Performance Evaluation of CoolMOS^{TM} and SiC Diode for PFC Applications

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***Abstract*—SiC diode exhibits almost zero reverse recovery charge and CoolMOS^{TM} achieves smaller R_{dson} and fast switching speed. These features make CoolMOS^{TM} and SiC diode attractive for the single-phase PFC AC/DC front-end converters. This paper examines the switching characteristics of CoolMOS^{TM} and SiC diode in comparison with the conventional Si devices. Based on that, one single-phase PFC CCM boost converter for distributed power system applications is built to evaluate the converter performance of using CoolMOS^{TM} and SiC diode. The experimental measurement results of the efficiency and the electromagnetic interference noise level indicate the substantial performance improvement with use of CoolMOS^{TM} and SiC diode.**

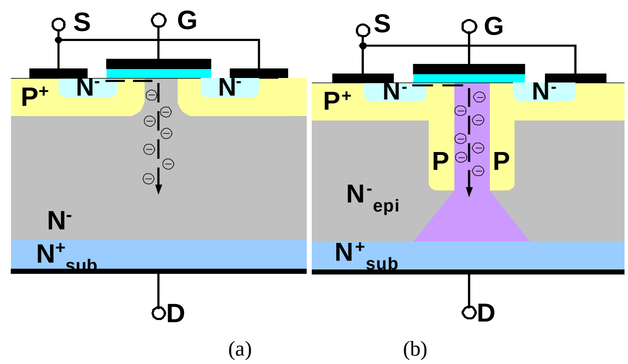

Fig. 1. Structure of MOSFET: (a) conventional (b) CoolMOS^{TM}.

I. Introduction

In the history of the power electronics technology, the new devices and the new topologies are always the pushing power of the development. The thyristor shows the beginning of the power electronics. When the gate turn off devices such as BJT and GTO come into existence, the power electronics technology got rapid development. The isolated gate devices such as MOSFET and IGBT make the power electronics devices easy to control and even much higher frequency. In the same time, people never stop the work to find a better topology to make use of the maximum capability of the devices.

For the AC/DC stage of the front-end distributed power system (DPS) applications, a single switch continuous-current-mode (CCM) boost PFC circuit is an attractive choice, in which a fast MOSFET and a fast recovery Si diode are used [1]. Although with the fast switching devices, the diode reverse-recovery related turn-on loss and the turn-off loss in the switch are still high, which mainly leads to low efficiency at the low line for a PFC rectifier designed for the wide input voltage range (90V-260V). Therefore, with the use of the conventional devices, there have been a good number of investigations on the snubber scheme for the single switch boost PFC. While most schemes complicate in either auxiliary power stage or additional control scheme, some passive snubber techniques have been demonstrated to be cost-effective in reducing the switching losses. Along with the efforts of exploring circuit topologies, the device technology is also continuously improved. New devices such as CoolMOS^{TM} and the SiC diode have come into commercial production recently, although the cost is high.

CoolMOS^{TM} is a new revolutionary technology for high voltage power MOSFETs [2]. As shown in Fig. 1, CoolMOS^{TM} implements a compensation structure in the vertical drift region of a MOSFET in order to improve the on state resistance. Such a structure makes it possible to reduce the on-state resistance R_{dson} of a 600V MOSFET by a factor of 5 for the same chip area. It literally changes the conception for the R_{dson} limitations of the conventional MOSFET technologies, which was $R_{dson} \propto V_{ds}^{2.5}$. In the mean time, CoolMOS^{TM} technology can largely reduce the junction capacitance, as compared with the normal MOSFET technology. It is claimed the CoolMOS^{TM} achieves the fastest switching given the same chip size.

SiC is a wide bandgap semiconductor material, and thus SiC Schottky can have a very low on-resistance with high rated voltage. From theory, the SiC Schottky diode can have a voltage rating more than 1000V and at present a commercial SiC Schottky diode has a maximum voltage rating of 600V, much higher than the Si Schottky diode. Another nice feature of SiC diode is almost no reverse-recovery charge. Therefore, the turn-on loss of the switch is expected to be substantially reduced.

In recent years, some evaluation results of SiC diodes showed signs of the improving switching loss of power devices but lower efficiency of the whole converter [3]. The reason was that, a couple of years ago SiC diode exhibited much higher conduction loss than Si diode. One most recent work presents the overall efficiency results using CoolMOS^{TM} and SiC diode in the PFC boost converter [4]. However, the loss reduction mechanism was not clearly

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explained and the evaluation did not fully target the DPS PFC front-end applications. In addition, the EMI noise performance was not addressed.

In this paper, the switching characteristics of CoolMOS^{TM} and SiC diode are obtained via the experiment. The device impacts on a PFC boost converter for DPS applications are able to be distinguished through the measurements based on different combinations of devices. Moreover, the EMI performance using SiC diode is presented.

II. SWITCHING CHARACTERISTICS EVALUATION

To evaluate the CoolMOS^{TM} and the SiC Schottky diode, a switching test bed is built to test the switching waveforms compare with the normal MOSFET and Si diode. The schematic of the switching test-bed is shown in Fig. 2. Applying the laminated power bus plane, as shown in Fig. 3 minimizes the parasitic inductance of the current loop comprised of the bus capacitor, the diode and the MOSFET.

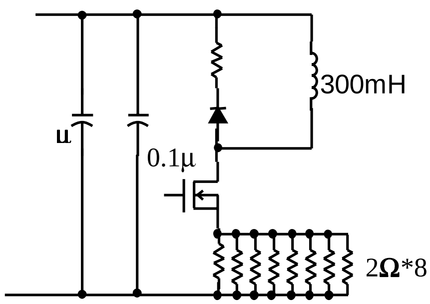

Fig. 2. Switching test-bed schematic

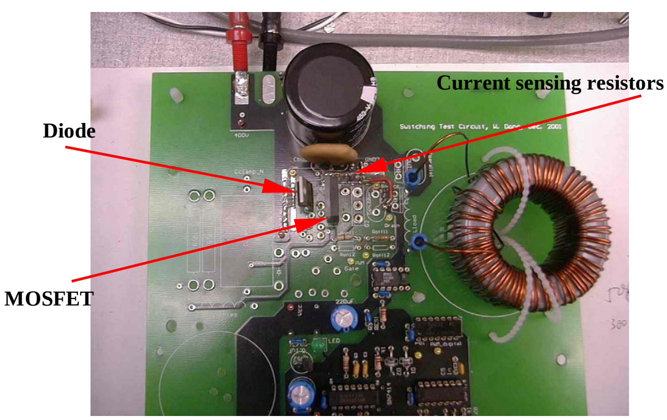

Fig. 3. Test-bed setup.

From this test-bed, we can not only obtain the switching waveforms to understand the switching features of the different devices but also get the switching loss caused by the voltage and current overlap, which is very useful for the total converter loss breakdown.

To compare with the CoolMOS^{TM} and SiC Schottky diode, we choose the widely used devices such as the MOSFT IRFP460 and the fast recovery diode RHRP860. The CoolMOS^{TM} is SPW20N60S5 and the SiC Schottky diode is SDP06S60, which are from Infineon Inc. We tested four combinations of these devices, as explained in Table I.

Table I. Device combinations used in switching test.

	Com. I	Com. II	Com. III	Com. IV
Diode	RHRP860	SDP06S60	RHRP860	SDP06S60
MOSFET	IRFP460	IRFP460	SPW20N60S5	SPW20N60S5

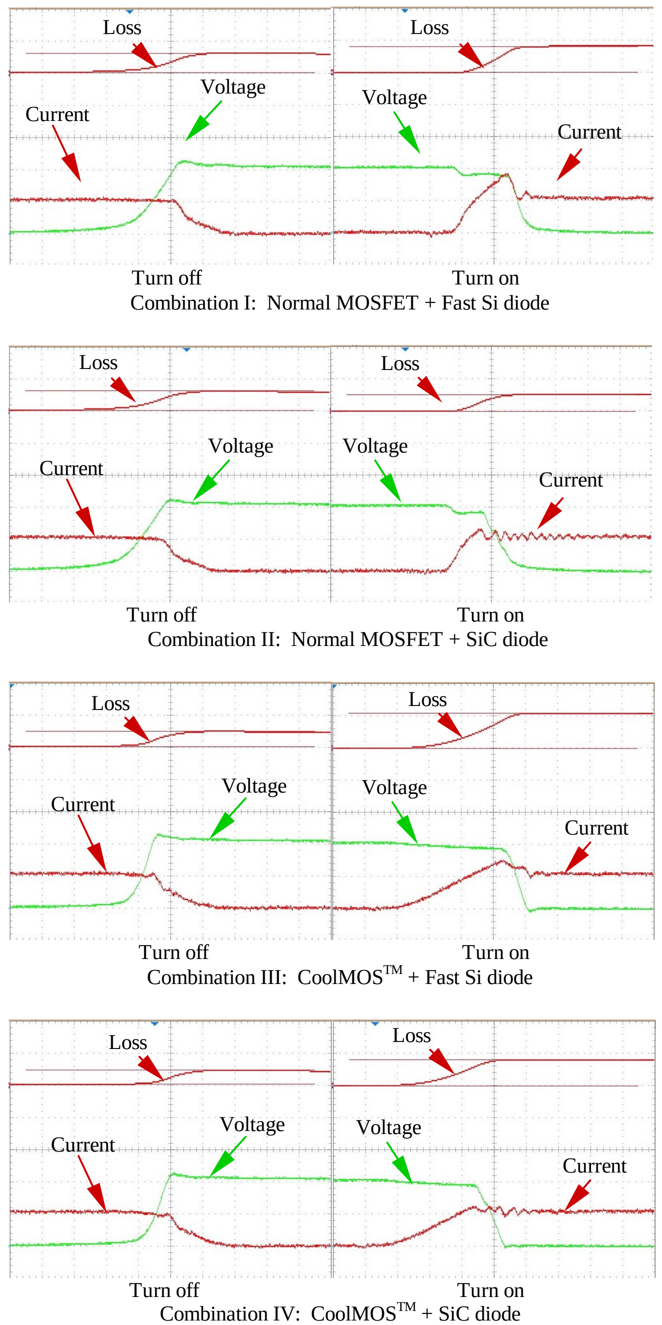

Fig. 4. Compare switching waveforms for different devices.
Voltage: 200V/div; current: 20 A/div; loss: 400μJ/div; time: 20nS/div.

The switching waveforms are shown in Fig. 4 and the gate resistor is 9.1Ω for all the combinations. Comparing the switching waveforms of combination I and combination II, it is easy to see the effect caused by the SiC diode. The turn off waveforms are almost identical because the turn off process is largely depended on the MOSFET's characteristics other than diode. At turn-on, the SiC diode exhibits minimal the reverse recovery current at the di/dt of 1100 A/µS while the Si diode shows about 16 A of the reverse recovery current. So the turn on loss is largely reduced by SiC diode, as confirmed in the waveforms of combination I and II of Fig. 4.

From combination I to III, the switch is changed from a normal MOSFET into a CoolMOS^{TM}. It can be easily seen that the CoolMOS^{TM} has a much faster turn off speed as compared with the normal MOSFET. The CoolMOS^{TM} takes just half of the turn off time that the normal MOSFET need, which can help reduce the turn off loss of the MOSFET. Specially, the CoolMOS^{TM} has the voltage rating of 600V while the conventional MOSFET in the same package can only block 500V. Therefore, at turn-off the CoolMOS^{TM} can be driven mush faster than the normal MOSFET. On the other hand, the current rising slope when CoolMOS^{TM} turns on is slower than the normal MOSFET. It is difficult to understand this phenomenon if assuming all the MOSFET junction capacitance has the same feature for both turn-off and turn-on. Therefore, more device structure level understanding is required to explain the phenomenon. From the application point of view, it is also desired to have a fast turn-on speed for CoolMOS^{TM}.

When using the CoolMOS^{TM} and SiC diode together, the switching feature is quite understandable based on the preceding analysis of the individual device' impact. As shown in combination IV of Fig. 4, both the CoolMOS^{TM} and the SiC diode affect the turn-on waveforms. The CoolMOS^{TM} causes a slower current rising while the SiC diode nearly eliminates the diode reverse recovery current. For the turn-off, the CoolMOS^{TM} leads to fast switching while the SiC diode has no effect on the switching loss.

When SiC diode is used, the adequate gate driving for switch can make turn-on speed fast and will not cause more reverse recovery charge. In addition, the CoolMOS^{TM} can be driven much faster at turn-off than the conventional MOSFET without causing excessive voltage stress. Therefore, it is expected the switching losses at turn-on and turn-off are greatly reduced with use of the CoolMOS^{TM} and SiC diode.

Figure 5 summarizes the measured turn-on loss for different combinations of devices. All the turn on losses are based on the 9.1Ω gate resistor. Since the CoolMOS^{TM} has a slower current rising rate, it causes larger turn on loss compare with the normal MOSFET. But we can drive the CoolMOS^{TM} faster to reduce the turn on loss. In figure 5, the turn on loss of CoolMOS^{TM} and SiC Schottky diode combination using 0Ω gate resistor is shown. It can be easily seen that the turn on loss is reduced by increasing the driving speed. So the turn on loss by using CoolMOS^{TM} can be similar to the normal MOSFET turn on loss. The comparison of turn-off loss energy is shown in Fig. 6. Regardless the switching current level, the turn-off loss can be reduced by the CoolMOS^{TM}. In the same time, the normal MOSFET can't be driven so fast since its voltage rating is only 500V, which means it doesn't have a large margin for the voltage overshoot caused by the parasitic inductor. For the CoolMOS^{TM}, since it has a voltage rating of 600V, which means a much larger margin compare with the normal MOSFET, it can be driven much faster to reduce turn off loss more. From this point of view, CoolMOS^{TM} can largely reduce the turn off loss. In figure 6, the turn off energy loss of CoolMOS^{TM} and SiC Schottky diode combination by using 0 gate resistor is shown, it can be seeing that by driving faster of the CoolMOS^{TM}, a much lower turn off loss can be achieved.

From the switching loss summary, it can conclude that with a suitable fast gate driving, the CoolMOS^{TM} and SiC diode are expected to lead to considerable switching loss reduction.

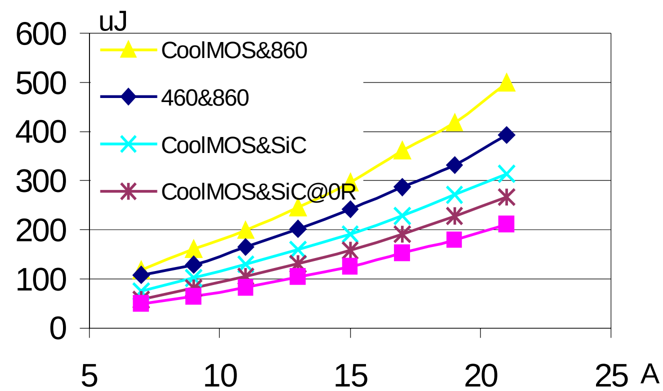

Fig. 5. Turn on energy loss.

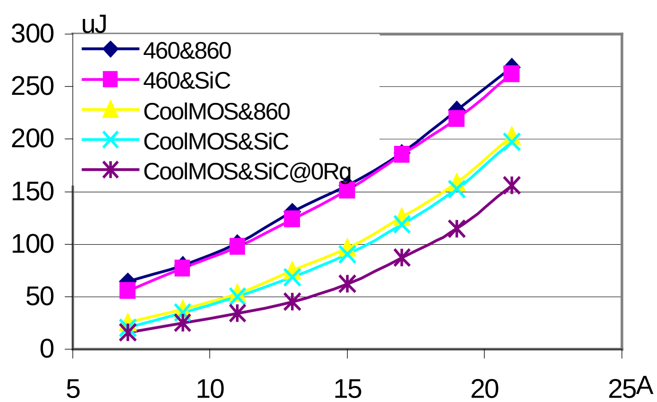

Fig. 6. Turn off energy loss.

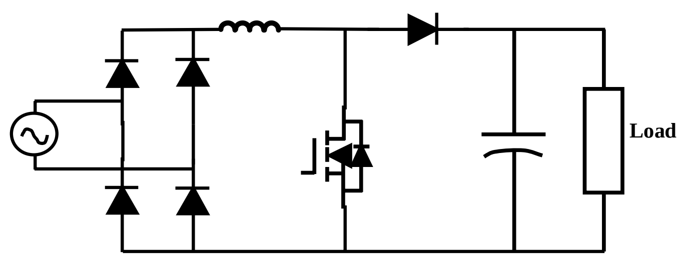

Fig. 7. Single switch boost PFC circuit.

III. CONVERTER LEVEL EVALUATION

To evaluate the performance of CoolMOS™ and SiC Schottky diode for DPS applications, a 1kW single switch CCM PFC circuit is built, as shown in Fig. 7. No any snubber circuit is implemented during the test. Two MOSFETs are paralleled to ensure the enough thermal handling capability at 90 Vac of low line input. The switching frequency is selected to be about 100 kHz and the output voltage is regulated at 390 Vdc.

The efficiency comparison of different combinations of the devices is shown in Fig. 8. It is clear that the CoolMOS™ and the SiC diode can achieve more than 4% efficiency increase, as compared with the conventional devices. From the switching loss evaluation, it is known that the turn-on loss is about twice of the turn-off loss for a pair of the conventional MOSFET and Si diode. However, the SiC diode alone in the PFC circuit achieves less efficiency increase compared with the combination of CoolMOS™ and Si diode. As we know, the CoolMOS™ also achieves smaller Rdson than the normal MOSFET. Therefore, it is reasonable for the CoolMOS™ to realize better efficiency performance than SiC diode. When use the CoolMOS™ with the Si diode, the switch's case temperature reach 70°C at 100Vac of input voltage and the converter almost enters the thermal run-away. There is no possibility for the converter to deliver 1kW at 90Vac of input. In comparison with the incapability of the delivering 1kW power when using either CoolMOS™ or SiC diode, the combination of the CoolMOS™ or the SiC diode offers the high efficiency at 90Vac of input. The switch's case temperature is only 47°C.

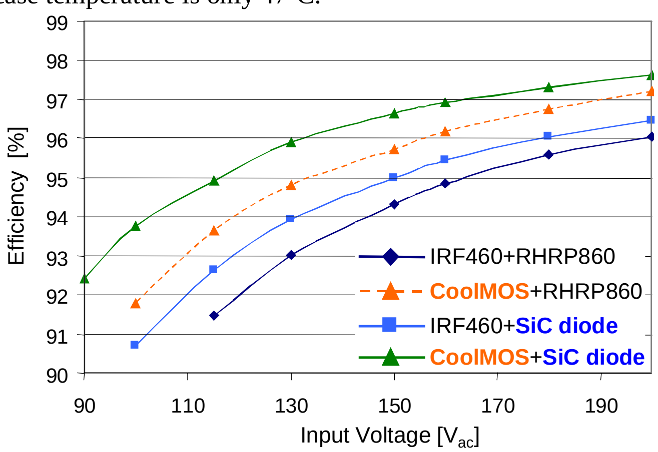

Fig. 8. Efficiency comparison of 1kW PFC circuit using different devices.

Since the SiC diode has no reverse recovery current during switch's turn-on, the voltage ringing across the diode, which often occurs due to snap feature of the conventional diode, is expected to be small. It is interesting to evaluate the EMI performance brought by the SiC and the CoolMOS™. Since the conventional device-based PFC converter can only operate at the input no less than 120Vac, the EMI test is conducted at 120Vac of input. Figure 9 gives the conducted

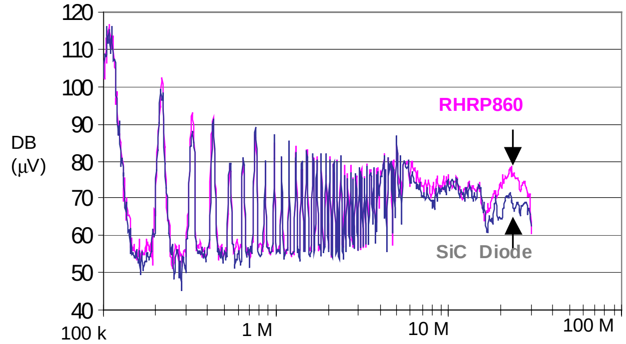

Fig. 9. Total EMI noise of the converter using RHRP860 and SiC diode.

EMI noise comparison between the Si diode and the SiC diode case on the 1kW CCM PFC converter. As seen from Fig. 9, the SiC diode-based converter shows the less EMI noise around 20~30 MHz. The EMI spectra in the rest of frequency region are essentially similar for both SiC and Si diode cases. Further decomposition of EMI noise measurement shows that mainly the common mode noise at 20~30 MHz is reduced with the use of SiC diode.

IV. CONCLUSIONS

In this paper, the CoolMOS™ and SiC Schottky diode were tested at the device level and the converter level. The experimental results show that the CoolMOS™ and the SiC diode can largely increase the efficiency of the front-end PFC for DPS applications for wide range of input voltage. The EMI performance using SiC diode is verified to be no worse than that using Si diode. Therefore, the evaluation results suggest the great possibility of applying CoolMOS™ and SiC diode in the front-end PFC converter.

V. ACKNOWLEDGEMENT

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