Comparative Evaluation of a Commercially Available 1.2 kV SiC MOSFET Module and a 1.2 kV Si IGBT Module

S. Tiwari, O.-M. Midtgård and T. M. Undeland
Norwegian University of Science and Technology
7491 Trondheim, Norway
Email: subhadra.tiwari@ntnu.no

Abstract—In this paper, a comparative performance evaluation of a 1.2 kV SiC MOSFET module and a 1.2 kV Si IGBT module is carried out under a series of different conditions such as similar dv/dt, di/dt, voltage overshoot, current overshoot, and ringings. Both the modules are commercially available in a standard plastic package and have the same stray inductances. Various parameters such as switching speed, energy loss, and overshoots are experimentally measured in order to address the comparative advantages and disadvantages of the selected modules. This paper demonstrates that SiC MOSFET can replace Si IGBT of similar voltage class or even higher voltage class, both in slow and fast switching applications.

I. INTRODUCTION

The commercially available SiC MOSFETs in a voltage class of 1.2 kV and 1.7 kV can replace Si IGBTs in the same voltage or even higher voltage areas [1], [2], [3], [4]. This is because of the higher breakdown electric field in SiC which allows the use of thinner and shorter drift layer, reducing the capacitances and on-resistances and making the SiC devices suitable for faster switching and higher voltage applications.

There are several publications comparing the switching performances of SiC devices and Si counterparts. For example, a six-pack SiC MOSFET module is compared with a six-pack Si IGBT module keeping similar gate resistance in [5] and under similar dv/dt conditions in [6]. Similarly, a half-bridge SiC MOSFET module is compared with a SiC IGBT module under same dv/dt conditions in [7].

However, few publications have compared the half-bridge SiC MOSFET module against the Si IGBT module under a series of different conditions such as similar di/dt, voltage and current overshoots and ringings, as carried out in this paper. It is important to quantify the switching speed limits of the fast switching SiC MOSFET modules compared to today’s fast switching Si IGBT modules. Therefore, in this paper, a commercially available SiC MOSFET module and a Si IGBT module are evaluated by observing their switching performances in all the aforementioned conditions, including also similar dv/dt conditions as in other publications. The selected SiC MOSFET module is CAS300M12BM2 from Cree and the Si IGBT module is SKM400GB125D from Semikron. Each of them have a voltage rating of 1.2 kV, a current rating of 300 A and also similar stray inductances inside the module ($L_{module}$).

II. METHODOLOGY AND LABORATORY SETUP

A standard double pulse test methodology is used for evaluating the stresses, for instance, current and voltage overshoots, ringing, dv/dt, di/dt, and switching energy losses in the device under test (DUT), as described in [8], [9]. An equivalent circuit with a hard switched arrangement is shown in Fig. 1. The total stray inductance in a switching loop ($L_{stray}$) is the sum of $L_{dcbus}$, $L_{byp}$, and $L_{module}$ which are depicted in Fig. 1. $L_{module}$ is the effective stray inductance which is distributed inside the module, represented by red coils.

![Fig. 1. Current paths show turn-on and turn-off processes in a buck converter during the double pulse test of lower MOSFET. $V_{gs}$ of -5 V is applied in the upper side MOSFET to ensure that it is turned off all the time.](image-url)

The dc-link is realized with a planar busbar except the termination parts (needed to facilitate the module connection) so that the stray inductance in the switching loop can be kept as low as possible. A current viewing resistor (CVR) SSDN-414-01 (400 MHz, 10 mΩ) from T&M research is used for measuring the drain current. The CVR replaces one of the screws in the SiC module as it is mounted directly on the screw terminal. This arrangement decreases the $L_{stray}$ even further as one screw hole is eliminated in the busbar. $L_{byp}$ and $L_{dcbus}$ are calculated using Ansys Q3D extractor, and is 14 nH in total [10]. The picture illustrating the placement of the CVR in the laboratory setup is shown in Fig. 2.

An inductive load with a single layer winding is used in order to ensure minimum stray capacitance [11].
gate driver with an adjustable output voltage [12] is used for driving the SiC MOSFETs where the gate voltage \( V_{gs} \) is set to 20 V for turn-on and -5 V for turn-off. The same gate driver is used for driving the Si IGBT with a small modification to achieve the required gate voltage of \( \pm 15 \) V. High voltage differential probes (THDPO200, 200 MHz) are used for drain voltage \( V_{ds} \) and gate voltage measurements.

Both the modules have been opened to see the internal layout and the distribution of the chips. The Cree module has 6 co-pack MOSFETs in each of the upper and the lower sides in the half-bridge configuration. In the Semikron module, there are 4 co-pack IGBTs in each of the upper and the lower side switches. SiC MOSFET has SiC Schottky barrier diode (SBD), while Si IGBT has Si pn diode as an anti-parallel diode. The opened modules are displayed in Fig. 3.

The typical characterizing parameters such as die size, input capacitances \( C_{iss} \), output capacitances \( C_{oss} \), and reverse transfer capacitances \( C_{rss} \) (sometimes called Miller capacitances) of the modules are listed in Table I [13], [14]. The gate charge \( Q_g \) is 1025 nC in the MOSFET and 2650 nC in the IGBT. The higher \( Q_g \) increases the cost of the gate driver circuit.

Each die in the Cree module has thickness of 200 \( \mu m \), and area of 26 \( mm^2 \), while the thickness is 180 \( \mu m \) and area is 122 \( mm^2 \) in the IGBT module [15], [16]. The total die size in Si IGBT is larger by a factor of 3 compared to SiC MOSFET. In addition, Si has higher dielectric constant than SiC. Both of these factors lead to a larger capacitances in the Si IGBT compared to the SiC MOSFET module. (A dielectric constant in Si is 11.9, while it is 10 in 4H-SiC.) An electrical breakdown field of 10 times higher in SiC compared to Si allows thinner and shorter drift layer. However, the thickness of chip and area is a trade-off between on-state resistance \( R_{ds(on)} \) and capacitances of the power MOSFET structure.

\[ R_{ds(on)} \text{ in the MOSFET is } 5 \Omega \text{ at } 25^\circ C \text{ and } 7.8 \Omega \text{ at } 125^\circ C. \text{ In the } \text{Si IGBT, } R_{ceon} \text{ is } 6.3 \Omega \text{ at } 25^\circ C \text{ and } 7.6 \Omega \text{ at } 125^\circ C. \text{ In addition, the } \text{Si IGBT has an on-state zero-current collector-emitter voltage } V_{CEo} \text{ of } 1.4 \text{ V at } 25^\circ C \text{ and } 1.7 \text{ V at } 125^\circ C. \text{ Using these parameters, the on-state power losses are calculated at a load current of 300 A. In the Si IGBT, these losses are } 2.2 \text{ times higher at } 25^\circ C \text{ and } 1.7 \text{ times higher at } 125^\circ C \text{ compared to the SiC MOSFET. Furthermore, at the same load current, the ratio of on-state losses in Si diode to that in SiC diode is } 1.25 \text{ at } 25^\circ C \text{ and } 0.99 \text{ at } 125^\circ C. \text{ Due to the pure Ohmic characteristics of the MOSFET, the ratio of conduction loss in the Si IGBT to that in the SiC MOSFET is higher at lower current, indicating that the SiC MOSFET is more favourable than the Si IGBT. The converse is true for the switching loss because of the tail-current in the IGBT which causes non-linear behaviour of turn-off loss with load current.}

The internal gate resistance \( R_{gint} \) in the MOSFET module is 3 \( \Omega \) and in the IGBT module, it is 1.25 \( \Omega \). A higher value of \( R_{gint} \) limits the speed of the device.

### III. Summary of Measurements with Varying Gate Resistances

All the turn-on and turn-off switching transients are evaluated for a dc-link voltage of 600 V and a drain-source current of 300 A in each of the modules at 25 \( ^\circ C \). Both the chosen modules are evaluated with varying gate resistance \( R_g \).
The turn-off switching transients for the selected modules at similar $dv/dt$ are illustrated in Fig. 4. The SiC MOSFET has lower turn-off losses compared to the Si IGBT, which is essentially due to the smaller voltage overshoot ($V_{os}$) in the SiC compared to the Si module. However, the reduced losses in the SiC come with high frequency oscillations (26 MHz) as indicated in Fig. 4 a). $V_{os}$ in the Si IGBT is higher compared to SiC MOSFET because of higher $di/dt$ (10.8 A/ns) in the IGBT with regard to the MOSFET (7.97 A/ns). These oscillations and overshoots can be kept at an acceptable level either by reducing $L_{stray}$, or by slowing down the device. The former solution expedites further reduction in losses as well, while the latter results in increased switching losses as exemplified in Subsection F.

**IV. COMPARISON OF SiC MOSFET AND Si IGBT**

**A. Similar $dv/dt$**

The turn-off switching transients for the selected modules at similar $dv/dt$ are illustrated in Fig. 4. The SiC MOSFET has lower turn-off losses compared to the Si IGBT, which is essentially due to the smaller voltage overshoot ($V_{os}$) in the SiC compared to the Si module. However, the reduced losses in the SiC come with high frequency oscillations (26 MHz) as indicated in Fig. 4 a). $V_{os}$ in the Si IGBT is higher compared to SiC MOSFET because of higher $di/dt$ (10.8 A/ns) in the IGBT with regard to the MOSFET (7.97 A/ns). These oscillations and overshoots can be kept at an acceptable level either by reducing $L_{stray}$, or by slowing down the device. The former solution expedites further reduction in losses as well, while the latter results in increased switching losses as exemplified in Subsection F.

**B. Similar $di/dt$ per module**

The anti-parallel diode in the Si IGBT module has a pn junction. Therefore, when the diode switches from the on-state to the reverse-blocking state, the current continues to flow until the stored charge within the drift region are swept out, which is referred as the reverse recovery phenomenon [17]. This negative current is added to the IGBT current during the turn-on of the IGBT, resulting in higher switching losses in the IGBT. The SiC MOSFET has SBD as an anti-parallel diode which has extremely low capacitive charge ($Q_c$). For instance, the reverse recovery charge ($Q_{rr}$) of the pn diode in the Si IGBT is higher by a factor of 14 compared to the $Q_c$ of the SBD diode in the SiC MOSFET as presented in Table II.

The laboratory measurement shows that the turn-on switching energy loss is 3 times higher in the Si IGBT compared to the SiC MOSFET. The example waveforms with similar $di/dt$ per module for the SiC MOSFET and the Si IGBT are depicted in Fig. 5.

**C. Similar $di/dt$ per chip**

The Cree module has 6 chips in parallel whereas the Semikron has only 4. Fig. 6 exemplifies the turn-on transients at similar $di/dt$ per chip. The turn-on energy loss is higher by a factor of 4.2 in the Si IGBT compared to the SiC MOSFET. Though the overshoots are similar in this case, the higher loss in the IGBT is caused mainly by the slower rise and fall time.

**D. Similar voltage overshoot**

The comparison of the case with similar $V_{os}$ are illustrated in Fig. 7. The turn-off switching energy loss is higher by a factor of 1.76 in the Si IGBT compared to the SiC MOSFET. The tail current in IGBT functions partly as a turn-off snubber, resulting in lower or no ringing. However, the MOSFET is

---

**TABLE III**

**SUMMARY OF LABORATORY MEASUREMENTS FOR CAS300M12BM2 (CREE)**

<table>
<thead>
<tr>
<th>$R_g$ (Ω)</th>
<th>$dv/dt$ (V/ns)</th>
<th>$di/dt$ (A/ns)</th>
<th>$V_{os}$ (V)</th>
<th>$I_{os}$ (A)</th>
<th>$E_{on}$ (mJ)</th>
<th>$E_{on} - E_{off}$ (mJ)</th>
<th>$dv/dt$ (A/ns)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>19.56</td>
<td>10.93</td>
<td>301</td>
<td>198</td>
<td>1.63</td>
<td>3.74</td>
<td>1.82</td>
</tr>
<tr>
<td>1</td>
<td>15.12</td>
<td>9.14</td>
<td>260</td>
<td>166</td>
<td>3.87</td>
<td>5.04</td>
<td>1.52</td>
</tr>
<tr>
<td>2.2</td>
<td>13.22</td>
<td>7.1</td>
<td>207</td>
<td>140</td>
<td>5.02</td>
<td>5.76</td>
<td>1.18</td>
</tr>
<tr>
<td>3.4</td>
<td>10.38</td>
<td>6.56</td>
<td>188</td>
<td>125</td>
<td>7.09</td>
<td>7.7</td>
<td>1.09</td>
</tr>
<tr>
<td>5</td>
<td>8.55</td>
<td>5.35</td>
<td>136</td>
<td>111</td>
<td>8.56</td>
<td>8.64</td>
<td>0.89</td>
</tr>
<tr>
<td>6.8</td>
<td>7.12</td>
<td>4.46</td>
<td>133</td>
<td>105</td>
<td>11.84</td>
<td>10.78</td>
<td>0.74</td>
</tr>
<tr>
<td>10</td>
<td>5.4</td>
<td>3.15</td>
<td>102</td>
<td>86</td>
<td>16.61</td>
<td>15.16</td>
<td>0.58</td>
</tr>
<tr>
<td>12</td>
<td>4.9</td>
<td>2.97</td>
<td>85</td>
<td>65</td>
<td>19.62</td>
<td>17.74</td>
<td>0.49</td>
</tr>
</tbody>
</table>

**TABLE IV**

**SUMMARY OF LABORATORY MEASUREMENTS FOR SKM400GB125D (SEMIKRON)**

<table>
<thead>
<tr>
<th>$R_g$ (Ω)</th>
<th>$dv/dt$ (V/ns)</th>
<th>$di/dt$ (A/ns)</th>
<th>$V_{os}$ (V)</th>
<th>$I_{os}$ (A)</th>
<th>$E_{on}$ (mJ)</th>
<th>$E_{on} - E_{off}$ (mJ)</th>
<th>$dv/dt$ (A/ns)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>16.64</td>
<td>12.2</td>
<td>233</td>
<td>393</td>
<td>3.94</td>
<td>7.68</td>
<td>3.04</td>
</tr>
<tr>
<td>1</td>
<td>13.23</td>
<td>9.07</td>
<td>270</td>
<td>279</td>
<td>11.9</td>
<td>8.87</td>
<td>2.26</td>
</tr>
<tr>
<td>2.35</td>
<td>9.8</td>
<td>5.7</td>
<td>296</td>
<td>168</td>
<td>24.9</td>
<td>10</td>
<td>1.42</td>
</tr>
<tr>
<td>3.9</td>
<td>7.32</td>
<td>3.58</td>
<td>276</td>
<td>118</td>
<td>36.2</td>
<td>12.15</td>
<td>0.89</td>
</tr>
<tr>
<td>4.7</td>
<td>6.57</td>
<td>3.05</td>
<td>270</td>
<td>108</td>
<td>40</td>
<td>13.62</td>
<td>0.76</td>
</tr>
<tr>
<td>6</td>
<td>5.21</td>
<td>2.41</td>
<td>236</td>
<td>89</td>
<td>49.5</td>
<td>16.4</td>
<td>0.60</td>
</tr>
</tbody>
</table>

The summary of the measurements taken during the experiments are listed in Table III and Table IV. $dv/dt$ is the voltage slew rate during the turn-off, $di/dt$ is the current slew rate per module, while $dv/dt/dt_1$ is the current slew rate per chip during the turn-on of the lower transistor. The $R_g$ influences turn-on speed and thereby turn-on losses significantly. The details are explained along with the example waveforms in Section IV.
room temperature is not a real environment for a practical module in this case. However, one should not forget that the in the SiC MOSFET is 2 times higher than the Si IGBT modules. The laboratory measurement shows that turn-off loss \( R_f \). Similar ringing during turn-off chip size of the Si IGBTs.

and higher deliverable power, but also allow the reduction in system efficiency by allowing the higher switching frequency reduction in switching losses, which will not only improve the temperatures of the IGBTs will be lower as a consequence of the SiC SBD in the Si IGBT module. Thereafter, the case Therefore, it is crucial to replace the Si anti-parallel diode with down to reduce ringings, it beats the Si IGBT in turn-on losses.

compared to the SiC. Nonetheless, the SiC MOSFET is slowed where the losses were higher in the Si IGBT by a factor of 4.2
dominated in Fig. 8. Laboratory measurements show turn-on E. Similar current overshoot

The waveforms at similar current overshoot \( I_{os} \) are elu-

cated in Fig. 8. Laboratory measurements show turn-on losses of 3.87 mJ for the Cree and 24.9 mJ for the Semikron module, which is 6.4 times higher. Subsection C showing the waveforms at similar di/dt per chip also has almost similar \( I_{os} \), where the losses were higher in the Si IGBT by a factor of 4.2 compared to the SiC. Nonetheless, the SiC MOSFET is slowed down to reduce ringings, it beats the Si IGBT in turn-on losses. Therefore, it is crucial to replace the Si anti-parallel diode with the SiC SBD in the Si IGBT module. Thereafter, the case temperatures of the IGBTs will be lower as a consequence of reduction in switching losses, which will not only improve the system efficiency by allowing the higher switching frequency and higher deliverable power, but also allow the reduction in chip size of the Si IGBTs.

F. Similar ringing during turn-off

The ringings during the turn-off are reduced using a higher \( R_g \) so that the losses can be compared between the selected modules. The laboratory measurement shows that turn-off loss in the SiC MOSFET is 2 times higher than the Si IGBT module in this case. However, one should not forget that the room temperature is not a real environment for a practical converter operation. The tail current in Si IGBT worsens with higher temperature, whereas the losses in SiC MOSFET increase a little or remain almost the same \([5], [6]\).

G. Similar ringing during turn-on

The ringings during the turn-on are reduced by slowing down the SiC MOSFET module. The switching waveforms are displayed in Fig. 10. The turn-on energy loss in the Si IGBT is 1.2 times higher than that in SiC MOSFET. This demonstrates that the SiC MOSFET beats the Si IGBT in turn-on losses.
**H. Summary of Section IV**

The analysis of the switching losses in Section IV is summarized in Table V. For a given dc-link voltage and a load current, the switching energy loss depends on the overshoots and rise and fall time of the switching current and voltage.

It is explicitly clear that the SiC MOSFET has lower switching energy losses compared to the Si IGBT in all the cases except the case with similar ringing during turn-off. However, $V_{os}$ in the Si IGBT is 38 %, while that in the SiC MOSFET is 17 % of the steady state voltage in the latter case.

**V. CHOICE OF GATE RESISTANCE**

From Table IV, it is evident that $V_{os}$ of the Si IGBT increases with $R_{goff}$, reaches a peak value and then decreases again. Therefore, $R_{goff}$ of 0 Ω is chosen as an optimized value, which also gives lowest loss. As a trade-off between $I_{os}$ and turn-on losses, $R_{gon}$ of 2.35 Ω is chosen. The switching transients with $R_{goff}$ of 0 Ω is exemplified in Fig. 9 b) and with $R_{gon}$ of 2.35 Ω in Fig. 8 a). Considering ringings, switching losses and overshoots, $R_{gon}$ of 5 Ω and $R_{goff}$ of 3.4 Ω are chosen for the SiC MOSFET. The turn-on waveform is displayed in Fig. 6 a) and turn-off in Fig. 11.

Table VI shows the specific switching energy loss for the selected gate resistances. The turn-off loss turns out to be equal for both modules, whereas the turn-on loss in the SiC MOSFET is 1/3 times that of the Si IGBT. The specific reverse recovery loss of SiC diode is 1/87.6 times that of Si diode.

<table>
<thead>
<tr>
<th>Parts</th>
<th>$R_{gon}$ (Ω)</th>
<th>$R_{goff}$ (Ω)</th>
<th>$E_{on-sp}$ (μJ/μA)</th>
<th>$E_{off-sp}$ (μJ/μA)</th>
<th>$E_{rr-sp}$ (μJ/μA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si IGBT</td>
<td>2.35</td>
<td>0</td>
<td>83</td>
<td>25.6</td>
<td>11.4</td>
</tr>
<tr>
<td>SiC MOSFET</td>
<td>5</td>
<td>3.4</td>
<td>28.5</td>
<td>25.6</td>
<td>1.3</td>
</tr>
</tbody>
</table>

**VI. DISCUSSION**

With $R_{g}$ of 0 Ω, the Cree module can switch at dv/dt of 19.6 V/ns during turn-off and di/dt of 10.9 A/ns during turn-on. The maximum speed of today’s fast switching Si IGBT
is 16.6 V/ns during turn-off and 12.2 A/ns during turn-on. The conduction loss in the SiC MOSFET is a factor of 0.45 and 0.58 at 25°C and 125°C respectively compared to the Si IGBT at a load current of 300 A. This fact explains that the SiC MOSFET competes even with the bipolar devices like Si IGBT with regard to conduction loss.

For the chosen $R_g$, the specific turn-off losses in both modules are similar, while the specific turn-on losses in the SiC MOSFET module is a factor of about 1/3 that of the Si IGBT at 25°C. The real operating temperature of a converter is higher than the room temperature. The losses in the Si IGBT converter increases much more than in a SiC MOSFET converter because the tail current in the IGBT and $Q_{rr}$ in the anti-parallel diode exhibit strong dependency on temperature. In the SiC MOSFET, the turn-on losses decrease and turn-off losses increase, and in overall the total losses slightly increase with increasing temperature as shown in previous work [6].

Moreover, the voltage overshoots are lower in the MOSFET compared to the IGBT. The turn-off losses in the MOSFET is 1/1.7 that of the IGBT, when both modules have similar $V_{os}$. These facts imply that the SiC MOSFET can replace the Si IGBT of the same or even higher voltage class.

The comparison with the similar ringings suggests that the SiC MOSFET beats the Si IGBT even in an application where lower dv/dt and switching frequency are required. With the reduced package and board parasitics, the SiC MOSFET outperforms the Si IGBT of the same or even higher voltage class. These facts imply that the SiC MOSFET can replace the Si IGBT even in higher voltage class.

For the chosen $R_g$, the specific turn-off losses in both modules are similar, while the specific turn-on losses in the SiC MOSFET module is a factor of about 1/3 that of the Si IGBT at 25°C. The real operating temperature of a converter is higher than the room temperature. The losses in the Si IGBT converter increases much more than in a SiC MOSFET converter because the tail current in the IGBT and $Q_{rr}$ in the anti-parallel diode exhibit strong dependency on temperature. In the SiC MOSFET, the turn-on losses decrease and turn-off losses increase, and in overall the total losses slightly increase with increasing temperature as shown in previous work [6].

Moreover, the voltage overshoots are lower in the MOSFET compared to the IGBT. The turn-off losses in the MOSFET is 1/1.7 that of the IGBT, when both modules have similar $V_{os}$. These facts imply that the SiC MOSFET can replace the Si IGBT of the same or even higher voltage class.

The comparison with the similar ringings suggests that the SiC MOSFET beats the Si IGBT even in an application where lower dv/dt and switching frequency are required. With the reduced package and board parasitics, the SiC MOSFET outperforms the Si IGBT of the same or even higher voltage class. These facts imply that the SiC MOSFET can replace the Si IGBT even in higher voltage class.

**VII. CONCLUSION**

The major conclusion derived from the comparative evaluation between the two modules are listed in the following 4 points.

i.) The highest achievable dv/dt is 19.5 V/ns and di/dt is 11 A/ns in the SiC MOSFET module. Similarly, in the Si IGBT module dv/dt is about 17 V/ns and di/dt is 12 A/ns. This information was missing in the datasheet of the modules.

ii.) The SiC MOSFET showed lower voltage overshoot while comparing the modules at similar dv/d, enabling a further increase in the dc-link voltage, i.e., the SiC MOSFET can replace the Si IGBT even in higher voltage class.

iii) The turn-on losses are lower in the SiC MOSFET even in the case with similar ringings. The higher losses in the Si IGBT is primarily because of the higher $Q_{rr}$ of the Si diode. Replacing this diode with the SiC SBD diode would lead to more proportionate turn-on losses between the two modules.

iv) The SiC MOSFET has lower conduction losses (a factor of 1/2.2 and 1/1.7 at 25°C and 125°C respectively at a load current of 300 A) compared to the Si IGBT, which strongly motivate in using unipolar SiC MOSFET instead of Si IGBT. Thus, the lower switching energy losses in both faster and slower switching conditions, the lower conduction losses at all temperatures, and the smaller overshoots indicate that the SiC MOSFET can replace the Si IGBT.

**ACKNOWLEDGMENT**

The authors would like to thank The Research Council of Norway and 6 industry partners who sponsor this project: EFD Induction, Siemens, Eltek, Statkraft, Norwegian Electric Systems, and Vacon AS.

**REFERENCES**


