The Cross Switch “XS” Silicon and Silicon Carbide Hybrid Concept

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Abstract

A parallel arrangement of a Silicon (Si) IGBT and a Silicon Carbide (SiC) MOSFET is experimentally demonstrated. The concept referred to as the Cross Switch “XS” hybrid aims to reach optimum power device performance by providing low static and dynamic losses while improving the overall electrical and thermal properties due to the combination of both the bipolar Si IGBT and unipolar SiC MOSFET characteristics. For the purpose of demonstrating the XS hybrid, the parallel configuration was implemented experimentally in a single package for devices rated at 1200V. Test results were obtained to validate this approach with respect to the static and dynamic performance when compared to a full Si IGBT and a full SiC MOSFET reference devices having the same power ratings as for the XS hybrid samples. Furthermore, an advanced Bimode Cross Switch Hybrid (BXS) is also demonstrated for 3300V devices by combining a Si RC-IGBT or BIGT with SiC MOSFETs. The BXS provides both Switch and diode mode of operation without a separate freewheeling diode.

1. Introduction

Due to the inherent advantages of wide bad-gap (WBG) semiconductor materials such as Silicon Carbide (SiC) and Gallium Nitride (GaN), WBG based power devices are fabricated on much thinner and higher doped n-base regions when compared to Silicon [1]. Therefore, such components can in principle provide a wide range of voltage ratings with improved electrical performance in terms of low conduction losses, very low switching losses and low leakage currents. Hence, making them suitable for applications targeting lower losses and higher operational frequencies and temperatures. For high power applications in particular, SiC based power devices are the preferred choice today for exhibiting relatively high current ratings due to the vertical structure such devices are based on. Whereas Silicon based unipolar power devices such as MOSFETs and Schottky Barrier Diode (SBD) do not exceed 1200V with respect to the voltage blocking capability due to the required thick and lightly doped n-base region and associated high on-state resistance $r_{ds(on)}$, unipolar SiC devices on the other hand can extend this range to well beyond 6.5kV [2]. In this particular voltage range, the SiC MOSFET and SBD are destined to compete with today`s popular Si IGBT and diode solutions for a wide range of power electronics circuits. In addition to the above mentioned advantages, SiC MOSFET also provides very low losses at low currents compared to the Silicon IGBT having an inherent pn junction barrier potential of around 0.7V. Therefore, for many applications where losses are taken into account for the full current range (i.e. sub-load conditions), the SiC MOSFET becomes an attractive prospect. Nevertheless, many challenges need to be overcome for permitting the widespread employment of SiC based devices in mainstream power electronics systems. One major obstacle is the significantly higher costs associated with SiC devices in particular due to starting substrate material manufacturing costs and expensive epitaxial growth processing especially for higher voltage devices with thick n-base regions.

To reduce cost, the utilization of less SiC device area is one approach but at the expense of higher thermal resistances and higher conduction losses. In relation, high voltage SiC unipolar devices display a strong positive temperature coefficient of the $r_{ds(on)}$ during current conduction which results in higher losses at higher temperatures. Furthermore on the device performance front, unipolar SiC devices suffer from oscillatory behaviour during switching transients due to the absence of excess carriers which normally provide bipolar devices with a slow declining current tail during turn-off for achieving softer characteristics [3-4]. Finally, unipolar SiC devices provide less fault current handling capability such as short circuit withstand capability for MOSFETs and surge current handling capability for SBDs compared to bipolar devices [5]. To resolve some of the above hindering issues for SiC technologies, while at the same time benefiting from the advantages of the well proven Silicon based devices, we demonstrate here a Cross Switch “XS” hybrid solution consisting of a parallel combination of a Si IGBT and SiC MOSFET. The cross sections of the two structures are shown in Fig. 1 along with the described parallel combination.

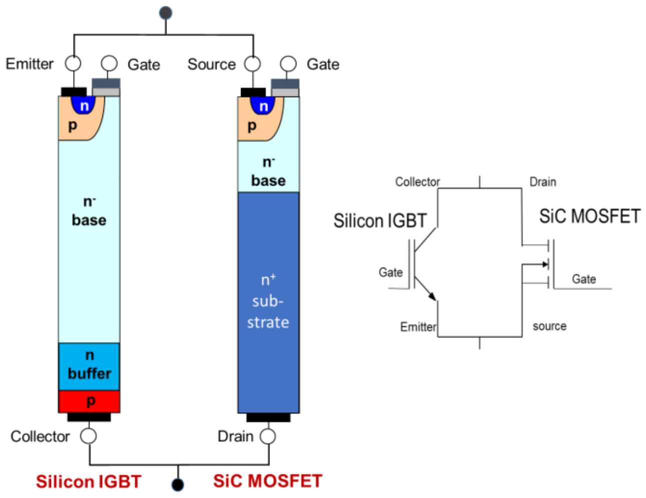

Fig. 1 Si IGBT and SiC MOSFET structures for the Cross Switch hybrid.

2. Power Semiconductors Hybrid Concepts

In practice, hybrid arrangements of different power semiconductor device structures target optimized performance by providing the combined advantages of the diverse device properties for a given application. To outline few examples, one of the first hybrid concepts was to provide an optimum Silicon fast recovery diode performance in terms of low losses and soft turn-off performance by combining a large area / thin n-base device with a smaller area / thick n-base diode [6]. With reference to Si and SiC devices, a popular hybrid combination utilizing a SiC SBD as the anti-parallel diode for a Si IGBT has been widely investigated and is currently employed in some applications for achieving lower reverse recovery and turn-on losses when compared to employing the standard Silicon bipolar fast recovery diode [7]. Furthermore, series connected hybrids were also proposed and investigated by combining a Si MOSFET in series to a SiC JFET to overcome the normally-on behaviour of the latter device [8]. More in relation to the current topic, a hybrid concept combining a Si IGBT and a Si MOSFET was proposed in the lower voltage range <600V in line with Si MOSFET performance capabilities [9-12]. This approach combines the advantages of both devices with low conduction losses for the IGBT and low switching losses for the MOSFET. For improved performance, Super Junction Si MOSFETs [13] rated at 600V were applied in parallel to 600V fast IGBTs with a separate gate unit per device to provide the required fast switching performance. The investigations produced results obtained from frequency tests under soft and hard switching conditions confirming the feasibility for realizing such a hybrid concept in real applications. Building on this trend and for a wider voltage and current range by employing SiC MOSFETs, the already proposed hybrid combination of an IGBT and MOSFET provides a potential solution to obtain overall improvements at lower cost for a given application requirement.

3. The Cross Switch Hybrid Concept, a 1200V Demonstration

The Cross Switch “XS” hybrid combines a Si IGBT and a SiC MOSFET in parallel. The main targets of such a combination are to provide low static and dynamic losses while improving the overall electrical and thermal properties due to the advantageous features both devices can offer in many power electronics applications. To investigate and validate the above concept, XS hybrid test samples were manufactured consisting of a single 1200V/25A Si Soft Punch Through (SPT) IGBT (6.5mm x 6.5mm) [14] in parallel to a 1200V/30A SiC MOSFET (4.1mm x 4.1mm) with an $r_{ds(on)}$ of 80mohm [15] on a single substrate as shown in Fig. 2. The active area ratio of the IGBT to the MOSFET was close to 3:1. The assumed nominal current rating of the combined XS hybrid was set at 50A. For the purpose of this investigation, both gates are connected and controlled by the same single gate unit. For comparison, reference samples were also made with one consisting of two paralleled Si SPT IGBTs and the other having two paralleled SiC MOSFETs to provide the same 50A rating per test sample. The same gate voltage signal was also applied for all chips in parallel. Furthermore, to analyze the behavior of the XS hybrid, test samples containing a single Si SPT IGBT and others containing a single SiC MOSFET were also fabricated. For the static parameters, Fig. 3 show the IV transfer curves at 25°C and output characteristics at 150°C for the XS hybrid. Curves for the single Si IGBT and SiC MOSFET are also depicted to show that the XS hybrid is a combination of both device characteristics.

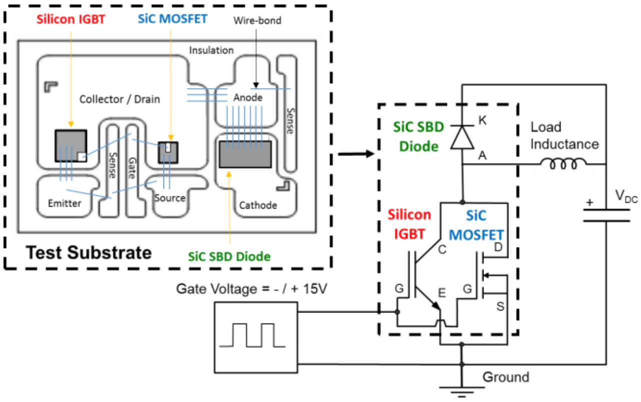

Fig. 2 Cross Switch XS hybrid test substrate arrangement and double pulse clamped inductive load test circuit diagram.

For the same 50A current rating, the IV output characteristics at 150°C comparing XS hybrid to the 2 x Si SPT IGBT and 2 x SiC MOSFET samples are provided in Fig. 4 which also shows the same IV output characteristics but only up to 10% of the nominal current. It is shown that the parallel combination offer the possibility to provide IGBT characteristics at high currents while still maintaining low losses at very low currents as for a MOSFET. This particular feature has always been a major hurdle for bipolar devices and thus such a combination offers an important advantage in power device performance [16]. In addition, the XS hybrid offers improved thermal resistance due to the large Si IGBT area. More reductions in MOSFET $r_{ds(on)}$ values will further lower the XS hybrid conductions losses when compared to the full Si-IGBT.

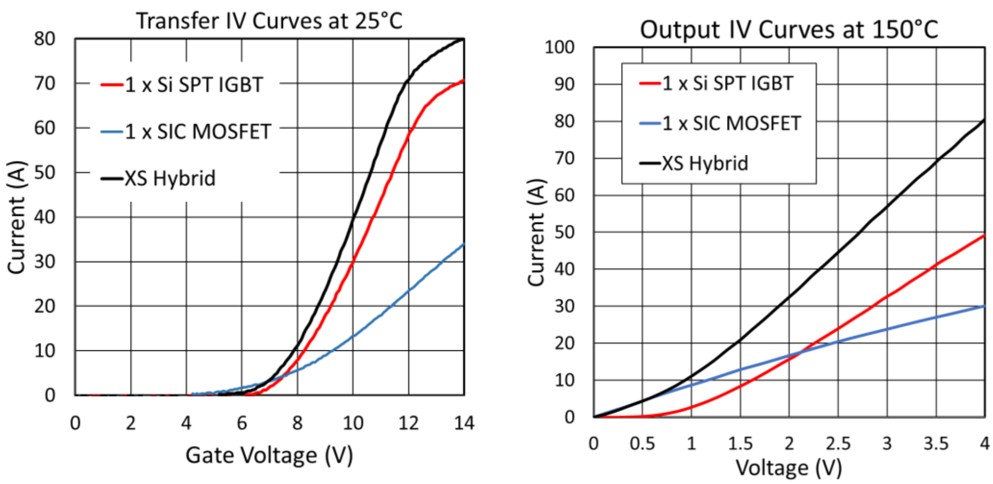

Fig. 3 IV transfer characteristics at 25°C and IV output characteristics at 150°C comparing the XS hybrid to a single Si SPT IGBT and a single SiC MOSFETs.

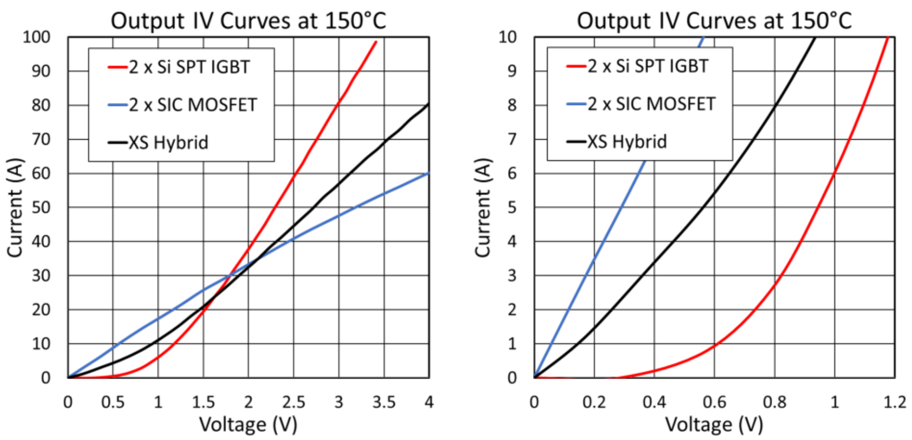

Fig. 4 IV output characteristics at 150°C comparing the XS hybrid to 2 x Si SPT IGBTs and 2 x SiC MOSFETs up to twice and 10% of nominal current.

The switching characteristics were measured using a double pulse clamped inductive test circuit shown in Fig. 2 having a stray inductance value of 60nH. A SiC SBD diode rated at 1200V and 50A was employed as the freewheeling diode. Fig. 5 shows the turn-off performance of the XS hybrid compared to the 2 x Si SPT IGBT and 2 x SiC MOSFET samples under nominal conditions and with an $R_{g(off)}$ of 10 ohms at 150°C.

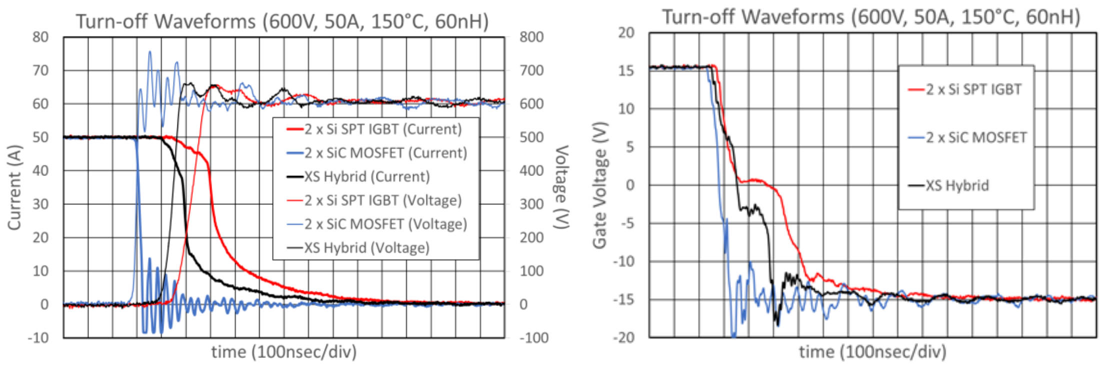

Fig. 5 Turn-off switching waveforms comparing the XS hybrid to 2 x Si SPT IGBTs and 2 x SiC MOSFETs at 50A, 600V, 150°C.

Under such switching conditions, the XS hybrid provides again a combination of the two device distinctive turn-off characteristics. The switching event is initiated with the SiC MOSFET turning off at an earlier time compared to the Si IGBT. The XS hybrid is therefore displaying a switching behavior corresponding to both device behavior patterns while clearly exhibiting a soft current tail due to the remaining excess charge in the IGBT. The softness of the XS hybrid is also confirmed with a low overshoot voltage when compared to the SiC MOSFET. In general, SiC MOSFETs are normally slowed down by increasing the gate resistor $R_{g(off)}$ to reduce the EMI and overshoot voltages especially at high currents. Therefore, the turn-off softness will improve in the XS hybrid by providing a current tail during turn-off and the possibility to employ the concept in high voltage and high current modules with a moderate stray inductance. To gain further understanding, the turn-off switching losses and softness dependence on the turn-off gate resistor $R_{g(off)}$ was further investigated. Fig. 6 show such dependency for the turn-off losses E_{off} at 150°C and maximum overshoot voltage V_{cem} at 25°C. Over the full $R_{g(off)}$ range, the XS hybrid offers 40% lower E_{off} compared to the Si IGBT reference sample and softer performance than the SiC MOSFET. By comparing the E_{off} when achieving similar overshoot voltages, the XS hybrid shows approximately 3mJ compared to 5mJ for the full Si IGBT at an $R_{g(off)}$ of 2.2ohms, and 1mJ for the full SiC MOSFET at an $R_{g(off)}$ of 47ohms.

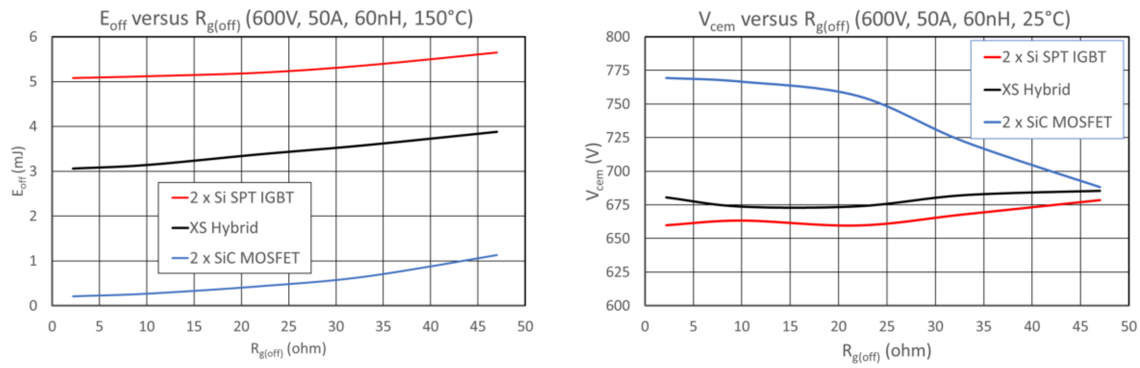

Fig. 6 E_{off} at 150°C and Vcem at 25°C as a function of R_{goff} comparing the XS hybrid to 2 x Si SPT IGBTs and 2 x SiC MOSFETs at 50A, 600V.

The turn-on switching waveforms of the XS hybrid under nominal conditions and $R_{g(on)}$ of 22 ohms at 150°C are also shown in Fig. 7 resulting in turn-on losses E_{on} of 2.8mJ. The turn-on measurements for the different samples including the full Si IGBT and full SiC MOSFET show that the losses are not influenced by the switch type but mainly dependent on the SiC SBD characteristic and switching conditions. Finally, the short circuit performance of the XS hybrid was verified at a DC voltage of 600V and a gate voltage of 15V at 150°C. Fig. 8 shows the short circuit waveforms of the XS hybrid while also providing the short circuit waveforms of the single Si SPT IGBT and single SiC MOSFET. As expected, the total short circuit current of the XS hybrid is the sum of the short circuit current of both paralleled device. The test was repeated successfully with increased gate voltages up to 19V.

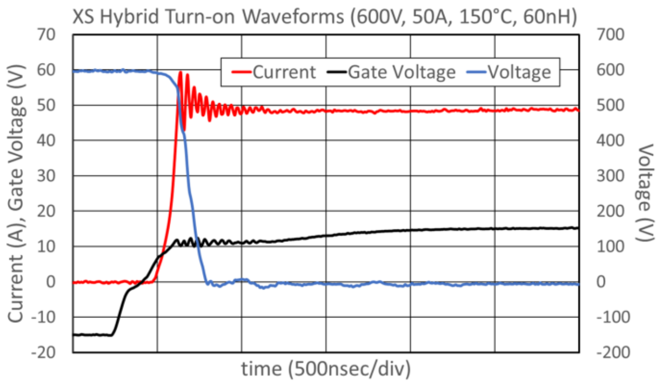

Fig. 7 Turn-on switching waveforms for the XS hybrid 50A, 600V, 150°C.

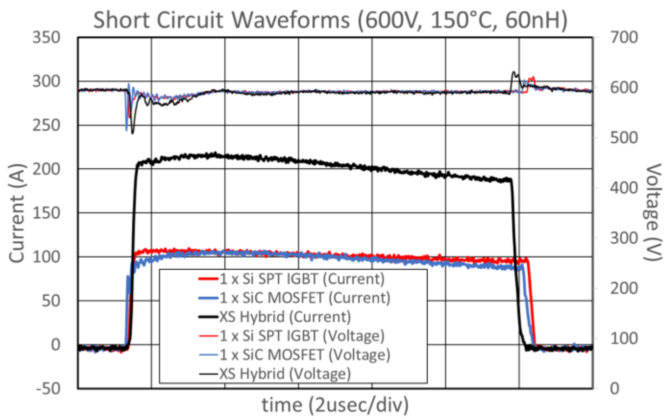

Fig. 8 Short Circuit switching waveforms for the XS hybrid, a single Si SPT IGBT and a single SiC MOSFETs at 600V and 150°C.

Compared to previous work on Silicon based IGBT/MOSFET hybrids, the XS Hybrid concept enables very high voltage rating up to 6.5kV and potentially beyond. Furthermore, in the following section we will discuss and demonstrate a more advanced high voltage XS Hybrid combining in parallel a Silicon Reverse Conducting RC-IGBT or BIGT [17] and a SiC MOSFET to provide the XS Hybrid with Bi-mode operation with integrated diode functionalities while eliminating the need for an external free-wheeling diode.

4. The Bimode Cross Switch Hybrid, a 3300V Demonstration

The Cross Switch XS hybrid discussed previously only provides the mentioned performance advantages in switch mode of operation. An external diode (preferably a SiC SBD) is still required for the diode freewheeling part since the small MOSFET area utilized is not sufficient to provide optimum performance in diode mode both electrically and thermally. To further enhance the XS performance and reduce cost, a combination of an RC-IGBT or BIGT with the SiC MOSFET can provide similar performance advantages albeit in both Switch and Diode modes of operation. We refer to this combination as the Bimode Cross Switch hybrid (BXS) as shown in Fig. 9. To demonstrate this concept, BXS hybrid test samples were manufactured consisting of a single 3300V/75A Si BIGT (20.4mm x 13.6mm) in parallel to six 3300V/12.5A SiC MOSFET (4.8mm x 4.8mm) from ROHM on a single standard module substrate. The active area ratio of the BIGT to the SiC MOSFETs is (1.6 : 1) The nominal current rating of this device was 150A, hence, two reference test samples were assembled for a full Si BIGT sample consisting of 2 x Si BIGT devices and a full SiC MOSFET sample consisting of 12 x SiC MOSFETs.

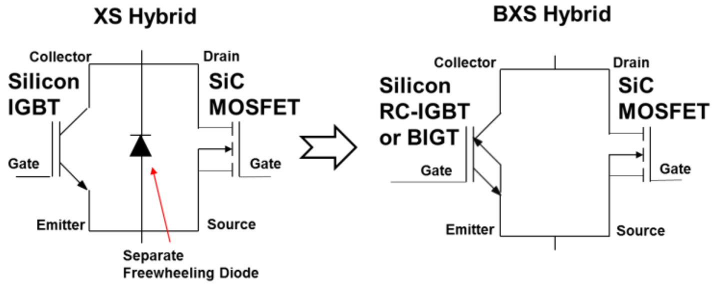

Fig. 9 Bimode Cross Hybrid (BXS) combination.

The output static characteristics are shown in Fig. 10 for both switch and diode modes at 150°C. The switch mode on-state forward voltage is similar for all three samples around 150A but both the SiC MOSFET and BXS samples show significantly lower voltage drops at very low currents due to the MOSFET when compared to the BIGT. More in relation to the BXS concept, the diode mode on-state characteristics show strong dependency on the applied gate voltage for all samples. The BIGT dependency is mainly related to the shorting of the BIGT anode when a positive gate voltage is applied resulting in higher forward voltages and hence increased conduction losses. The SiC MOSFET on the other hand provides two modes of forward conduction, the first is a unipolar channel diode conduction similar to the MOSFET with a positive gate voltage, and the second having an applied negative gate voltage is attributed to the MOSFET internal bipolar diode conduction. Due to the wide band-gap material, a built-in potential of around 2.5V is observed as expected before the bipolar diode starts conducting, hence exhibiting high conduction losses. The BXS hybrid combines the characteristics of both the Si BIGT and SiC MOSFET and their dependency on the gate voltage polarity while also exhibiting low conduction losses at very low currents.

The turn-off switching characteristics in both switch and diode modes are shown in Fig. 11 at 25°C and 150°C respectively. The switch turn-off waveforms show the expected turn-off behaviour from the three samples. The BXS sample was capable of switching at much lower gate resistance values with little increase in the overshoot voltage as observed previously for the XS hybrid tests. In addition, the diode turn-off or reverse recovery waveforms show strong reductions in the reverse recovery current and charge compared to the BIGT and hence resulting much lower switching losses for the diode and also for the switch during turn-on. The SiC MOSFET shows very low reverse recovery charge which is attributed to the internal bipolar diode.

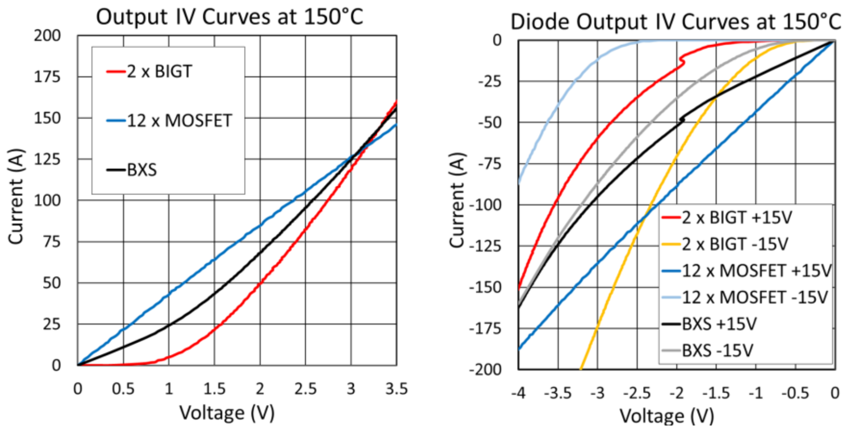

Fig. 10 IV output characteristics at 150°C for the BXS hybrid, 2 x BIGTs and 12 x SiC MOSFETs.

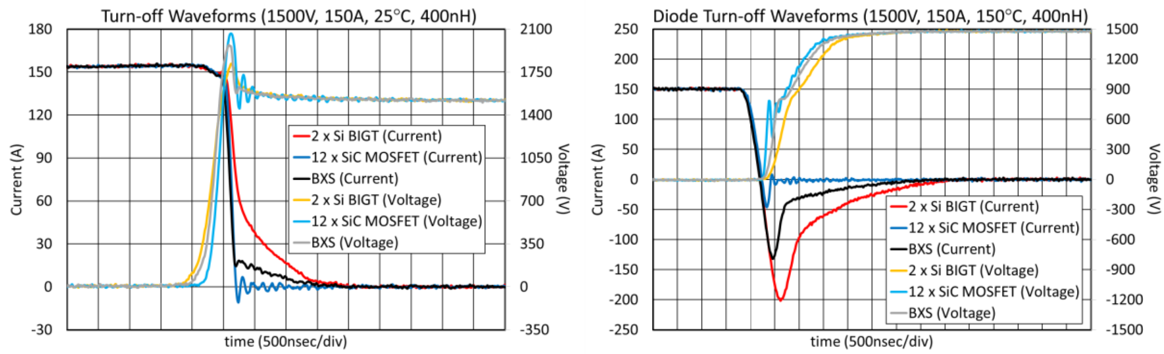

Fig. 11 Turn-off switching waveforms comparing the BXS hybrid to 2 x BIGTs and 12 x SiC MOSFETs at 150A, 1500V. The switch turn-off is carried out at 25°C and $R_{g(off)}$ =22ohm while for the diode turn-off it was performed at 150°C and di/dt = 600A/usec.

Table 1 shows the overall conduction and switching losses for the three samples at 1800V, 150A, 400nH and 150°C. The $R_{g(oN)}$ is 22ohm for all samples while the $R_{g(off)}$ is at 15ohm for the BIGT and BXS samples and 33ohm for the SiC MOSFET to obtain low overshoot voltages for all devices during turn-off. The turn-on and reverse recovery losses were measured for the BIGT and BXS while applying a MOS gate control feature with positive gate single applied on the freewheeling sample during diode conduction followed and a 2usec gate reversal delay time prior to reverse recovery [17]. This feature has a stronger impact on the BXS compared to the BIGT due to the presence of the MOSFET strong conduction sharing with a positive gate voltage. The BXS and SiC MOSFET show a reduction of 31% and 56% in E_{total} respectively when compared to the BIGT. The BXS shows a reduction of 49% in E_{rec} compared to the BIGT. On the other hand, the SiC MOSFET has close to 90% lower recovery losses as for the BIGT.

Table 1	2 x BIGT	12 x MOSFET	BXS
Vce (V)	3.35	3.6	3.4
Vf (V) -15V	2.8	4.3	3.8
Vf (V) +15V	4	3.3	3.8
Eoff (mJ)	252	100	158
Eon (mJ)	333	158	247
Etot (mJ)	585	258	405
Erec (mJ)	171	15	86

With careful optimization of the BIGT switching characteristics through plasma engineering and gate MOS control for faster switching performance while utilizing an optimum BIGT to SiC MOSFET area ratio, further reductions in the BXS switching losses are possible. In addition, through similar means, the BXS can also be optimized with low conduction losses over the full current range for targeting low frequency applications. Future work will focus on these aspects and also on the fault condition advantages in terms of short circuit and diode surge current capability of the BSX hybrid. The above demonstrations provide an initial insight into the XS hybrid concept and validates the potential of such a combination for future power electronics applications. Results confirm that in addition to the potential lower cost, the main expected advantages of the XS hybrid combinations are (a) low conduction losses over the full current range, (b) low switching losses, (c) low thermal resistance, (d) soft turn-off performance, (e) high switching robustness and (f) improved fault current protection in short circuit and surge current capability.

5. Conclusion

The Cross Switch XS hybrid concept by paralleling a Si IGBT and SiC MOSFET was discussed and demonstrated. Static and dynamic test results on 1200V / 50A devices were obtained showing potential improvements in terms of loss reductions, soft performance, good short circuit capability and the prospect for lower overall cost compared to full SiC solutions. A more advanced Bimode XS hybrid concept was also demonstrated by paralleling a Si BIGT and SiC MOSFETs for 3300V class devices. The BXS provides both switch and diode modes of operation without the need for a separate free-wheeling diode. Both types of XS hybrids can therefore provide a conceivable path for further optimization for a targeted power electronics application at the required operational frequency.

Acknowledgments

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6. Literature

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