Comparative Analysis of False Turn-ON in Silicon Bipolar and SiC Unipolar Power Devices

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***Abstract*— The temperature and *dV/dt* dependence of false turn-ON has been analyzed for Silicon Carbide (SiC) Unipolar and Silicon Bipolar transistors, with switching rates varied by the gate resistances while temperature is varied by a hot plate connected to power modules. Self-heating is also investigated by measuring the temperature rise of the modules at high switching frequencies (8 kHz). This has resulted in continuous false turn-on occurrence in the device which has increased the device junction temperature significantly due to the repetitive shoot-through energy. Temperature rises of up to 150°C within just a few minutes have been observed as a result of repetitive shoot-through currents at high frequencies. To understand the impact of different mitigation techniques, the temperature rise is also observed after applying the corrections. It is seen that using the correction methods in the devices reduces the temperature rise significantly and therefore is vital for the applications of both Silicon and SiC devices.**

Keywords*— Silicon Carbide, MOSFETs, False turn-ON, Half Bridge, Temperature

I. Introduction

Half bridge topologies are the simplest, though the most popular topology of semiconductor devices in converter applications. The power devices in this topology often switch in turn, with respect to certain defined dead-times. In the past couple of years, silicon IGBT devices have been the most popular choice of semiconductor devices in these converters for medium voltage applications. However the recent development of SiC devices have also opened up new avenues in converter applications where high switching speeds are required. However, high switching speeds have certain disadvantages which should be investigated. An example could be the repetitive occurrence of false turn-on in power devices, which can lead to excessive temperature rises, thermal runaway and eventually destruction of the device. In a half bridge topology, when the high side device turns on, the DC link voltage drops on the low side device, imposing a significant *dV/dt* which in turn coupled with the miller capacitance and gate resistance of the low side device, will induce a voltage to the gate of the low device [1]. This voltage drop is rapid and its speed depends on many factors, most importantly the gate resistance connected to the gate of the high side device. The induced voltage on the low side device can exceed the threshold voltage of the devices, especially in case of SiC MOSFETs, resulting in a partial turn-on. This causes a semi-short-circuit condition thereby allowing a shoot-through current to flow through the devices [2]. This can have a significant reliability impact [3]. To investigate this problem, measurements have been done to understand how the false turn-on occurs in different operating conditions and how mitigation techniques can reduce its impact. Additionally, the self-heating problem has been investigated to understand how false turn-on contributes to temperature stresses and how the mitigation technique can reduce the self-heating. In this paper, two similarly-rated silicon and SiC power modules are used to perform the measurements with different switching rates and the shoot-through energy is analyzed as a function of temperature. Using a thermal camera, the temperature rise of the modules is also studied before and after the correction methods are applied.

II. The Measurements Set-Up

Fig. 1 shows the schematic of the measurement test rig where the half bridge topology and possible correction methods are shown and Fig.2 shows the experimental set up where the silicon bipolar (DM2G100SH12AE) and SiC unipolar (CAS100H12AM1) modules are tested with a range of external R_G connected on the gate drivers on both modules. An electric hot-plate is connected to the heat sink of the modules and is used to vary the junction temperature of the device under test. As seen in Fig.1, both the high side and low side devices are connected to a gate resistance. The gate resistances in these measurements are varied between 10 to 100 Ω. This is done for two purposes as follows.

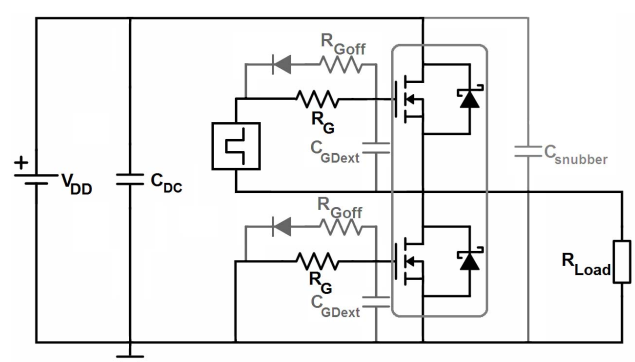

Fig. 1. The schematic of the test rig set-up.

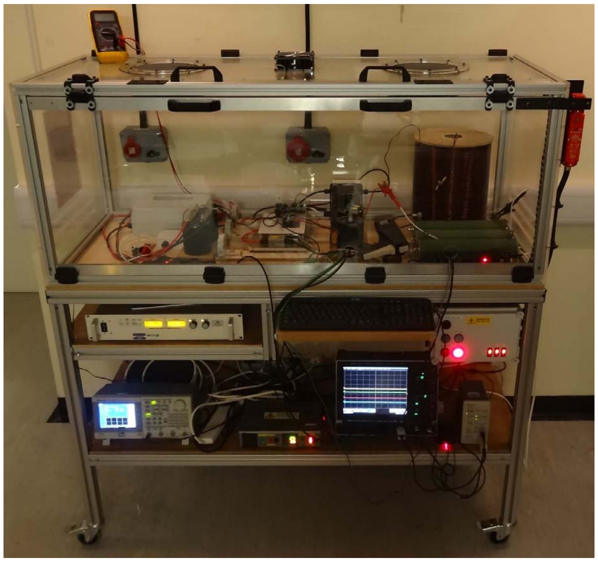

Fig. 2. The experimental measurement set-up to analyze the false turn-ON issue in Silicon and SiC power devices.

The gate resistance connected to the high side device is varied within this range to provide a full control over the applied *dV/dt* on the low side device. This gives the opportunity to investigate how a false turn-on can occur when devices are switched at high and low switching rates. This approach has also been used in previous publications such as [4] where R_G in the range of 100 Ω was used to intentionally slow down the device. The gate resistance connected to the low side device is varied within this range to simulate the cases where a significantly higher *dV/dt* is applied, or where a device with higher die size and higher miller capacitance is used. The parasitic gate voltage on the low side device is given by the following equation

$$V_{GS} = R_G C_{GD} \frac{dV_{DS}}{dt} \tag{1}$$

where R_G is the gate resistance and C_{GD} is the miller capacitance. Hence, increasing the low side R_G to resistances as high as 100 Ω can help to emulate the impact of high switching rate and large miller capacitances. Fig. 3(a) shows the parasitic gate voltage on the low side silicon IGBT for different R_G on the low side device while the high side device R_G is constant at 10 Ω. Fig. 3(b) shows the corresponding shoot-through current through the silicon IGBT module for the different R_G on the low side device. As can be seen in Fig. 3, increasing the R_G used to switch the low side device is increasing the induced voltage both in terms of amplitude and the duration period. This in turn results in an increase in the shoot-through current from 5 to 80 A.

Likewise, Fig. 4(a) shows the impact of increasing the R_G on the parasitic gate voltage on the low side device in the SiC MOSFET module with the high side R_G held constant at 10 Ω. Fig. 4(b) shows the corresponding shoot-through current where it can be seen that the amplitude and duration has increased from 20 A to approximately 50 A. As seen in Fig. 4, the low side gate resistance used to switch the low side device has caused ringing in the Schottky diode [5, 6]. This ringing in the voltage across the low side SiC MOSFET/Schottky diode has been transmitted through the miller capacitance to the low side parasitic gate voltage. Hence, the ringing appears in the parasitic gate voltage as well as in the shoot-through current.

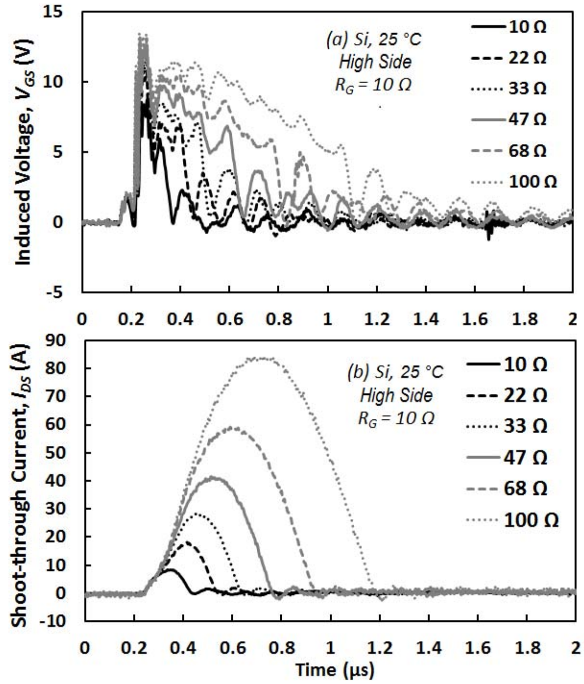

Fig. 3(a). The induced parasitic voltage (b) Corresponding shoot-through current in the Si IGBT module for different low side R_G with the high side R_G=10 Ω.

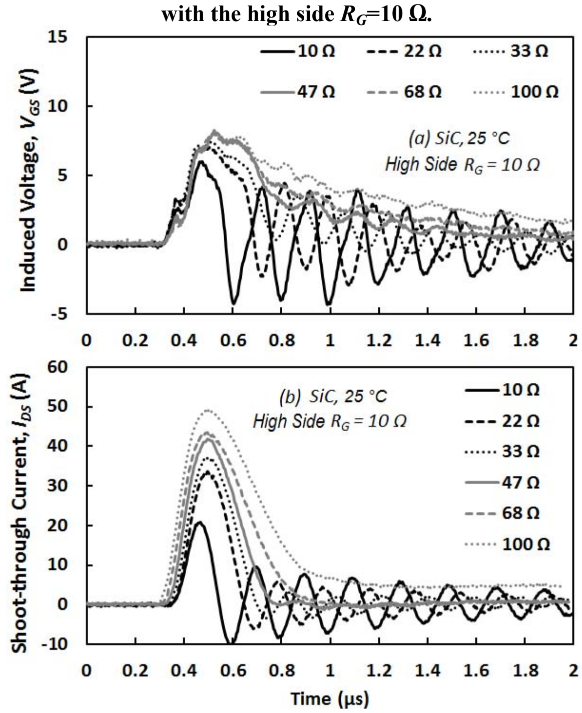

Fig. 4(a). The induced parasitic voltage (b) Corresponding shoot-through current in the SiC MOSFET module for different low side R_G with the high side R_G=10 Ω.

Fig. 5(a) shows the impact of temperature rise on the induced voltage and Fig. 5(b) shows similar for the shoot-through current of the silicon bipolar device. In Fig. 5, the high side and low side devices are switched with R_G=100 Ω. In this case, to avoid self-heating and to keep the temperature at the same level during the measurements, the switching frequency of the circuit has been reduced significantly to only 100 Hz. This reduces the recurrence of shoot-through significantly and hence due to the presence of a temperature monitoring system and a metal plate connected to the base of the module, the temperature stays constant in measurements.

As can be seen in Fig. 5, the increase in temperature has had a minor effect on the induced voltage level. However, it has significantly increased the shoot-through current due to the reduced threshold voltage of the device. A similar trend is also seen in Fig. 6 where the impact of temperature rise on the SiC MOSFET module is shown. Fig. 6(a) shows that the temperature has no impact on the parasitic gate voltage whereas Fig. 6(b) shows that temperature significantly increases the shoot-through current. For both technologies, the shoot-through current increases with temperature because of the negative temperature coefficient of the threshold voltage which means that the short circuit has a higher peak and duration. SiC devices normally have lower threshold voltages due to low effective p-body doping and the threshold voltage also further reduces with an increase in temperature (due to the increase in the intrinsic carrier concentration in the channel). This results in the increase of the shoot-through current with the same induced voltage since the difference between the induced voltage and the threshold voltage is now higher with increased temperature.

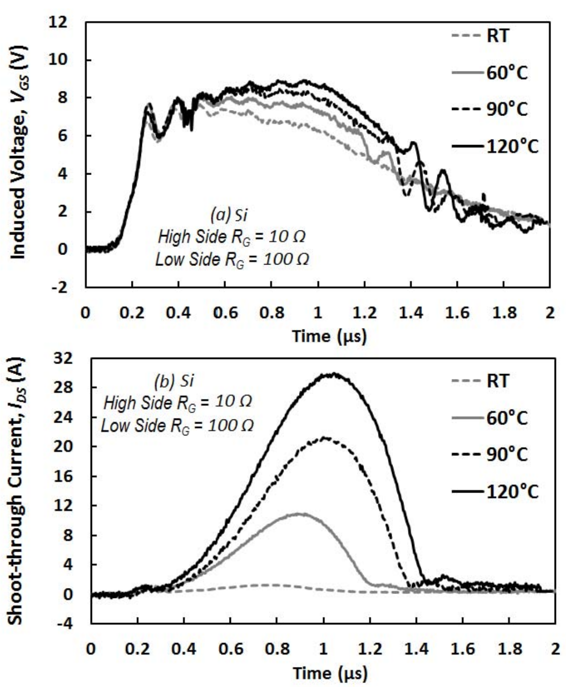

Fig. 5(a). The induced parasitic voltage (b) Corresponding shoot-through current in the Si IGBT module with high and low side R_G=100 Ω at different temperatures.

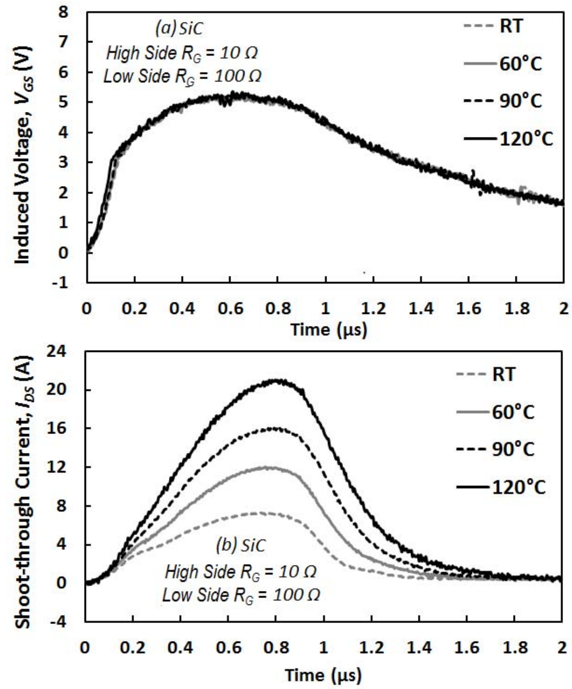

Fig. 6(a). The induced parasitic voltage (b) Corresponding shoot-through current in the SiC MOSFET module with high and low side R_G=100 Ω at different temperatures.

III. Effectiveness of The Correction Methods Applied on the Devices

To counter the false turn-on, different correction methods can be used both in the circuit and also on the gate drive. For example, using a bipolar gate driver is normally expected to correct the issue since it increases the offset between the induced voltage and the threshold voltage. In these measurements, -5 V is used. This is because in most cases, the induced voltage is in the range of a few volts hence, a negative bias of -5 V should negate the impact of the induced voltage. This, although is effective in IGBT devices, does not fully counter the issue in SiC devices since the threshold voltage is lower (at around 2 Volts) thereby making false turn-on still possible. Additionally, the gate oxide of the SiC devices is not as robust as that in silicon [7] therefore imposing is an upper limit on the level of negative voltage applicable on the device. Although the issue can also be countered with higher negative values (i.e. -10 V), however this causes a constant negative voltage to be applied to the gate of the device which will have its own reliability issues regarding gate oxide integrity [8]. This limit has also been confirmed on the datasheet of the devices.

Another shoot-through mitigation technique comprises of using different resistive paths for the turn-on and turn-off transients [9]. This method seems more effective with fewer complexities compared to design of a bipolar gate driver as it slows down the device on turn-ON and reduces the imposed *dV/dt* on the low side device. It must be noted that due to oscillations of the SiC device, use of snubber capacitor is also preferable.

A. Snubber Capacitor

The snubber capacitor is a parallel capacitor in the module which charges and discharges as the voltage on the device changes. In the instant that there is an increase or decrease of the DC link voltage, this change will be countered by the charging/discharging of the snubber capacitor thereby stabilizing the DC link voltage. Fig. 7(a) shows the measured DC link voltage during shoot-through for the silicon IGBT module while Fig. 7(b) shows that of the SiC MOSFET module. As can be seen in Fig. 7 (a), at the time of the false turn-on occurrence, there is instability in the DC link voltage. This happens because the shoot-through current is derived from the charge in the DC link capacitors. The DC link capacitor subsequently tries to recharge through the voltage on the DC link which causes the voltage undershoot/overshoot. The problem is more severe in the case of SiC device due to the ringing imposed by the low side SiC Schottky diode as is explained in [5]. The snubber capacitor only reduces the consequences of the false turn-on on the DC link voltage and does not remove the shoot-through current or the induced voltage. However its presence in the case of the SiC module is required for stability of the circuit.

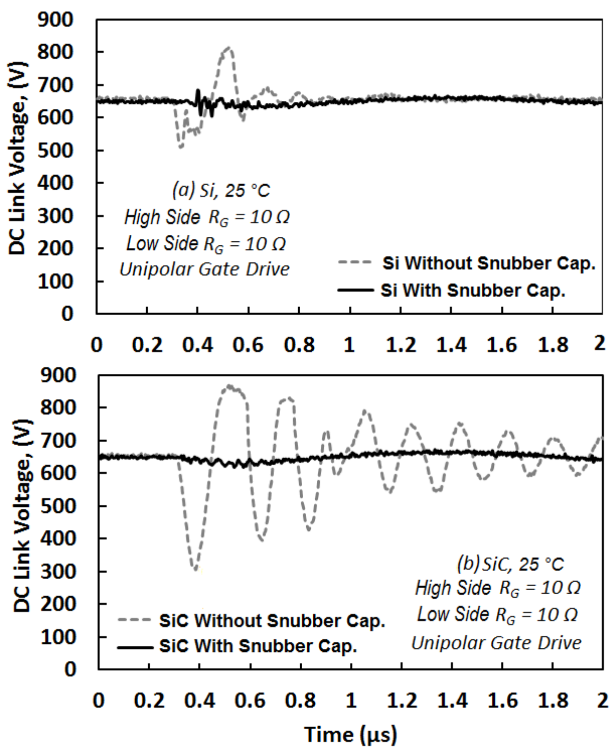

Fig. 7. The DC link voltage of the (a) Si IGBT (b) SiC MOSFET module showing the impact of the snubber capacitor.

B. Bipolar Driver and 2 resistive paths

Fig. 8(a) shows the effect of the bipolar gate driver on the shoot-through current in the silicon IGBT module. Fig. 8(b) shows the effect of using 2 resistive paths on the shoot-through current in the silicon IGBT module. Both measurements were done at 25 °C and it can be seen that the shoot-through current is significantly suppressed for the Si IGBT module. Fig. 9(a) shows the effect of the bipolar gate drive on the shoot-through current in the SiC module where it can be seen that the peak current is reduced, however not as effectively as was the case for the silicon IGBT module in Fig. 8(a). This is because the negative bias was limited to -5V for the SiC devices. Fig. 9(b) shows the effect of the 2 resistive path method on the SiC MOSFET module.

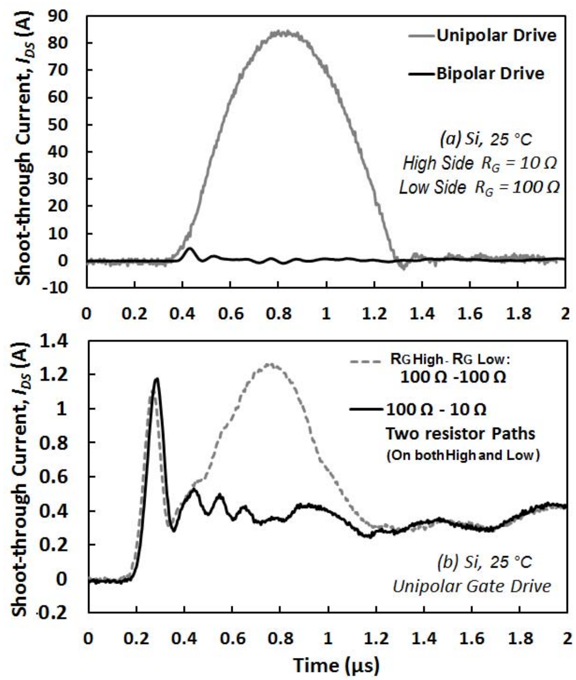

Fig. 8. Shoot through currents in the Si IGBT module with (a) Bipolar gate drive correction (b) 2 resistive path method.

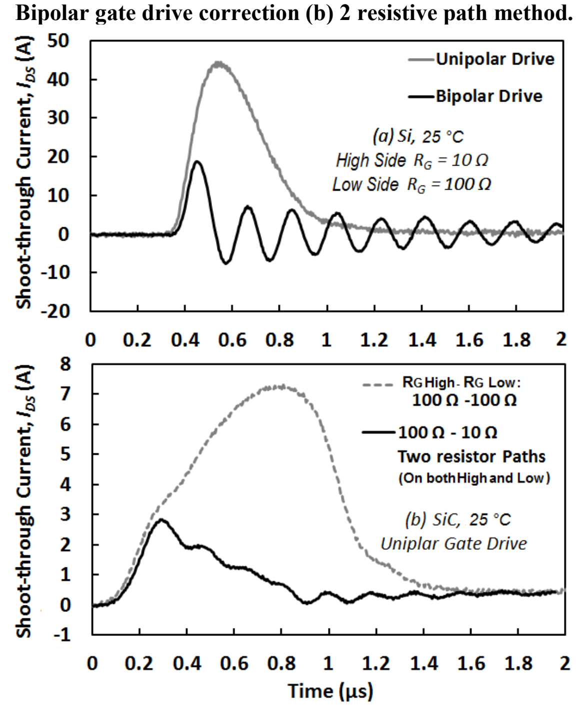

Fig. 9. Shoot through currents in the SiC MOSFET module with (a) Bipolar gate drive correction (b) 2 resistive path method.

IV. TEMPERATURE RISE AS A RESULT OF FALSE TURN-ON IN SIC DEVICES IN A BUCK CONVERTER

The shoot-through energy of the devices can contribute to significant temperature rise in the devices especially at higher switching frequencies. For example, the measurements presented here are done at a voltage of 650 V and with a load resistance of 1 kΩ. This results in a device current equivalent to 0.65 A which is very low for a module rated at 100 A. Hence, the switching energy on its own could not have resulted in a significant temperature rise. However as will be seen in the next section, the temperature rise as a result of the shoot-through energy can be very high. Fig.10 shows the shoot-through energy of the (a) Silicon IGBT module and (b) SiC MOSFET module over a range of gate resistances between 10 to 100 Ω.

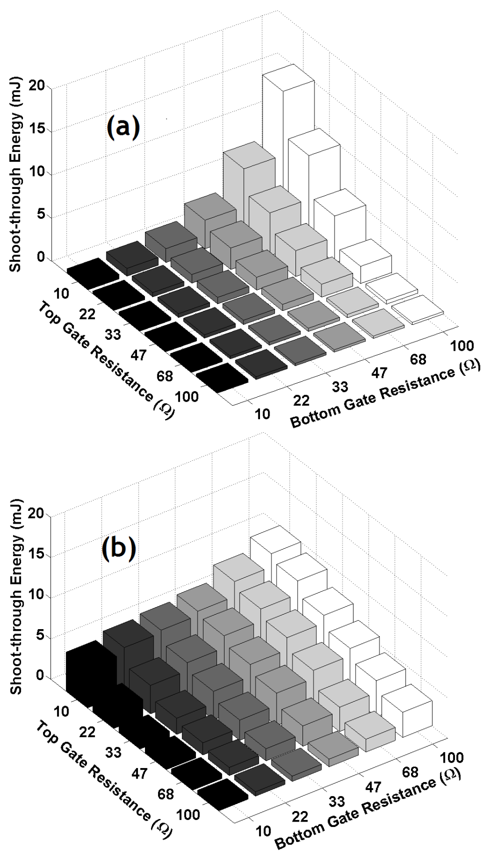

Fig. 10. The measured shoot-through energy as a function of the low side gate resistance and the high side gate resistance in the (a) Silicon IGBT and (b) SiC modules.

Fig. 11 shows the shoot-through energy of the (a) Silicon and (b) SiC device for different gate resistances over temperature. These measurements are made without any of the mitigation techniques for limiting the shoot-through current. A trend of increase of shoot-through energy with temperature is seen in both cases, the slope of which is higher for the Silicon bipolar device.

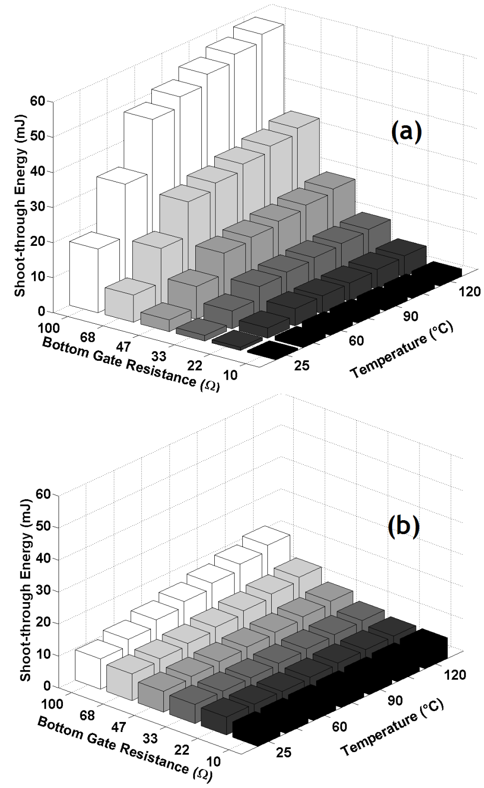

Fig. 11. The measured shoot-through energy as a function of the low side gate resistance and junction temperature in the (a) Silicon IGBT and (b) SiC modules.

Fig. 12(a) shows a thermal camera picture taken of the SiC MOSFET module after 8 minutes of continuous switching at 8 kHz in a buck converter topology with both the high side and low side R_G=10 Ω. A temperature rise of up to 50 °C can be observed in Fig. 12(a). Fig. 12(b) shows a thermal camera picture after 8 minutes of switching at 8 kHz with the high side R_G=10 Ω and the low side R_G=100 Ω. It can be seen in Fig. 12(b) that a temperature rise exceeding 150 °C can be observed in the SiC MOSFET module. The difference in the temperature rise between the 2 measurements is attributable to false turn-ON. This temperature rise is the result of the different shoot-through energies shown in the Fig.10 (b) which also increases when the temperature rises.

Fig.13 shows the impact of lowering the switching rate of the high side device. In Fig. 13(a) the high side device is switched with R_G=10 Ω and the low side device with R_G=100 Ω. In Fig. 13(b), both the high side and low side devices are switched with R_G=100 Ω. It can be seen by comparing the pictures that slowing down the high side device commutation rate reduced the *dV/dt* on low side device thereby causing smaller shoot-through currents resulting in lower shoot-through energy and a smaller temperature rise. This has the disadvantage of slowing down the device and causing higher switching losses. Since high switching rates are preferred in SiC technology, this is not a preferred correction method.

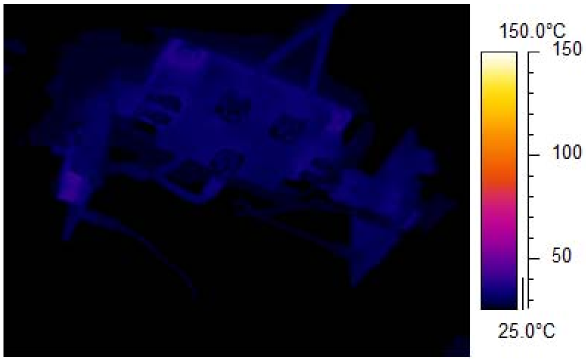

Fig. 12(a). A thermal camera image of the power module switching with the low side and high side R_G at 10 Ω.

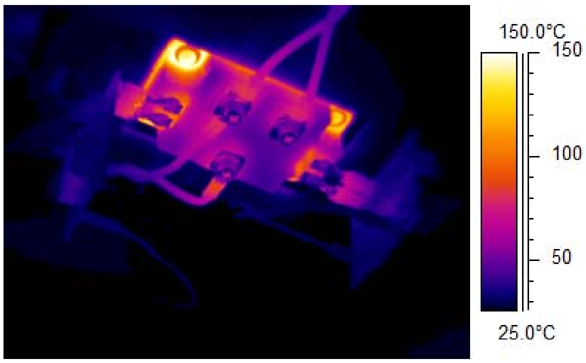

Fig. 12(b). A thermal camera image of the power module switching with the low side at R_G=100 Ω and high side R_G = 10 Ω.

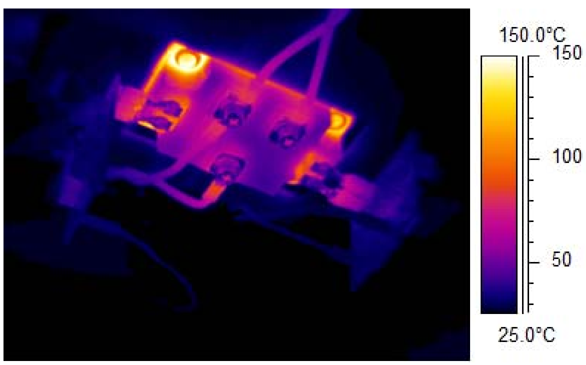

Fig. 13(a). Thermal camera picture of the SiC MOSFET module switched with the low side at R_G=100 Ω and high side R_G = 10 Ω.

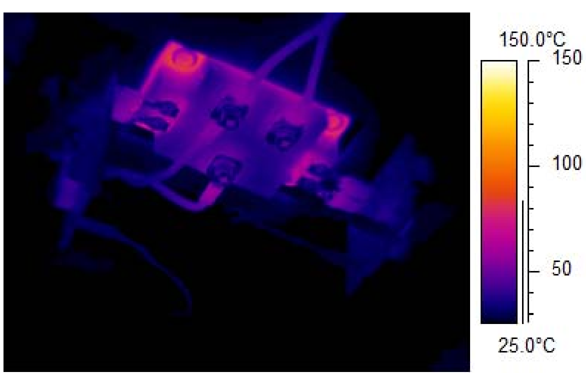

Fig. 13(b). Thermal camera picture of the SiC MOSFET module switched with the low side at R_G=100 Ω and high side R_G = 100 Ω.

As was seen in Fig. 7 previously, there are considerable oscillations associated with the application of SiC power devices. These oscillations, if not dealt with, will cause even higher losses due to overshoots occurring. To counter this, a snubber capacitor must be connected on the DC link connection of the power module, ensuring that the oscillations are effectively removed. This snubber capacitor will reduce the elevated shoot-through energy and will slightly reduce the temperature rise. It should be noted that as was explained earlier, the snubber capacitor does not remove the false turn-on but only reduces its consequences. The impact of using this snubber capacitor can be seen in Fig. 14 where a thermal camera image is shown for the SiC MOSFET module without a snubber capacitor and a module with a snubber capacitor.

Fig. 14(a). Thermal camera image of the SiC MOSFET module without the snubber capacitor when the R_G on the high side device is 10 Ω and on the low device is 100 Ω.

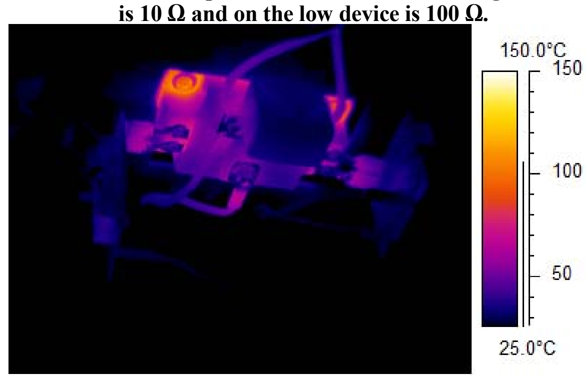

Fig. 14(b). Thermal camera image of the SiC MOSFET module with the snubber capacitor when the R_G on the high side device is 10 Ω and on the low device is 100 Ω.

Fig.15 shows the impact of using the unipolar and bipolar gate drivers on the SiC module where the high side device is switching with 10 Ω and the low side device is connected to a gate resistance of 100 Ω. It is seen that the bipolar gate driver has reduced the impact of the temperature rise on the module as a result of the false turn-on, however this is not a complete mitigation and the temperature rise continues to take place at a slower rate. Hence, should the converter operate for a considerably long period, it will eventually heat up to a significant degree, although later than the case where the unipolar driver is used. The increase of the temperature follows an exponential trend, as increase of the temperature increases the shoot-through current which will further increase the temperature. This positive feedback loop can potentially lead to thermal runaway and the destruction of the device. As a result, the two resistive paths method should also be applied to reduce the possible temperature rise in the SiC module.

Fig. 15(a). Thermal camera image of the SiC MOSFET module switching at 8 kHz with a unipolar gate drive. The high side device R_G = 10 Ω and low side device R_G = 100 Ω.

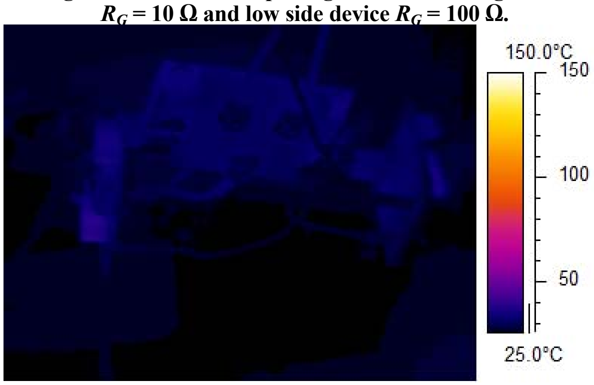

Fig. 15(a). Thermal camera image of the SiC MOSFET module switching at 8 kHz with a bipolar gate drive. The high side device R_G = 10 Ω and low side device R_G = 100 Ω.

As was expected, the two resistive paths solution is also needed to damp the shoot-through current, especially in the case of the SiC MOSFET module. To provide a fair comparison, the thermal images of two cases with gate resistances with a value of 100 Ω are presented in Fig.16 (a) and Fig. 16(b). Fig. 16(a) shows the thermal image of the module with a single resistive path while Fig. 16(b) shows a thermal image of the module switching with 2 resistive paths. As can be seen, using the two resistive paths solution has significantly reduced the temperature rise of the module. Hence it is recommended that in all cases, especially where SiC modules are to be used, the two resistive paths method to be applied along with the use of a bipolar gate driver with a negative value of at least -5 V (in-line with datasheet requirements) and snubber capacitor placed on the DC link connection of the module (here with a values of 100nF).

Fig.17 shows the temperature rise plot of the module base temperature for each of the silicon IGBT and SiC MOSFET modules. As can be seen in Fig.17, increasing the low side gate resistance has increased the rate at which the temperature of the modules rises, while the increase is more uniform in case of SiC compared with the Silicon device.

Fig. 16(a). A thermal camera image of the SiC MOSFET module switching at 8 kHz with a single resistive gate path.

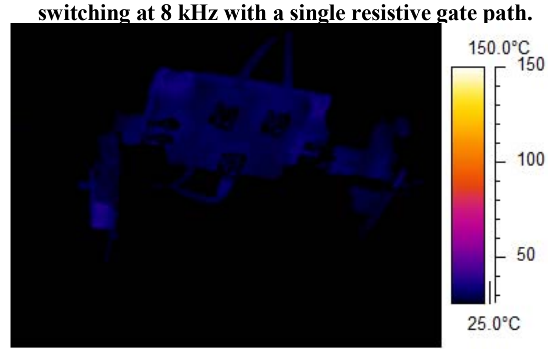

Fig. 16(b). A thermal camera image of the SiC MOSFET module switching at 8 kHz with two resistive gate paths.

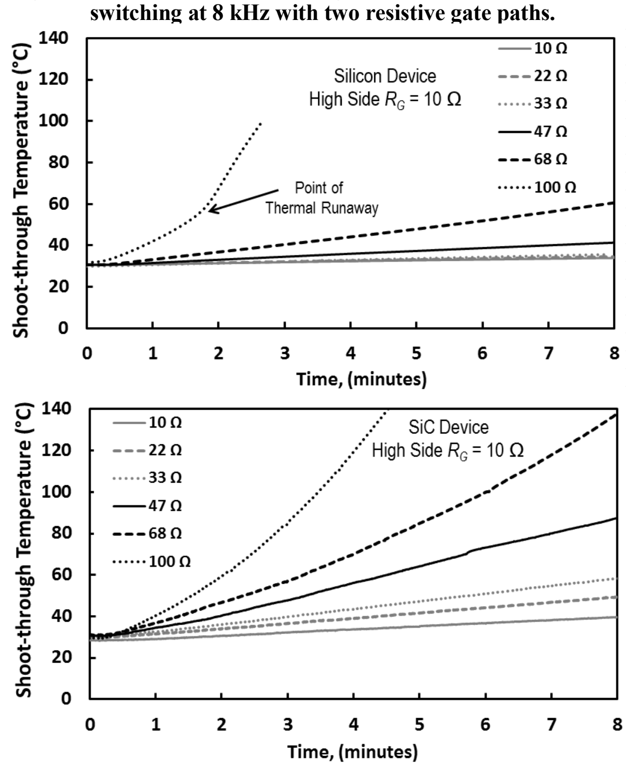

Fig. 17. The temperature rise in the (a) Si IGBT and (b) SiC module as a result of the increasing the low side gate resistance.

It can be seen that although the temperature rise in the SiC MOSFET module in most cases is higher than that of the silicon IGBT module, however the change of slopes is more uniform and the slope in the temperature rise in the silicon module is higher, i.e. where the low side device is connected to 100 Ω, the silicon device reaches the thermal runaway point faster. The SiC module, due to the higher bandgap and better packaging can cope with temperatures up to 150 °C easier, while in the case of Silicon device, the device has been destroyed after reaching a temperature around 120 °C.

Fig.18 provides a clearer comparison between the temperature rise of the silicon and SiC modules. In this case, the low side gate resistance is 100 Ω in all cases and the high side gate resistance is changed between 10 and 100 Ω in both cases of the silicon and SiC modules.

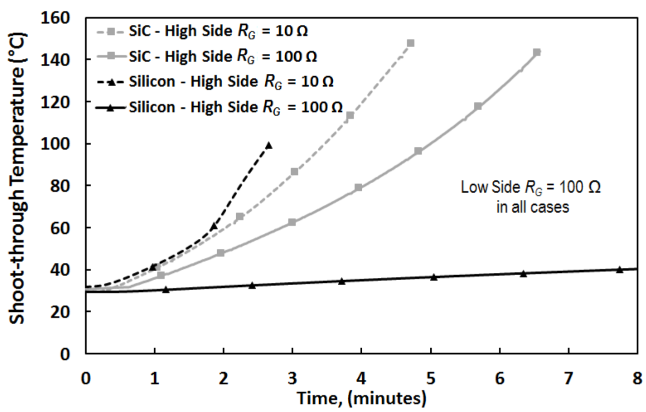

Fig. 18. The temperature rise due to shoot through currents in both modules with the low side R_G = 100 Ω.

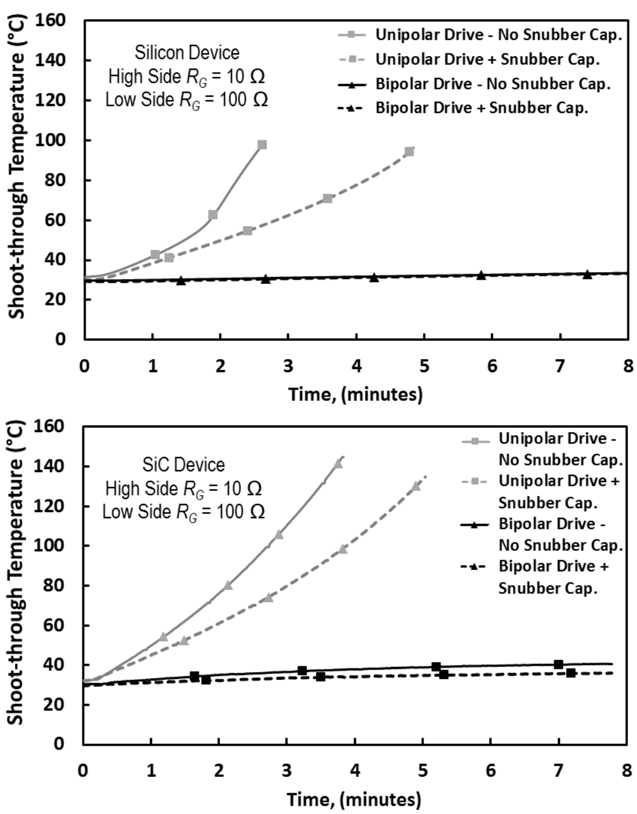

Fig. 19. The temperature rise due to shoot through currents in (a) Si IGBT and (b) SiC modules with and without snubber capacitors and bipolar gate drives.

As can be seen in Fig. 18, the difference between the temperature rises in the two cases for the silicon module is more explicit compared to the case of the SiC module. The reason for this difference is the change of shoot-through energy with R_G and is clear in the Fig. 10.

Fig.19 shows the temperature rise in both modules (a) for the silicon module and (b) for the SiC module, where a snubber capacitor and a bipolar drive is connected. The presence of the bipolar drive in both cases has considerably reduced the temperature rise, though the reduction is more significant in the case of the silicon module. The snubber capacitor has also reduced the temperature rise slope, which is due to the reduction of the shoot-through energy through damping the overshoots and ringing of the voltages.

V. CONCLLUSION

The induced voltage on the silicon IGBT module is higher than that of the SiC MOSFET module due to the significantly higher Miller capacitance of the device. This results in higher shoot-through current in most cases, however the shoot-through energy of the SiC device is higher than that of the silicon module due to the ringing present on the SiC module. The shoot-through energy is increasing more rapidly with temperature in the silicon module compared with the SiC module. This is due to the significant difference between the miller capacitance of the devices and higher stability of the threshold voltage of the SiC device compared with the Silicon IGBT device with changes in temperature. Several correction methods have been employed to remove the false turn-on issue, and it is concluded that in the case of SiC device, the bipolar gate driver should be used along with the snubber capacitor and the two-resistive paths. Several measurements are done to investigate the self-heating issue of the modules as a result of the false turn-on and as was seen, if the issue is not mitigated, it can lead to very high temperatures on the module with serious reliability consequences.

REFERENCES

[1] Nishigaki, A.; et al., "An analysis of false turn-on mechanism on power devices," *Ener. Conv. Cong. & Expo.*, pp.2988-93, 14-18 Sept. 2014.

[2] Khanna, R.; et al., "An analytical model for evaluating the influence of device parasitics on Cdv/dt induced false turn-on in SiC MOSFETs," *APEC 2013,* pp.518,525, 17-21 March 2013.

[3] Yamamoto, M., et al., "Full SiC soft switching inverter — Stability performance for false turn on phenomenon," *Power Electronics and Drive Systems (PEDS),* 10th Inter. Conf., pp.159,164, 22-25 April 2013.

[4] Jih-Sheng Lai; et al., "Characteristics and utilization of a new class of low on-resistance MOS-gated power device," *Industry Applications, IEEE Transactions on* , vol.37, no.5, pp.1282,1289.

[5] Jahdi, S.; et al., "The Impact of Temperature and Switching Rate on the Dynamic Characteristics of Silicon Carbide Schottky Barrier Diodes and MOSFETs" *Ind. Elec., IEEE Trans.*, vol.62, no.1, pp.163,171, Jan. 2015.

[6] Jahdi, S.; et al., "The impact of silicon carbide technology on grid-connected Distributed Energy resources", *ISGT Europe*, 6-9 Oct. 2013.

[7] Ouaida, R.; et al., "Gate Oxide Degradation of SiC MOSFET in Switching Conditions," *Electron Device Letters, IEEE* , vol.35, no.12, pp.1284,1286, Dec. 2014.

[8] Thanh-That Nguyen; et al., "Gate Oxide Reliability Issues of SiC MOSFETs Under Short-Circuit Operation," *Power Electronics, IEEE Transactions on* , vol.30, no.5, pp.2445,2455, May 2015.

[9] Markus Hermwille; "Gate Resistor – Principles and Application", Application Note AN-7003, Nov. 2007.