Performance comparison of switching losses of SiC DMOS vs Si IGBT

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Abstract. Silicon Carbide Double Diffused Metal Oxide Semiconductor (SiC-DMOS), having a more comprehensive bandgap, fast switching and low power losses, has been rapidly developed and applied. This paper elaborates a detailed analysis of switching losses by comparing Si IGBT and SiC DMOS under the same voltage parameters and identical conditions. The switch’s characteristics are evaluated and contrasted in various gate resistances. In addition, a gate driver is designed to calculate the switching losses of IGBT and SiC DMOS at different frequencies. Then they are respectively used in the buck converter. The experimental platform is built to test and validate that the SiC DMOS buck converter achieves faster dynamic performance and higher efficiency than Si IGBT.

1. Introduction

The development of power devices is closely related to the innovation of power electronics technology. In 1957, a silicon-controlled rectifier (SCR) based on silicon (Si) material came out, indicating the start of power electronics technology. In the 1970s, to fulfill the requirements of the various derivatives of thyristors emerged, the most important of which are gate turn-off (GTO), MOSFET and giant-transistor rectifier (GTR) [1]. The early 1980s, IGBT overcame the power electronics business like a storm. However, the advancement of Si power devices in the past approached the theoretical limit of Si materials. Silicon Carbide (SiC) material appeared at the start of the 21st century. However, the characteristic of the Si material, the switching frequency $f_s$, blocking voltage $V$ across terminals of the power module, rated power and junction temperature of Si devices are restricted [2]. To improve the system functioning and make it more efficient, a highly developed switch with high blocking voltage, fast switching speed and low on-resistance was urgently required.

The physical properties of SiC suggest its superiority in terms of the extensive bandgap, more suitable for switching devices because of its power electronic superiority in comparison to its counterpart Si IGBT. Based on the wide bandgap of SiC, it can endure higher junction temperature, block much higher voltage, shift faster, and have comparatively low on-state resistance [3].

The size of the harmonic filter depends on the range of switching frequency of the inverter, so SiC DMOS and Si IGBTs are competitors to each other in a lot of power electronic applications. As of 2019, the market of SiC DMOS is still small as compared to Si IGBTs, due to high cost and lack of maturity. Higher the switching frequency of the power module, the more stable output can be obtained,
and the size of the converter will be smaller [4]. Minimum on-times eradicate little material and produce smaller craters. High frequency makes a smooth output surfaces with a smaller amount of thermal damage to the electronic devices.

A simple gate driver is designed to compare the switching losses of SiC DMOS and Si IGBT. The PWM of switching frequency is from the Arduino controller, which is a better choice as Arduino can give an output frequency of 1-50000 Hz. The switching frequency is varied from 100 to 30 kHz, and switching losses are calculated at different frequency ranges and analyzed how the rate affects switching losses. The gate voltage is also varied and also investigated its effects on switching losses. The requirement of a high switching rate and High-power density converter necessitate that the power device is turned as fast as possible to reduce the losses, which can be possible by using SiC DMOS [5]. Switching losses of SiC DMOS are much smaller, which enables its capability to be used in hard switching converter of frequency range up to 100 kHz. However, its counterpart Si IGBT is just limited to 20 kHz [6-8]. Therefore, an Arduino microcontroller is being used so that the gate driver’s frequency can be changed according to the analyzing requirements. To fully utilize SiC switching device, more attention is needed to fulfill the demand for high speed and low switching losses.

The composition of the article is as follows. The introduction is exhibited in Section 1. The characteristic Comparison of SiC DMOS and Si IGBT are analyzed and discussed in Section 2. The comprehensive analysis and execution of the gate driver for SiC DMOS and Si IGBT that ensures fast transients are explained in Section 3. While in Section 4, the proposal and methodology are discussed, whereas, in Section 5, Experimental Results at 30 kHz of SiC DMOS and Si IGBT based buck converter switching losses are compared. An impact of circuit parasitic limitations on SiC MOSFETs’ performance, particularly the effect of voltage and current fluctuations on gate driver during switch-on and switch-off transients, is presented. Some conclusions are given at the end of Section 6.

2. Characteristics of SiC DMOS and Si IGBT
To employ SiC-DMOS and Si-IGBT properly, its critical characteristics like parasitic capacitance, min and max gate voltage, and on-state resistance are kept in mind as shown in Table 1.

| Parameters                      | SiC DMOS (ROHM Semiconductors) | Si IGBT (Infineon) |
|--------------------------------|--------------------------------|-------------------|
| Package                        | BSM080D12P2C008                 | FF50R12RT4        |
| Voltage rating                 | 1200V                          | 1200V             |
| Current rating                 | 80A                            | 50A               |
| Gate Threshold voltage         | 1.6V to 4V                     | 5.2V to 6.4V      |
| Min. and Max. gate voltage     | -10V to 20V                    | -20V to 20V       |
| limitations                    |                                |                   |
| Rds-on                         | 0.4m Ω                         | 0.65m Ω          |
| IGT Internal Gate Resistor     | 3 Ω                            | 4 Ω               |

**Figure 1.** Output waveform across Si-IGBT and SiC-DMOS when $R_G=300\Omega$.

**Figure 2.** Output waveform across Si-IGBT and SiC-DMOS when $R_G=100\Omega$. 
2.1. SiC DMOS and Si IGBT on resistance $R_{ds(on)}$

$R_{ds(on)}$ is the resistance of the drain terminal to source terminal of the power module. While the switch is at on state, $R_{ds(on)}$ is directly proportional to the gate resistance and inversely proportional to the gate voltage \([9, 10]\). As shown in Figure 1, while the gate resistance is 300Ω, the rising time is 100μs for Si IGBT and 50μs SiC-DMOS. When the gate resistance is minimized to 100Ω, the rising time, as shown in Figure 2 decreased to 40μs for Si IGBT and 30μs for SiC-DMOS, respectively. The decrement is not as much as in the case of the Si IGBT with changing gate resistance.

However, to make SiC DMOS and Si IGBT switching very fast, the gate resistance must be kept as low as possible, and the gate voltage must be maintained to a required maximum amount. By analyzing the results, it is evident that the higher the gate to source voltage, the lower the $R_{ds(on)}$ is. Hence the switching losses are lower. By profoundly analyzing and comparing Figure 1, Figure 2, it is concluded that decreasing gate resistance $R_G$ can decrease the rise and fall time of switching power module, whether it is Si IGBT or SiC DMOS. Still, it affects the Si IGBT more than SiC DMOS in terms of shifting time. This performance of SiC DMOS is mainly because of channel resistance, JFET resistance, and drift layer resistance \([11]\).

2.2. The gate threshold voltage of SiC Vs. IGBT

Gate threshold voltage needs to meet the stated elementary requirements for optimized switching of SiC DMOS and IGBT. Both are approximately the same. A gate driver, which consists of two major parts, a pulse generator and an optocoupler gate driver IC, is designed to keep the control circuit safe and separate from high voltage. An optically isolated gate driver is especially proposed for testing and evaluating in a variety of applications. The drive circuit of the optical isolation gate has the advantages of a variable duty cycle, strong anti-nosiness ability and high isolation voltage \([12]\). Also, the propagation delay time is significant. According to the technical documents of Infineon \([13]\), an optically isolated gate driver for evaluating has been realized, and the schematic of the driver is shown in Figure 3.

![Figure 3. Schematic diagram of gate driver of power module.](image)

Two different power supplies are required in the proposed gate driver circuit, one for an optocoupler and one for the gate driver circuit. All the power supplies must have the same standard reference to avoid voltage measuring faults. The pulses generated by the Arduino controller can vary the duty cycle, and it can also change in both frequency and duty cycle of PWM. So, this is better for performance evaluation and switching losses calculations, for both IGBT and SiC DMOS. As both SiC DMOS and Si IGBT are evaluated under the same conditions and with the same gate driver, SiC DMOS and Si IGBT are responding correctly to a simple gate driver. The switching frequency of the PWM generator is controlled by Arduino software and can be changed according to the testing requirements.

3. Isolated gate driver for Si-IGBT and SiC-DMOS

A simple gate driver that can drive both SiC DMOS and Si IGBT has been designed.
3.1. Requirements for designing a gate driver
The fundamental character of the gate driver is to supply or remove the required gate voltage for properly switching of a SiC DMOS and Si IGBT to turn on and off abruptly and efficiently. Gate driver must be designed by keeping in mind about the fast switching transient’s process. And the gate driver circuit is required to hold a high peak current to instantly charge the Miller Capacitor and power module’s gate. According to the Gate resistance $R_G$, the peak current value is set. During turning-off, the gate driver needs to suddenly change the gate charge to a negative voltage at the power module’s gate terminal to reduce turn-off losses. Secondly, a sophisticated gate voltage plays a vital role in SiC DMOS and Si IGBT’s, as it is quite apparent that the higher the gate voltage, the lower the on-resistance of the SiC DMOS and Si IGBT’s (shown in Figures 1-4) and the turning-on switching losses [14-15]. So, the gate driver must deliver a stable higher voltage to the gate of the SiC MOSFET and IGBT during turning-on to minimize the on-resistance $R_{ds(on)}$ over the specified normal room temperature range. The low threshold voltage of SiC DMOS, and Si IGBT (typically $V_{GS(th)} = 2.5V$). Therefore, the negative Potential of -4V is applied to the gate during the turning-off state [16].

3.2. FOD3180 optically isolated gate driver IC
The gate driver must fulfil all the elementary requirements for efficient and fast switching of a gate driver. For a gate driver design, the executed circuit is composed of three major parts, i.e., a pulse generator, an optocoupler, and a gate driver IC [17].

The propagation delay time is also significant. According to the technical documents of Infineon for Si IGBT and ROHM for SiC DMOS, an optically isolated gate driver for evaluating purpose has been implemented, and the schematic diagram of the proposed Gate driver is presented in Figure 5.

This circuit comprises of two different power supplies, and the gate driver integrated circuit. The main gate driver integrated circuit is FOD3180 from Fair-Child [17]. The two power supplies are linked through the standard connection of the reference source terminal. Thus, VCC determines the positive voltage pulse at the gate, and $-VEE$ decides the negative pulse voltage at the gate. A PWM generation circuit has been controlled by Arduino microcontroller. The input gate drive signals, the switching frequency and the duty cycle, can be changed by adjusting the programming of Arduino software. Depending on Arduino controller programming and requirement of the evaluation design, system control can be a closed-loop or an open-loop.

The frequency range of Arduino controller from 1Hz to 50kHz, which is quite suitable for testing and evaluation of Si IGBT and SiC DMOS.

3.3. Unique design and PCB layout of the evaluation kit
A simple PCB layout design is implemented to make the evaluation procedure as simple as possible. But the circuit is digitalized by connecting it to Arduino controller as most essential parameters like duty cycle, and switching frequency can be adjustable, by altering values in the Arduino software, no need to adjust potentiometer, again and again. The gate driver circuit is implemented on a separate PCB. The minimum current needed by the SiC DMOS and Si IGBT is calculated according to the switching frequency requirements, and the minimum current requirement for SiC DMOS is nearly about 80mA to 100mA for 20kHz switching frequency [5].

$R_G$ (Gate Resistance) must be selected carefully, three different $R_G$ are inducted into a system, and the performance of the power module is being evaluated and find out the effect of $R_G$ on switching losses. The gate driver output ranges from 0 volts to 20 volts, which is suitable for abrupt switching of the power module. The loop inductance of the gate needs to be reduced as low as possible. Otherwise, the gate loop inductance will have an insignificant effect on the switching speed and fluctuations in the form of switching waveforms of SiC DMOS and Si IGBT.

3.4. Gate driver circuit evaluation
In order to evaluate the fast switching transients of SiC DMOS and Si IGBT, a suitable measurement system is required, which can measure the current and voltage at a very high frequency. The RIGOL
digital oscilloscope DS1102E has a bandwidth frequency of 100MHz and is capable of a sampling rate of 1GS/sec. For measuring current, a current sensor HKA10-YSC 10A/4V is being used, and its output is directly measured and plotted with the help of the digital oscilloscope. The Gate driver output at 30 kHz shows in Figure 4 illustrates that this particular design and gate driver IC is suitable for this evaluation gate driver circuit.

The gate driver output is attached with different RG to illustrates the impact on gate driver resistance and the transient switching behaviour of the SiC DMOS and Si IGBT. The results are then observed, and losses at different RG at different frequencies are compared and observed. At the same time, the output voltage remains constant at 150Volts. As shown in Figure 5, when RG = 300 Ω, the overall switching losses vary from 44.64W for IGBT to 30.96W in case of SiC DMOS relatively a comparison which indicates that this resistance is too high for the gate voltage.

![Figure 4. Gate driver output waveform.](image)

![Figure 5. Switching losses when R_G 300Ω.](image)

![Figure 6. Switching losses when R_G 100Ω.](image)

![Figure 7. Switching losses when R_G 10Ω.](image)

Moreover, when R_G decreased from 100Ω to 10Ω, as shown in Table 2 and Figure 6 and Figure 7, the switching losses decreased to a deficient level of 3.6 W in the case of IGBT and 1.08 W of SiC DMOS. It demonstrates that by reducing R_G, the switching losses can be controlled to a minimum level. Figure 6 also explains the decreasing level of power losses with the significant decrement in gate resistance.

Switching losses $P_{SW}$ are calculated by the given formula.

$$P_{SW} = \frac{1}{2} \times V_{IN} \times I_o \times (t_r + t_f) \times f_{SW}$$

- $V_{IN}$ = Input voltage [V]
- $I_o$ = Output current [A]
- $t_r$ = MOSFET rise time [Sec]
- $t_f$ = MOSFET fall time [Sec]
- $f_{SW}$ = Switching frequency [Hz]

By comparison of this Figure 5 to Figure 7, it is evident that gate resistance has a significant impact mainly on the rising time of the power module. The falling time of the power module is not as slow as the rising time. Moreover, in the case of SiC DMOS Schottky barrier diode is responsible for fast turning off of the SiC DMOS, which also make SiC DMOS capable of handling frequency of about...
100 kHz. But Si IGBT has much more switching losses as it does not even reach a stable voltage when \( R_G = 300\Omega \) and its rising time is too much high. The switching losses of Si IGBT are much higher as compared to its counter SiC DMOS, which makes SiC DMOS a better switching device that makes the system electrically optimized.

| Power Module | \( R_G = 300\Omega \) | \( R_G = 100\Omega \) | \( R_G = 10\Omega \) |
|--------------|-----------------|-----------------|-----------------|
| Frequency    | 30kHz           | 30kHz           | 30kHz           |
|              | 20kHz           | 30kHz           | 20kHz           |
| Rise Time    | 2.5\( \mu \)s   | 2\( \mu \)s     | 1.25\( \mu \)s  |
| Falling Time | 600ns           | 150ns           | 500ns           |
| Turn-On Loss | 36W             | 28.8W           | 36W             |
| Turn-Off Loss| 8.64W           | 2.16W           | 7.2W            |

4. Switching loss comparison of a buck converter

Figure 8 shows the evaluation platform by using Arduino. While Figure 9 elaborates the schematic diagram of the simple buck converter circuit. Q1 signifies a power module (SiC DMOS and Si IGBT) from ROHS Semiconductors package BSM080D12P2C008 1.2KV/80A or Infineon FF50R12RT4 1.2kV/100A. Then D1 denotes a Diode, and in the case of SiC DMOS, there is an additional SiC SBD (Schottky barrier diode) which ensures fast turning of SiC DMOS Switch. The simple design circuit of a buck converter is established to work in a continuous current mode: the standard chart of the buck converter schematic is displayed in Figure 9.

A film capacitor and ceramic technology capacitor are put in parallel to the terminals of the power module to their maximum vicinity of the dc bus. To reduce the stray inductance, dc bus a decoupling layer of high frequency from the rest of the parasitic inductance between dc bus, high-speed of switching process might be the reason for the insufficient damping of voltage, and current oscillations and because of too small diode losses dissipation. This undesirable dissipation can be limited by slowing down the switching frequency. In the Buck converter, it is already discussed that the switching speed can be reduced by increasing the gate driver resistance, and more comprehensive experimental results will be provided in the expanded scheme.

5. Experimental results comparison

Figure 10 shows SiC DMOS switching waveform at 30kHz, as it describes that voltage surge in case of SiC DMOS turning on which is 25% more than average voltage, can be minimized to a certain low level by using a ceramic capacitor across switching terminal of the power module. This voltage surge is dangerous for the well-being of the switching power module as it also affects its life span, and this voltage surge problem can be reduced by adding a parallel capacitor. The voltage gets to stable faster.
in the case of SiC DMOS as compared to Si IGBT. The performance of SiC DMOS shows that it can also switch to a higher rate as it has a minimal amount of tail current and its voltage and current value stables in very less time about nanoseconds. But in the case of Si IGBT, the voltage waveform takes more time to get it stable because of the more tail current and more rising and falling time of the current waveform.

The current drawn by the system in the case of Si IGBT is much higher at 30 kHz, which shows its incapable of withstanding at a high rate even at 30kHz. There is a problem in Si IGBT in the case of less duty cycle as when the duty cycle is limited to less than 15%, and it does not even reach its maximum value, which shows its incapable of performing at a very high frequency. Figure 11 shows switching waveform of Si IGBT at 30 kHz, the current waveform elaborates that the tail current losses are too much in case of Si IGBT as it takes too much time to rise and fall to instructed value. The current spikes in the case of Si IGBT are much higher ranging -7 to +7 while in the case of SiC DMOS it is just -1.5 to 3 which is not as large as in the case of Si IGBT. Hence it results in a loss of a massive amount of current occurs, which also increase the temperature of Si IGBT and its losses. The current surge is very much higher in the case of Si IGBT, which indicates its incapability of handling the high frequency and shows high power losses and makes a considerable heat loss, which shows the limitation of Si IGBT in compared with SiC DMOS.

![Figure 10. Switching waveform DMOS V & Gate V & I.](image1)

![Figure 11. Switching waveform of IGBT V & Gate V & I.](image2)

Figure 10 and Figure 11 depict that the switching losses are much higher in the case of Si IGBT, and the current value goes to zero at a slower rate. This problem can be eliminated to a minimal extent by replacing it with SiC DMOS as it is capable of handling more high frequency with approximately the same value of current and voltage.

![Figure 12. An output waveform comparison of inverter.](image3)

For an optimized and efficient system, it is necessary to replace the old Si IGBT switching power module with new SiC DMOS, which not only makes the system more efficient but also decreases the size of the converter, and increase the lifespan and durability of the system. A simple buck converter
circuit is established, and the experimental tests are provided. Efficiency ($\eta$) of the buck converter is calculated by the formula given below:

$$\eta_{\%} = \frac{P_{\text{out}}}{P_{\text{in}}} \times 100$$

$P_{\text{out}}$ = output power of buck converter.

$P_{\text{in}}$ = input power of buck converter.

The initial results are shown in Figure 12 prove that the SiC DMOS is better than Si IGBT for high-frequency DC/DC converter applications. The output comparison illustrates that the output of the SiC DMOS based buck converter is 3-6% more efficient than simple Si IGBT based buck converter.

6. Conclusions

This paper mainly focuses on replacing Si IGBT with SiC DMOS. Si IGBT employed in converters can be replaced with SiC-DMOS to make the system much more efficient, requirements of the SiC DMOS is approximately the same as Si IGBT. This paper is based on experiments replacing Si IGBT based system with advanced SiC-DMOS remaining all other conditions same also comparing the switching performances of the SiC DMOS and Si IGBT. For low switching devices, the Si IGBT has approximately the same switching losses, but with the increment in the frequency, the switching losses increase too, as shown in Figures 5, 6, 7. Improvement in the efficiency is mainly because of the material superiority of the SiC DMOS and mainly fast turning-on and turning-off the power module. SiC DMOS can easily replace old power modules Si IGBT in many applications, i.e., VFDs, DC/DC converter, DC/AC inverter, and much more. Increasing switching frequency can accelerate the system response, make the system more stable and decrease the size of the inverter.

Moreover, the switching frequency increases the value of inductor and capacitor needed for the circuit can be minimized, and so does the size of the converter. The switching losses can be reduced about three to six percent, which shows it can be used in the bidirectional hybrid energy storage system of an electric vehicle. It is suitable for recovery of braking energy because of its voltage and frequency range which makes the system more optimized and more efficient.

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