Cross Switch XS - Silicon and Silicon Carbide Hybrid

Due to the inherent advantages of wide bandgap (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. Therefore, in principle they can 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 making them suitable for applications targeting lower losses and higher operational frequencies and temperatures. **Munaf Rahimo, Charalampos Papadopoulos, Francisco Canales, Renato Amaral Minamisawa, Umamaheswara Vemulapati, ABB Semiconductors Lenzburg, Switzerland**

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 Diodes (SBD) do not exceed 1200 V with respect to the voltage blocking capability, unipolar SiC devices on the other hand can extend this range to well beyond 6.5 kV.

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 0.7 V. 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 cost associated with SiC devices, in particular due to starting substrate material manufacturing cost and expensive epitaxial growth processing especially for higher voltage devices with thick n-base regions.

High performance at lower cost

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 behavior 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. 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. 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 Figure 1 along with the described parallel combination.

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. 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. Hybrid concept combining a Si IGBT and a Si MOSFET have also been investigated in the lower voltage range <600 V in line with Si MOSFET performance capabilities. This approach combines the advantages of both devices

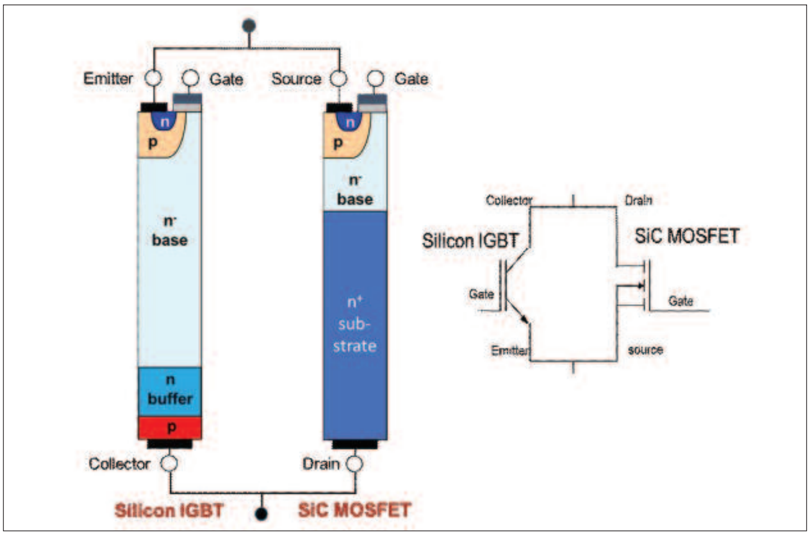

Figure 1: **Si IGBT and SiC MOSFET structures for the hybrid Cross Switch**

with low conduction losses for the IGBT and low switching losses for the MOSFET. Building on this trend and for a wider voltage and current range by employing SiC MOSFETs, the basic hybrid combination of an IGBT and MOSFET provides a potential solution to obtain overall improvements at lower cost for a given application requirement.

Hybrid 1200 V demonstration

The Cross Switch “XS” 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 1200 V/25 A Si Soft Punch Through (SPT) IGBT (6.5 mm x 6.5 mm) in parallel to a 1200 V/30 A SiC MOSFET (4.1 mm x 4.1 mm) with an $R_{ds(on)}$ of 80 mΩ on a single test substrate. 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.

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, Figure 2 shows 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.

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 Figure 3 which also shows the same IV output characteristics but only up to 10 % of the nominal current. It is shown that the parallel combination offers 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. In addition, the XS hybrid offers improved thermal resistance due to the large Si IGBT area. More reductions in MOSFET Rds(on) values will further lower the XS hybrid conduction losses when compared to the full Si IGBT. The switching characteristics were measured using a double pulse clamped inductive test circuit having a stray inductance value of 60 nH. A SiC SBD diode rated at 1200 V and 50 A was employed as the freewheeling diode. Figure 4 shows the turn-off performance of the XS hybrid compared to the 2 x Si SPT IGBT and 2 x SiC MOSFET samples under

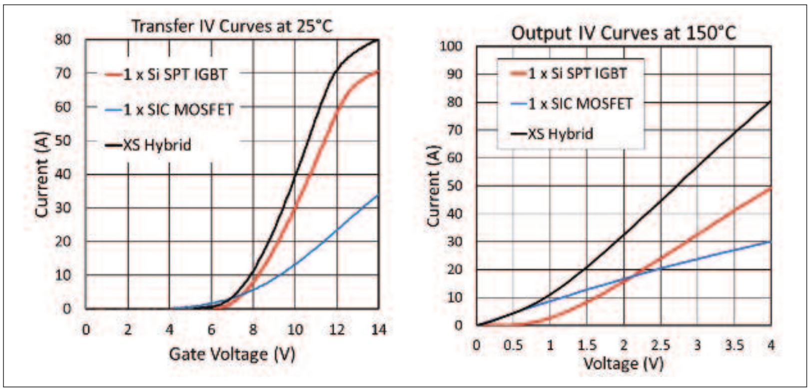

Figure 2: IV transfer characteristics at 25°C (left) and IV output characteristics at 150°C comparing the XS hybrid to a single Si SPT IGBT and a single SiC MOSFETs

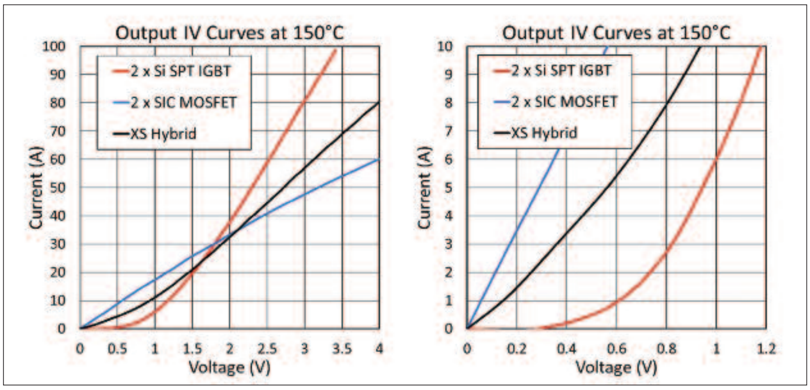

Figure 3: IV output characteristics at 150°C (left) comparing the XS hybrid to 2 x Si SPT IGBTs and 2 x SiC MOSFETs up to twice and 10% of nominal current

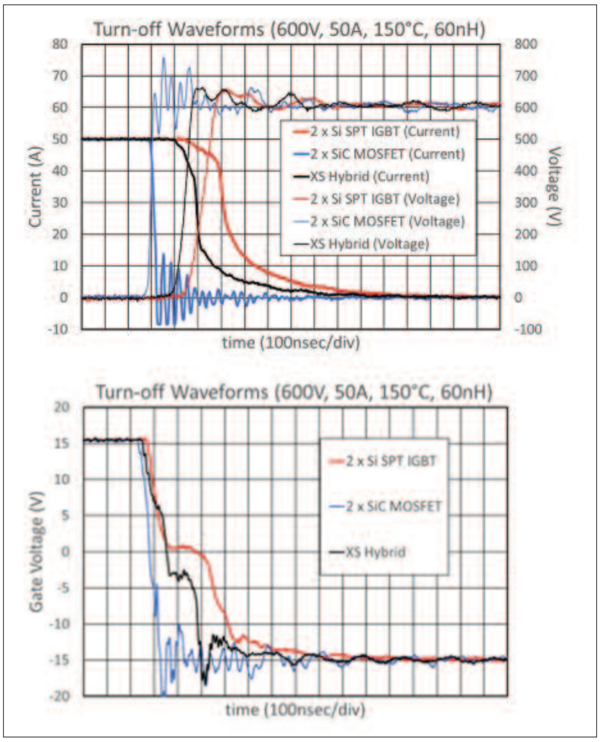

Figure 4: Turn-off switching waveforms comparing the XS hybrid to 2 x Si SPT IGBTs and 2 x SiC MOSFETs at 50 A, 600 V, 150°C

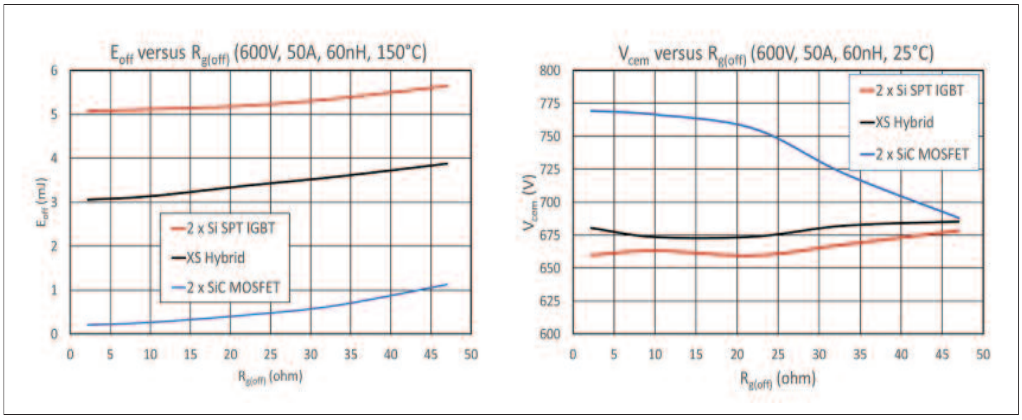

Figure 5: E_{off} **at 150°C (left) and** V_{cem} **at 25°C as a function of** R_{goff} **comparing the XS hybrid to 2 x Si SPT IGBTs and 2 x SiC MOSFETs at 50 A/600 V**

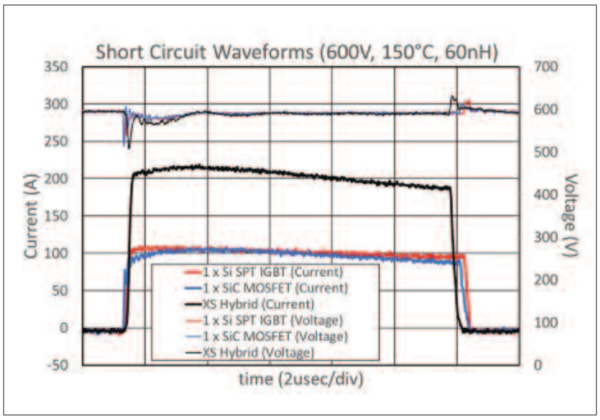

Figure 6: Short Circuit switching waveforms for the XS hybrid, a single Si SPT IGBT and a single SiC MOSFETs at 600 V and 150°C

nominal conditions and with an $R_{g(off)}$ of 10 Ω at 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.

Figure 5 shows such dependency for the turn-off losses Eoff 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 Eoff compared to the Si IGBT reference sample and softer performance than the SiC MOSFET. By comparing the Eoff when achieving similar overshoot voltages, the XS hybrid shows approximately 3 mJ compared to 5 mJ for the full Si IGBT at an $R_{g(off)}$ of 2.2 Ω, and 1 mJ for the full SiC MOSFET at an $R_{g(off)}$ of 47 Ω.

The turn-on losses E_{on} of the XS hybrid under nominal conditions and $R_{g(on)}$ of 22 Ω at 150°C was measured at 2.8 mJ. 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 600 V and a gate voltage of 15 V at 150°C. Figure 6 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 19 V.

Compared to previous work on Silicon based IGBT/MOSFET hybrids, the XS Hybrid concept enables a very high voltage rating up to 6.5 kV and potentially beyond. Future work will focus on a more advanced high voltage XS Hybrid combining in parallel a Silicon Reverse Conducting RC-IGBT or BIGT and a SiC MOSFET to provide the XS Hybrid with Bimode operation with integrated diode functionalities while eliminating the need for an external freewheeling diode.

Conclusion

The above demonstrations provide an initial insight into the XS hybrid concept and validate 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. The XS hybrid also provides a conceivable path for further optimization for a given targeted power electronics application at the required operational frequency.

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