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Investigation of Parasitic Turn-ON in Silicon IGBT and Silicon Carbide MOSFET Devices: A Technology Evaluation

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Keywords

« Device application », « Device characterization », « Silicon Carbide (SiC) », « High temperature electronic »

Abstract

This paper investigates the switching rate and temperature dependence of parasitic (false) turn-on of power transistors when switched in power converters implemented in silicon IGBTs and Silicon Carbide (SiC) MOSFETs. It is shown that although high switching rates are normally desirable for minimizing the switching losses, this can result in shoot-through arm currents due to the combination of a Miller capacitance and high *dV/dt*. The power losses arising from this can be significantly larger than the normal switching losses since the device will still be blocking a considerable voltage. Even though SiC MOSFETs have a significantly smaller Miller capacitance compared with silicon IGBTs, this problem is no less of an issue due to higher switching speeds and lower threshold voltages. Additionally it is seen that the overshoot current increases with temperatures due to the negative temperature coefficient of the threshold voltage in both device technologies. Various solutions to overcome this have been analyzed for both device technologies. It is seen that the effectiveness of the mitigation techniques differs, and in general due to the lower threshold voltage of the SiC device, the solutions proposed are less effective.

I. Introduction

In 3-phase power inverters or synchronous DC converters, power devices are employed in half bridge legs. Ideally it is expected that each device switches individually without affecting the other device in the same phase, however in reality there is some electrical interference between the devices [1,2]. During the turn-on transient of the high-side device in power module leg, the DC link voltage drops on the lower device with a rate corresponding to the *dV/dt* of the top device. This *dV/dt* causes a current to flow through the Miller capacitance of the low-side device [3]. The current will flow through the internal and external gate resistances of the device and will induce a voltage on the gate of the low device [4]. If this induced voltage is higher than the threshold voltage of the low device, the low side device is unintentionally switched on thereby resulting in a short-circuit of the DC link [5]. The implication is that both devices are in the on-state while a significant voltage is applied on the DC link of the module, resulting in a significant shoot-through current. The level of this current depends on different factors such as the threshold voltage of the device, the parasitic induced voltage, the ambient temperature and performance of the device with low gate voltages. The induced voltage also depends on the size of the Miller capacitance and the gate resistance on the device gate [6]. This paper presents a systematic comparative analysis of this phenomenon for silicon IGBTs and SiC MOSFETs and investigates how effective the solutions are for both technologies at different temperatures.

II. Investigation of the Induced Voltage and the Shoot-through Current

To investigate the parasitic turn-on of the power devices, a dedicated test rig has been designed and equipped with a hot plate for setting the case temperatures of the power module as shown in Fig. 1. Two devices are used for comparison in this study. A silicon IGBT half bridge module with datasheet number DM2G100SH12AE and a SiC MOSFET half bridge module with datasheet number CAS100H12AM1. Both devices are of the same voltage and current ratings (1.2kV and ~150-160 A in 25 °C). The Miller capacitance of the Si-IGBT module is 0.34 nF while the Miller capacitance of the SiC-module is 0.037 nF, nearly nine times smaller. The threshold voltage of the Si-IGBT module is significantly higher with a value of 5 to 8 Volts compared with only 2 Volts in the SiC module. The applied voltage in the measurements is set at 650 V and the load has been set to 500 Ω with a power rating of 1 kW.

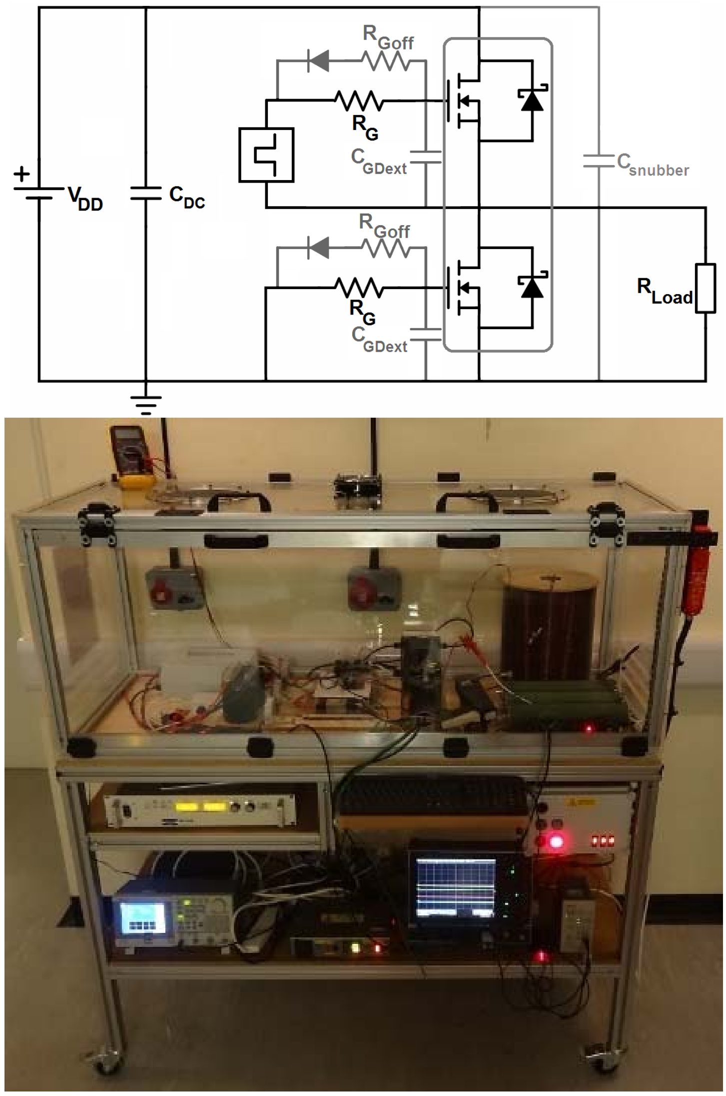

Fig.1. The schematic and actual the test rig used to investigate the parasitic turn-ON behavior.

As can be seen in Fig.2, both modules have been opened up to measure the exact size of the power devices. Fig. 3 shows a picture of the opened modules with the power devices exposed.

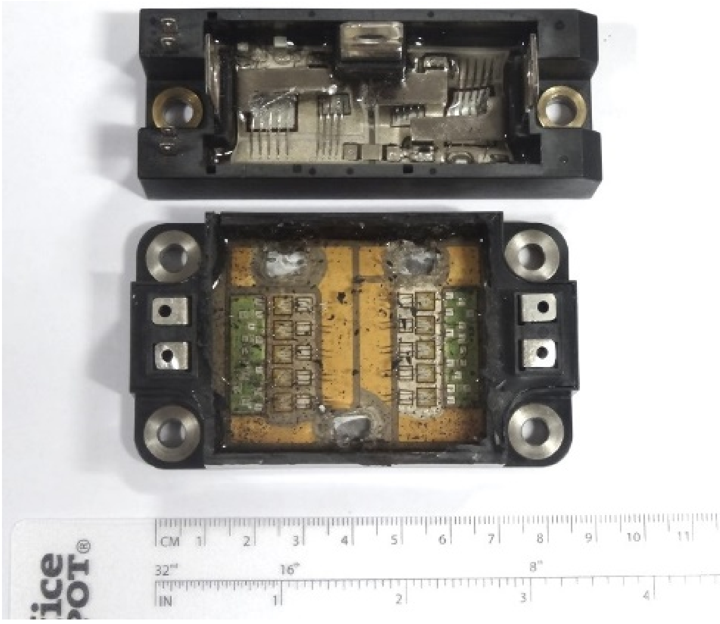

Fig.2. Comparison of the die size and structure of the Silicon IGBT and SiC MOSFET power modules.

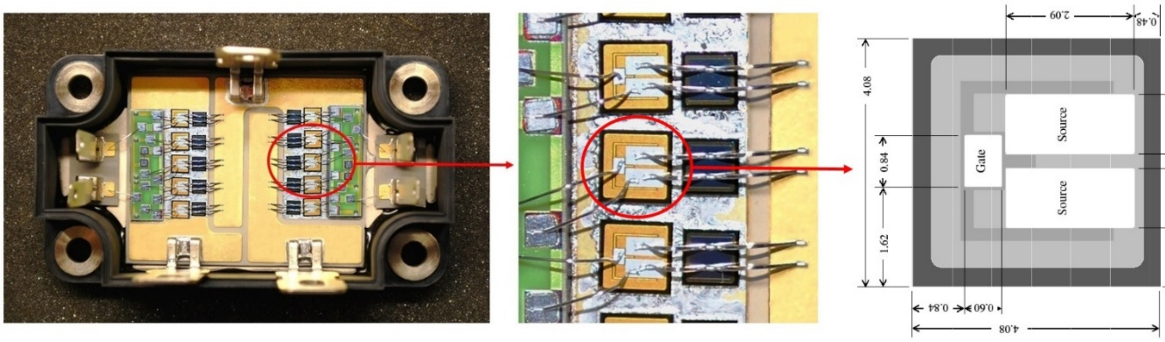

Fig.3. The die size and die numbers of the SiC module.

A closer look at the SiC die structure in Fig.3 (picture by the manufacturer) shows the exact die dimensions of all 5 dies per device [7]. Therefore, using die dimensions, the die size of the total SiC device can be easily calculated as: 5 x 4.08 x 4.08 = 83.24 $mm^2 \approx 0.83\ cm^2$. However, with regard to the Silicon IGBT module, estimation of the Silicon die dimensions requires approximate measurements since it has not been provided by the manufacturer. Looking at Fig. 2, it is can be seen that unlike the SiC module where there are 5 dies in parallel are required to meet the current rating, the Si-IGBT module is comprised of a single die per device. The dimensions of the die are measured as approximately 10.5 by 10 millimeters. Therefore, the die area can be estimated as approximately 105 mm^2 (1.05 cm^2) which is in the expected range; i.e. as the datasheet of ABB devices in [8].

To investigate the impact of the switching rate on the induced voltage and shoot-through current, the top side device is switched with high switching rate (coupled with a low gate resistance of 10 Ω) while the gate resistance on the low side device is varied between 10 Ω to 100 Ω. As can be seen in Fig. 4, the induced gate voltage has increased up to 14 V, which is well above the threshold voltage of the device, thereby causing a significant shoot-through current. This peak shoot-through current can be as much as 80 A. Fig. 4 shows that increasing the low side gate resistance increases the duration of the induced gate voltage transient thereby resulting in a higher duration of the shoot-through current. Therefore, the simultaneous increase of the induced gate voltage and its longer duration causes high amplitude of shoot-through current flowing through the device for a long period of time. This, in turn, causes a significant reliability issue for the performance of the device, as the junction of the device can easily over-heat and consequently fail.

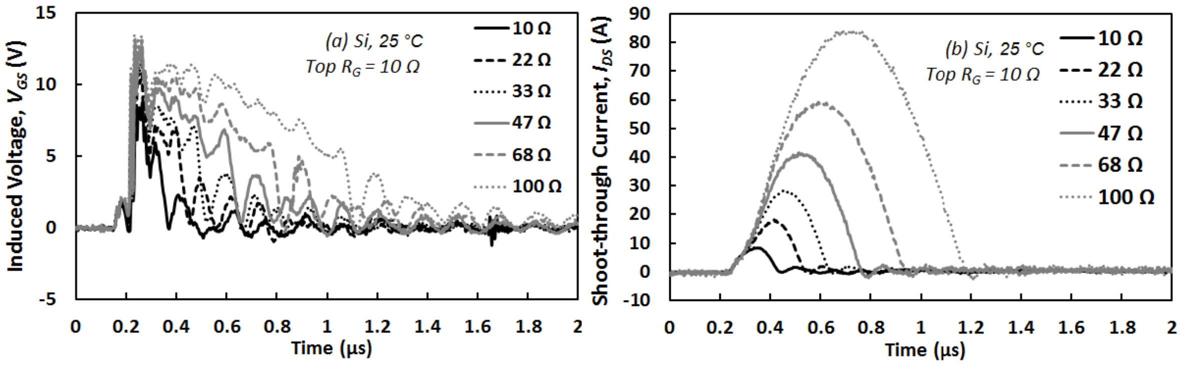

Fig.4. The induced Parasitic voltage and shoot-through current on Silicon IGBT with upper device switching with 10 Ω and lower device connected to a range of resistance varying between 10 Ω to 100 Ω. Note the induced voltage to reach a peak of 14 volt and shoot-through current reaches close to 80 A, resulting in significant stress on low side device.

Likewise, in the SiC device, the amplitude of the shoot through current and duration of the induced voltage increases with the low side gate resistance as shown in Fig. 5(a) and 5(b). It should be noted that although the Miller capacitance of the SiC devices is significantly smaller than that of silicon IGBTs, the lower threshold voltage and higher *dV/dt* imposed on the device has contributed significantly to the high shoot-through current. The oscillations occurring in the measurements at low gate resistances (high switching speeds) are due to the ringing of the antiparallel SiC Schottky diode in the bottom device which in turn increases with the switching rate [9,10].

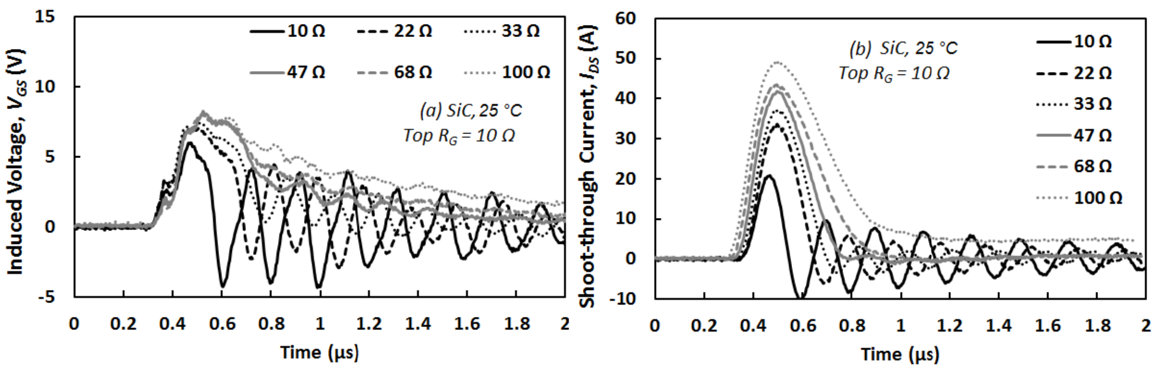

Fig.5. The induced Parasitic voltage and shoot-through current on Silicon Carbide MOSFET with upper device switching with 10 Ω and lower device connected to a range of resistance varying between 10 Ω to 100 Ω. Note the induced voltage to reach a peak of 8 V and shoot-through current to over 40 A, due to lower threshold voltage.

Fig.6 shows a 3D schematic of the shoot-through energy density as a result of the simultaneous transient voltage (which is equal to the voltage on the load) and the shoot-through current. It can be seen that the SiC device initially exhibits a higher shoot-through energy density compared with the silicon device, however its rate of change with gate resistance is lower. Therefore, as the gate resistance on the bottom device is increased, the shoot-through energy density of the Silicon device eventually increases beyond that of the SiC device. This goes back to the difference between Fig.4(b) and Fig.5(b), where the rate of change of the shoot-through current with switching speed in the Silicon device is higher.

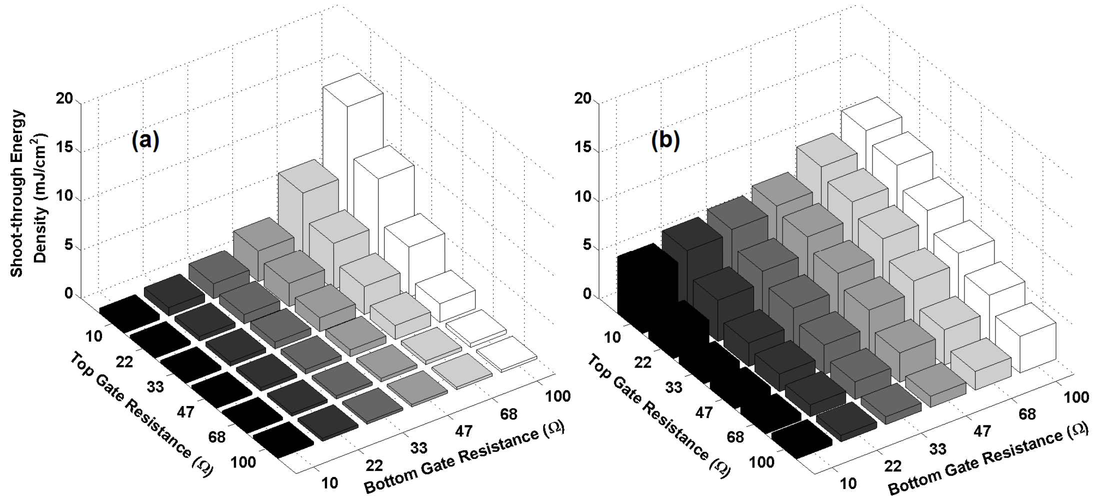

Fig.6. Comparison of the shoot-through energy density of the devices when different gate resistances ranging from 10 to 100 Ω are connected to the top and bottom devices in (a) the Silicon-IGBT device and (b) the SiC-MOSFET device.

The impact of the temperature on this problem is also very significant. It can be seen from Fig. 7(a) and 7(b) that increasing the temperature from room temperature to 120 °C in three steps of 30 °C in Silicon IGBT, the shoot-through current of the combination of gate resistances with values of 10 Ω on the top device and 100 Ω on the bottom device is increased from 80 A to 130 A. The change in the parasitic induced voltage is minimal (and is probably due to the change in Miller capacitance of the device), however the main contribution factor is the decrease of the threshold voltage with temperature. It should be noted that in most power devices, the rated currents reduce with increasing temperature. For example, in the case of the Silicon-IGBT module, the rating is 150 A at 25 °C and 100 at 80 °C. Therefore, the lower rating of the device, coupled with higher shoot-through current flowing through it causes a significant reliability issue and can potentially lead to destruction of the device.

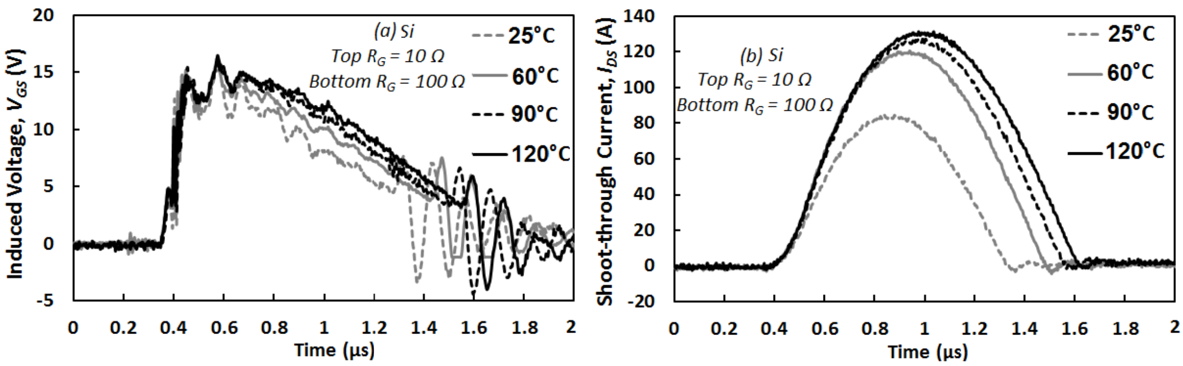

Fig.7. The induced parasitic voltage and shoot-through current on Silicon IGBT in room temperature and to up to 120°C with upper device switching with 10 Ω and lower device connected to 100 Ω.

The SiC MOSFET also behaves in a similar manner to the silicon IGBT, with a minimal change in the parasitic induced voltage and significant rise in the shoot-through current with temperature. It is seen in Fig.8 that in the 10 Ω -100 Ω combination of R_G, the increase of temperature has increased the shoot-through current from 40 A to 60 A. The rate of increase in the shoot-through current with temperature is lower compared with the silicon IGBT as a result of lower variation of the threshold voltage with temperature. This can easily be confirmed by checking the datasheets of the devices, where the change of threshold voltage in the SiC modules is less than 0.7 V for an increase in temperature from 25 °C to 150 °C while the change in the threshold voltage of the Silicon-IGBT device is around 3 V.

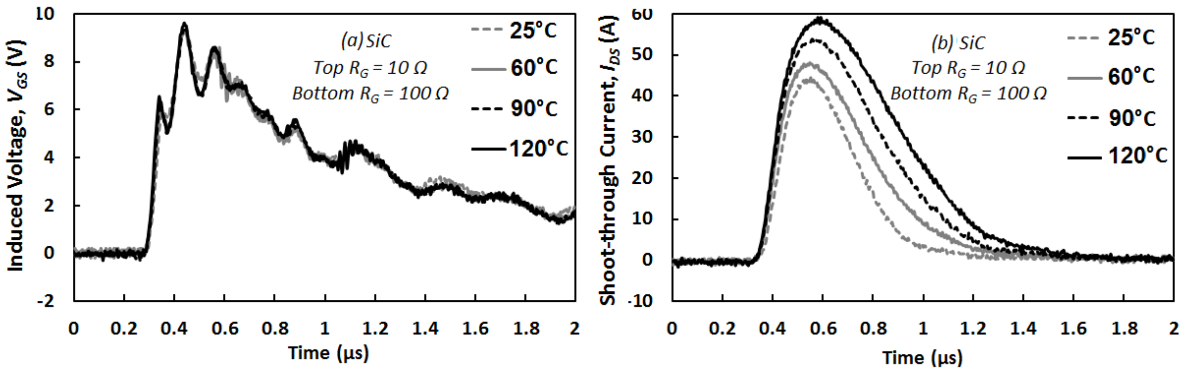

Fig.8. The induced parasitic voltage and shoot-through current on Silicon Carbide MOSFET in a range of temperatures from room temperature to up to 120°C with upper device switching with 10 Ω and lower device connected to a 100 Ω resistance. The significant rise in the shoot-through current is due to the lower threshold voltage.

Fig.9 shows the 3D representation of the shoot-through energy density of both the (a) Silicon-IGBT module and (b) the SiC-MOSFET module when the top device in all cases is switched with a 10 Ω gate resistance, and the gate resistance on the bottom device along with the temperature of the module is changed. As seen, the change of the shoot-though energy density in the Silicon device with temperature is relatively rapid, especially in higher gate resistances, whereas the slope of the chance for the SiC device in (b) is milder. As explained earlier, this is due to the higher stability of the threshold voltage of the SiC device compared with the Silicon device. Therefore, as can be confirmed by Fig. 6 and Fig. 9, the overall rate of change of shoot-through current and energy density with the switching rate and temperature is higher for the Silicon device compared with the SiC device.

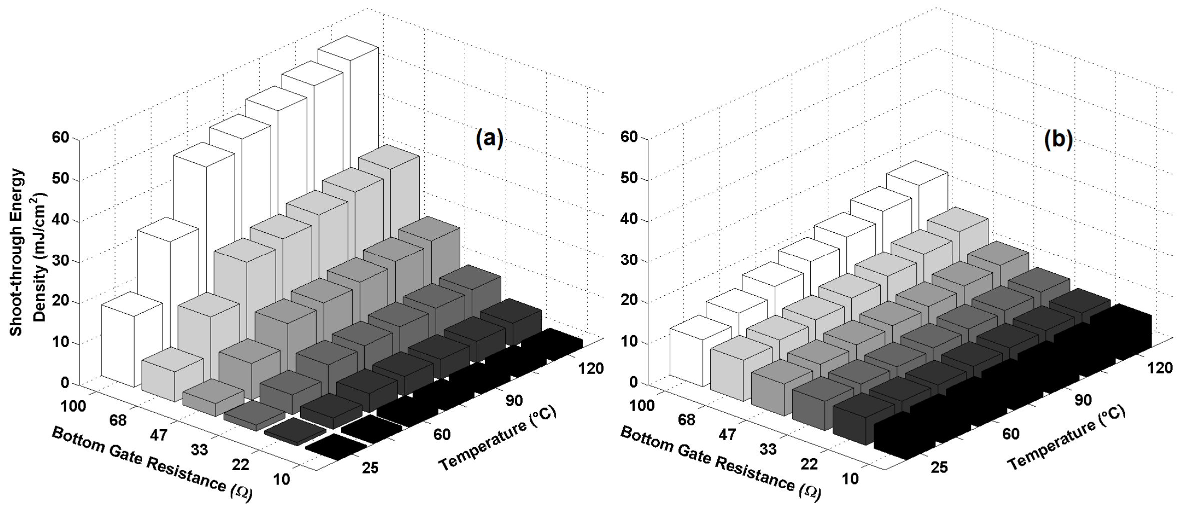

Fig.9. The shoot-through energy density of both devices is increasing with temperature, where it can be seen that the increase of the shoot-through energy with temperature in (a) silicon-IGBT device is faster than that of (b) SiC-MOSFET device.

III. Solutions to Parasitic Turn-On

To overcome the parasitic induced voltage and the consequent shoot-through current, different approaches have been developed. These include the use of a bipolar gate driver with a negative bias, use of two resistive paths for the turn-on and turn-off, use of gate-source capacitance connected in parallel to the gate resistance and using the snubber capacitor to prevent high *dV/dt*. These solutions are implemented on both the Silicon IGBT and SiC MOSFET modules. Initially, a snubber capacitor is applied to the DC link voltage to damp the oscillations seen in the DC link. As shown in Fig.10, the DC link voltage had considerable fluctuations with SiC device due to the oscillations in SiC Schottky diode, however the snubber capacitor damped the oscillations.

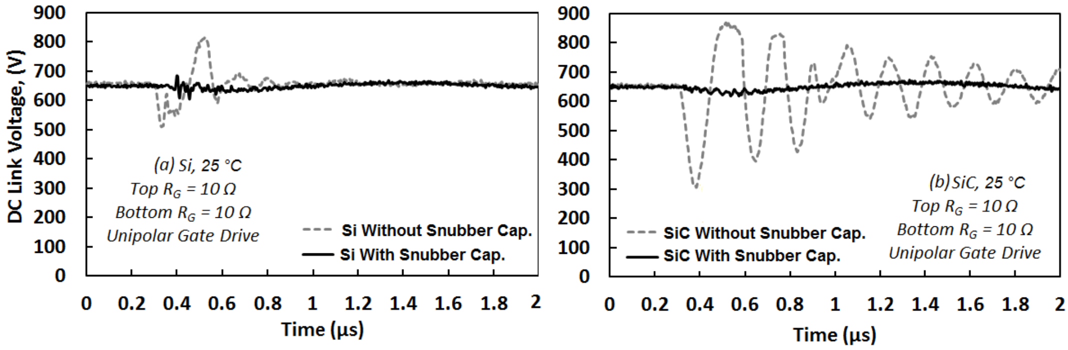

Fig.10. The DC-link voltage of silicon and SiC device corrected using a 100nF snubber capacitor.

As seen in Fig.10, the importance of the snubber capacitor in the case of the SiC MOSFET module is evident from comparing the characteristics with and without the snubber capacitor. The SiC unipolar devices, due to high switching rates coupled with the parasitic capacitance and inductance of the test rig, pose a major reliability issue in terms of oscillations in the device voltage, which in turn can be mirrored on the DC link voltage. The presence of a small snubber capacitor can damp these oscillations and consequently, as seen in Fig.10, remove the ringing from the DC link voltage. Hence, compared to the case of silicon bipolar devices, the SiC unipolar devices always require a snubber capacitor connected on the modules.

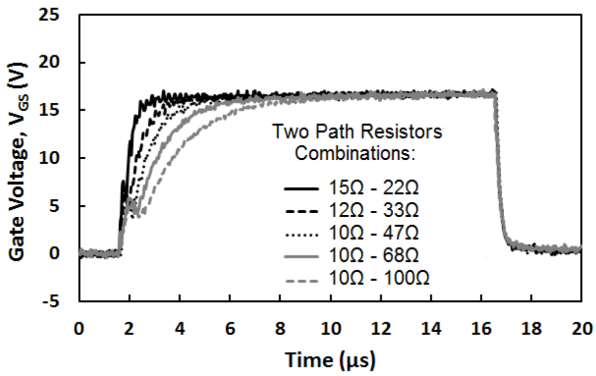

Fig.11. The two-resistive paths slowing down the turn-on while keeping the turn-off in the same rate.

In addition to use of a bipolar gate driver to bias the gate voltage, another solution to reduce the possibility of parasitic turn-on is to use two resistive paths as shown in the Fig.11. This method reduces the *dV/dt* on turn-on while keeping the turn-off *dV/dt* constant. As seen in Fig. 12, using a bipolar gate driver with a negative bias of 5 V in Silicon IGBT device has significantly reduced the shoot-through current. This is due to the fact that the induced voltage is not surpassing the threshold voltage with a significant margin. However the lower threshold voltage at high temperatures is still problematic. To overcome this, the two resistive paths proposed in Fig.11 can be applied to avoid the Miller capacitance current flowing through a high gate resistance. This is also shown in Fig. 12.

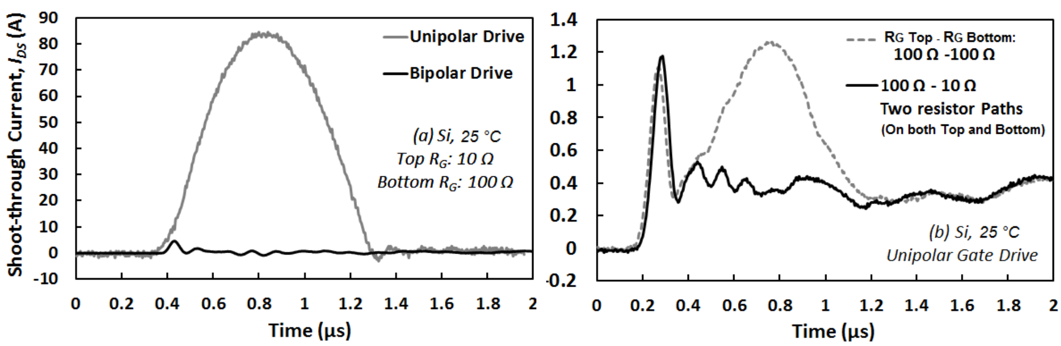

Fig.12. Solutions for the correction of the shoot-through current for the Silicon IGBT.

Similarly, the shoot-through current in SiC device has been reduced by using the bipolar gate driver as shown in Fig. 13, however the reduction is not as effective as is the case for the silicon IGBT.

Hence, in spite of the bipolar gate drive, there is still a significant shoot-through current of up to 20 A. This is mainly due to lower threshold voltage and larger internal gate resistance of the SiC device. Therefore to suppress the peak, the two resistive paths are still essential for the SiC devices, even when the devices are operating at room temperature. This can be accounted for as another major difference between the SiC MOSFET module and Silicon IGBT module in terms of parasitic turn-on.

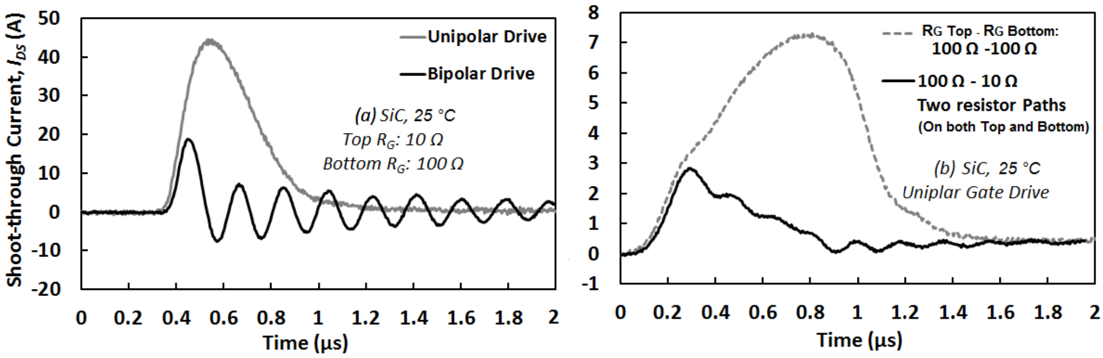

Fig.13. Solutions for the correction of the shoot-through current as a result of the induced voltage for the Silicon Carbide MOSFET as use of a bipolar driver and two path resistors.

IV. Conclusion

The SiC MOSFETs exhibits lower shoot-though currents at room temperature because of a lower Miller capacitance in spite of having a higher *dV/dt* and lower threshold voltage. SiC MOSFETs also show a higher stability in shoot-through currents and energy density against the change of the gate resistances. Furthermore, the SiC MOSFET module exhibits a more stable shoot-through current and energy density as a function of temperature variation due to the lower temperature coefficient of the threshold voltages in the devices. However the proposed solutions are more effective for the silicon IGBT modules whereas for the SiC MOSFET modules, the shoot-through currents are not completely suppressed. This is because the lower threshold voltage of the SiC device means that the devices are susceptible to parasitic turn-on even when the induced voltages are low. Furthermore, for the SiC MOSFET module, presence of the snubber capacitor on the module is critical for suppressing the voltage oscillations on the DC link that arise due to the ringing of the Schottky diode. Hence, even though the SiC device exhibits less shoot-through currents, suppressing them is more challenging.

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