Nonetheless, apart from these differences we can clearly see from Table II that substrates built using 1.7 kV SiC diodes also have significantly low energy losses as compared to their Si counterparts. Different electrical parameters extracted using a double- pulse test for these substrates are shown in Table II. The test conditions are exactly same which are used to test 3.3 kV hybrid substrates. As expected Qrr value is more than that of hybrid substrate with 3.3 kV diodes only, as in 1.7 kV SiC approach the reverse recovery charge contribution is coming from two SiC diodes. Similarly, the reverse recovery current (I_{rr}) is higher in the latter case. One main drawback with this approach is the cost, as we have to use 12 SiC diodes per substrate, as compared to 4 diodes employed in building 3.3 kV SiC hybrid substrates. The main advantage with this design is that the conduction losses are lower at HT as compared to 3.3 kV SiC substrate design and also 1.7 kV diodes are easily available from different suppliers.

Based upon the electrical performance of different substrate designs, and to keep the hybrid solution more cost effective to their Si counterparts, we decided to use 3.3 kV, 50 A SiC diodes to build hybrid SiC modules.

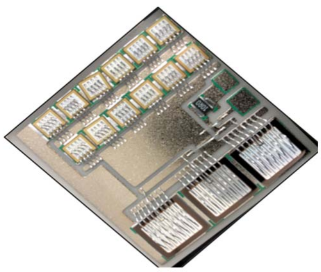

Fig. 6: A picture of hybrid SiC - 3.3 kV, 200A substrate. Two 1.7 kV SiC diodes are connected in series to achieve a blocking voltage of 3.3 kV.

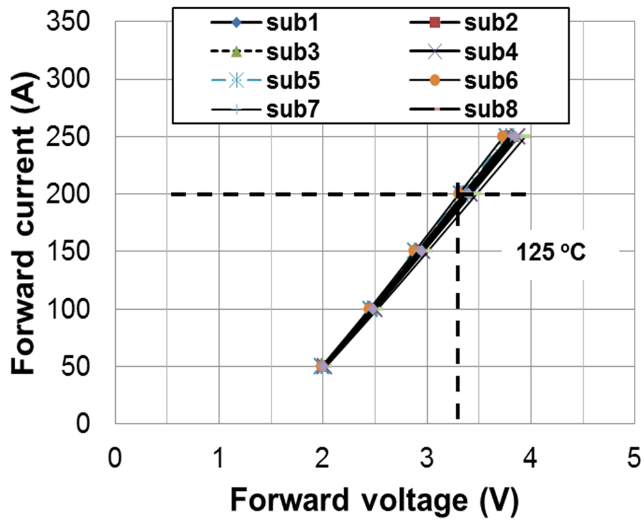

Fig. 7: Forward static characteristics of a hybrid SiC - 3.3 kV, 200A substrate at HT (125 °C).

Table III: The forward voltage drop V_F of the substrates at different current levels and HT.

T= 125 °C and V_F is in volts								
Sub1 I_F (A)	Sub1 V_F	Sub2 V_F	Sub3 V_F	Sub4 V_F	Sub5 V_F	Sub6 V_F	Sub7 V_F	Sub8 V_F
50	2.005	2	2.01	2.015	1.99	1.985	2.005	2
100	2.485	2.465	2.49	2.5	2.455	2.445	2.48	2.47
150	2.94	2.91	2.95	2.96	2.89	2.88	2.93	2.915
200	3.38	3.35	3.4	3.42	3.325	3.305	3.38	3.355
250	3.835	3.79	3.85	3.875	3.765	3.735	3.82	3.795

Full hybrid SiC modules

A 3.3 kV, 1100 A hybrid module is assembled using 3.3 kV, 50 A SiC diodes and its picture is shown in Fig. 8. Forward characteristics of the module at different temperature are shown in Fig. 9. A corresponding Si module is also built and tested under similar conditions. For the sake of brevity only hybrid SiC modules results are plotted in this work. The forward

Fig. 8: A picture of hybrid SiC 3.3 kV, 1100 A module.

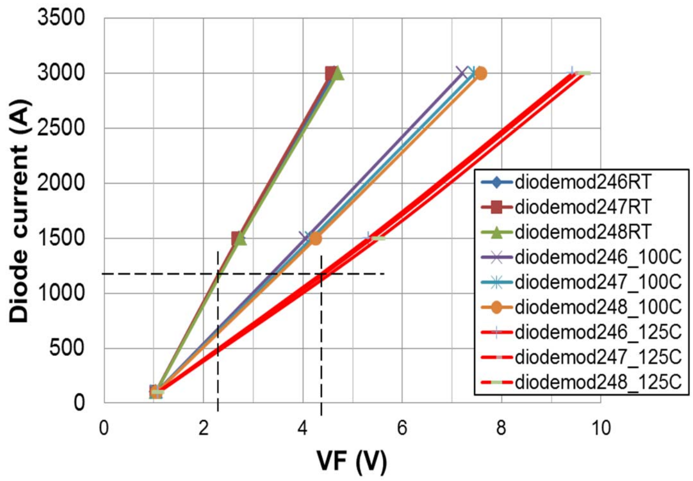

Fig. 9: Forward static characteristics of a hybrid SiC - 3.3 kV, 1100A modules at different temperatures RT (20 ºC), 100 ºC ad HT (125 ºC).

voltage drop of the module increases with increasing temperature. All the modules built (3 in total)

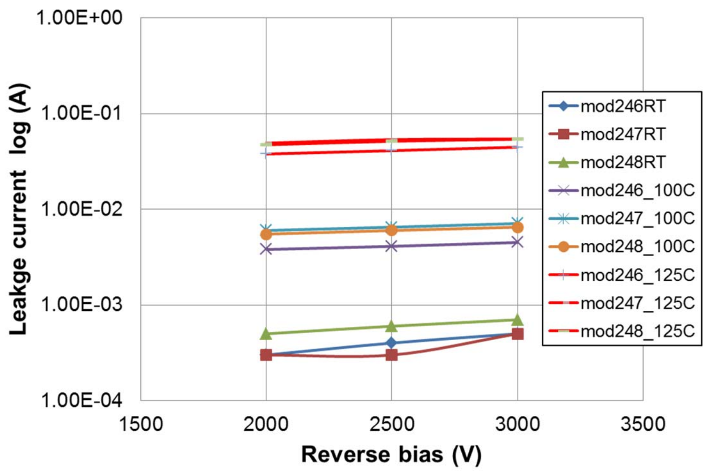

Fig. 10: Leakage current characteristics of a hybrid SiC - 3.3 kV, 1100A modules at different temperatures RT (20 ºC), 100 ºC ad HT (125 ºC).

have shown similar behaviour. The forward voltage drop (V_F) increases from 2.20 V to 4.30 V as we increase the temperature from RT to HT at 1100 A. The performance of the module under reverse bias is shown in

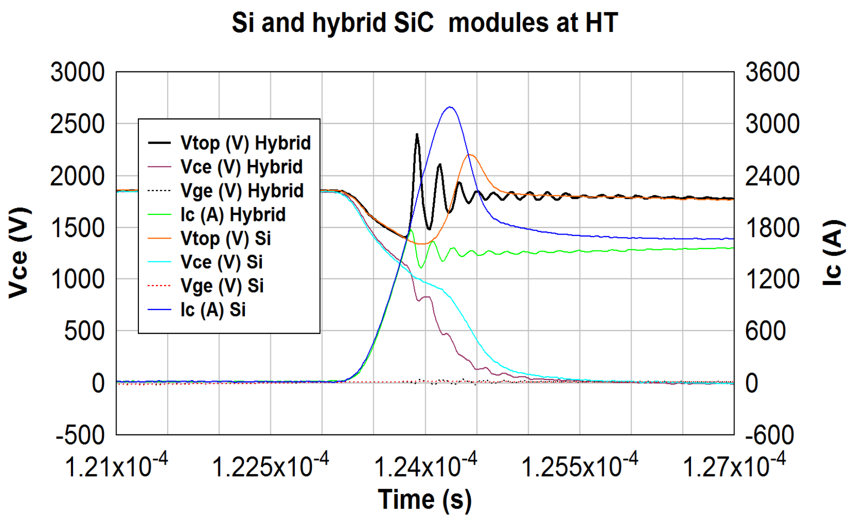

Fig. 11: The switching waveforms of Si and hybrid SiC modules at HT during the second turn-on of the IGBT. Unlike Si modules there is no current overshoot observed in hybrid SiC modules.

Fig. 10. The leakage current is plotted on a log scale and at 125 °C is around 55 mA as compared to 0.5 mA at room temperature. The waveforms obtained after a double pulse test for Si and hybrid SiC modules are shown in Fig. 11. Different R_{goff} , R_{gon} are used to perform the dynamic test, e.g. 1.8 Ω, 6 Ω. Also, load inductance (L) values are different under conditions (L = 70 µH for R_{gon} = R_{goff} = 1.8 Ω and L = 213 µH for R_{gon} = R_{goff} = 6 Ω). These waveforms are observed during the second turn-on of the IGBTs. Different parameters, like I_{rr} (reverse recovery collector current overshoot), Q_{rr} (stored charge), E_{on} (energy loss during the 2nd turn-on) and E_{rec} (reverse recovery energy loss) are extracted at different temperatures (RT and HT) and values are listed in Table IV. As expected there is no E_{rec} in the case of hybrid SiC modules. At R_{gon} (Ω) = R_{goff} (Ω) =6, as we increases the temperature from RT to HT there is no change in the value of E_{rec} . This implies that without comprising the performance, these modules can be used at high as well as low temperatures. The comparison of different parameters at HT with R_{gon} (Ω) = R_{goff} (Ω) = 1.8 shows that hybrid modules, not only able to withstand high current (1500 A) but also maintain a low energy loss (E_{on} and E_{rec}) behaviour. The E_{rec} value is 95 % lower than that of Si modules. Also, because of high di/dt = 6500 A/µs, lower E_{on} losses are observed for hybrid modules. The E_{on} loss is almost 50% (1.13 J) lower at high di/dt = 6500 A/µs, as compared to Si (2.18 J).

Table IV: Comparison of different electrical parameters - I_{rr} (A), Q_{rr} (µC), E_{on} (J), E_{rec} (J) and E_{off} (J) calculated for hybrid SiC modules. Although the hybrid module is rated up to 1100A, it could withstand a 1500 A current during the test. For the sake of comparison, Si module results are also included.

Module	Temp (°C)	R_{gon} (Ω), R_{goff} (Ω)	$Ic_{\_off1}$ (A), V_{line} (V)	dVce/dt (V/µs)	di/dt (A/µs)	I_{rr} (A)	Q_{rr} (µC)	E_{on} (J)	E_{rec} (J)
Hybrid SiC module	20 °C	6Ω, 6Ω	1129, 2007	3047	1060	55	11	4.39	0.01
Hybrid SiC module	125 °C	6Ω, 6Ω	1153, 2005	2927	1252	73	27	4.64	0.01
Si module	125 °C	1.8Ω, 1.8Ω	1507, 1851	6416	3198	253	49	1.13	0.05
Hybrid SiC module	125 °C	1.8Ω, 1.8Ω	1513,1850	6559	3222	1665	959	2.18	1.04

In addition to this, a reverse bias safe operating area (RBSOA) test is done on hybrid modules and the waveform is shown in Fig. 11. This test describes safe operating conditions at turn-off for the IGBT. The module is tested at 1900 V and 2200A, twice its nominal current rating (desired for this hybrid modules) at 125 °C.

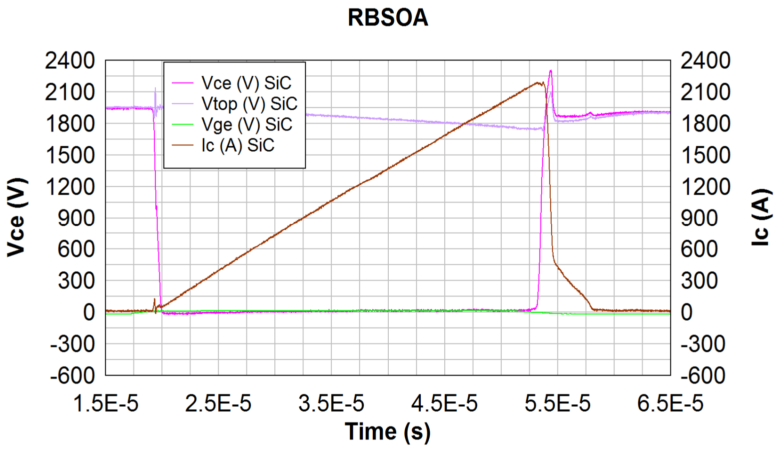

Fig. 11: The RBSOA test result of a hybrid Si 3.3 kV, 1100A module. The test is performed at twice the rated current.

At present we analysing the performance of these modules at 150 °C with a current rating of 1200 A and higher (max. 1500A). The results will be reported somewhere else.

Conclusion

In conclusion, with the use of 3.3 kV hybrid SiC substrates/modules we are able to reduce the switching losses considerably and hence potentially could build more energy efficient power systems. 1.7 kV and 3.3 kV diodes, rated at 50 A has been used to build modules/substrates in this work. Because fewer number of SiC diodes are needed to implement 3.3 kV hybrid approach, we used 3.3 kV, 50 A diodes to build some hybrid modules. Both, hybrid and Si modules are rated for 3.3 kV and 1100 A. Experimental data have shown that the hybrid SiC solution outperformed its Si counterpart. Also, it has been observed that although the V_F of 1.7 kV, 50 A SiC diodes is optimized, more efforts are still needed to improve the static performance (V_F) of 3.3kV SiC diodes.

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