Comparative evaluation of SiC/GaN “MOSFET” transistors under different switching conditions

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ABSTRACT

The aim of this paper is to conduct a mutual comparison of switching energy losses in cascade gallium nitride (GaN) and silicon “super junction” MOSFET transistor, in both cases designed for a maximum operating voltage of (650 V). For the analysis of switching characteristics of transistors used double pulse test method by using detailed SPICE simulation model. Data on transient on and off processes were generated using the “LTspice” simulation package in a wide range of drain currents with two different gate resistance values of the tested transistors. The total energy losses in the GaN have been simulated during one transistor at (on and off cycle). The obtained results indicate that the superior switching characteristics of GaN devices for a drain current of (30 A) is five to eight times less than the switching characteristics of silicon “MOSFET” transistor when compared to silicon components, especially during operation of transistors with high drain currents.

1. INTRODUCTION

The energy converters and their wider application represent a trends that widely present in the modern industry [1]. The main way to reduce the dimensions of power converters is to limit energy losses of semiconductor switches, both in the steady state and during transient processes caused by current interruptions in transistors [2]. Operation with low drag-source resistances, as well as high maximum operating temperatures of power transistors, make it possible to use smaller dimensions [3]. The operation of energy converters at high switching frequencies enables the use of inductive elements of small dimensions [4]. Until recently, silicon (Si) energy MOSFET transistors were commonly used in low-power (kW) and medium-voltage (100–900 V) converters [5].

In order to achieve a significant reduction in drain-source resistance (RDS(on)) in MOSFET transistors, in the last twenty years in the world (for operating voltages higher than 200 V) are often used “super junction” MOSFET transistors [6]. Such power transistors have many times lower resistance of drains-sources at high operating voltages compared to the standard MOSFETs [7].

However, in recent years, energy transistors based on semiconductor materials with a wide band gap (WBG) have appeared on the market, which have much better physical characteristics than silicon [8]. The most commonly used WBG materials are silicon carbide (SiC) and gallium nitride (GaN) [9]. Unlike the standard metal-oxide-semiconductor field effect transistors (MOSFETs), in which a conductive channel is established or terminated under the gate control electrode due to the presence of an electric field in the
insulating oxide [10]. In gallium-nitride transistors there is a thin conductive layer between two heterostructures (usually GaN and AlGaN), called two-dimensional electron gas (2DEG) [11].

In the range of medium operating voltages, it is expected that gallium-nitride energy transistors (HEMT) have significantly better characteristics than silicon components, primarily due to the high mobility of charge carriers [12]. Moreover, some topologies of energy converters, such as the totem pole of a power factor correction (PFC) circuit, could not even be practically realized with standard silicon transistors [13]. For these reasons, before the development of a new generation of low-power energy converters began, the justification for using new GaN HEMTs instead of existing Si MOSFET transistors was considered [14]. Only switching transistors in a tripod housing type TO-247, which can be controlled by standard igniters (drivers) for Si MOSFET transistors, are considered [15]. There is not much data in the available world literature on experiments in which a comparative analysis of switching losses of GaN HEMT and SJ MOSFET energy transistors was conducted. A comparison of one GaN HEMT, SiC MOSFET and Si SJ MOSFET was performed [16]. However, the focus of the test in these cases was on the analysis of transient processes of voltages and currents (determining the values of dV/dt and di/dt). Compared to the SJ MOSFET, GaN HEMT switches have much more pronounced oscillations during transients (ringing), even in the case of operation with an optimized ignition circuit [17]. Quantification of switching energy losses in this work has not performed.

Duarteand et al. [18] conducted an experimental comparison of switching losses in eight different energy transistors based on materials with a large energy gap: four unnamed SiC MOSFETs and GaN HEMTs were tested each. However, the conducted research was limited to the analysis of losses caused by the output capacitance of the transistor. No experiments were performed with Si SJ “MOSFET”, but the experimental results of SiC and GaN transistors were compared with the data on losses in silicon FETs, reported in the literature [19]. Depending on the manufacturer and the type of the super junction MOSFET, large variations of the influence of the interruption frequency on the total energy losses of the transistor have been established. However, the total switching losses were not quantified in this case.

In our paper, for the analysis of switching characteristics, simple simulation models of lighter circuits were used, due to attenuated transients during power switching were obtained. Their use for modeling the response of the MOSFET with open feedback is completely justified, since such silicon transistors have large input capacitances.

The super junction MOSFET has a fairly fast response when open feedback is interrupted, but requires a much more advanced igniter circuit when interrupted with closed feedback. On the other hand, GaN HEMT has low input capacitance and high conductance, which makes it sensitive to the oscillatory response, but also gives the opportunity to achieve optimal transients using advanced lighters. A large influence on the voltage and current slopes (dV/dt and di/dt) during transients can be achieved by using drivers that have the ability to digitally control the gate currents. By applying the mentioned methods, it is possible to suppress the oscillatory response of the transistor and reduce the switching losses.

For these reasons, to fully exploit the potential of semiconductor switches based on materials with a large energy gap, it is necessary to use very advanced driver topologies. However, in the presented paper, we did not take into account the effects of the ignition circuit construction on the switching characteristics of the tested energy transistors. This topic remains to be considered in some of the future research.

2. METHOD

The paper presents a comparison of switching losses of two types of modern power transistors, designed for a nominal operating voltage of 650 V and a drain current of 30 - 40 A. The first transistor tested is a silicon “super junction” (SJ) MOSFET with induced channel, “STW57N65M5”, while the second considered element is “TP65H035WS”, a transistor of complex cascade structure, composed of a control low-voltage silicon “MOSFET” and a high-voltage embedded gallium H-gallium channel.

Transistor manufacturer of the power translator “STW57N65M5” [20] states that this n-channel V MOSFET is a typical representative of the MDMESH series, which is characterized by extremely low drain-source resistance, unmatched among silicon MOSFETs from other manufacturers. On the other hand, the transistor manufacturer “TP65H035WS” cites this component as an optimal switching element that combines the superior switching characteristics of GaN transistors with the reliability and affordability of silicon power MOSFETs [21].

2.1. Simulation model

Figure 1 shows the electrical circuit diagram used in the simulation model for the calculation of switching energy losses. The method of testing double-pulse energy transistors (DPT) was simulated. Testing of the dynamic characteristics of power transistor Q1 is performed as: i) at the beginning of the process the...
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electrolytic capacitor \( S_{11} \) is charged (\( V_{\text{out}} = 385 \text{ V} \)), and power transistor \( Q_1 \) is off; ii) during the first switching on of transistor \( Q_1 \), current from capacitor \( S_{11} \) flows through inductor \( L_{11} \), and energy accumulates in it; iii) after a certain time, transistor \( Q_1 \) is switched off; the current through the inductor \( L_{11} \) remains constant and it is possible to record the voltage waveforms and the tripping current of transistor \( Q_1 \), iv) after the defined time has elapsed, transistor \( Q_1 \) is switched on again and the current through the inductor \( L_{11} \) continues to rise and during the switching on of the transistor \( Q_1 \), the recording of voltage and current waveforms is performed.

Since the control elements of both tested devices are silicon MOSFET transistors, the lighter models at the gates had the same characteristics. A very simple circuit was used, with two voltage sources and a push-pull configuration of two driver MOSFET transistors in each igniter circuit for testing energy transistors. The driver circuit model consists of one source of constant DC voltage of 13.5 V (\( V_{31} \)), connected to the source of the channel MOSFET push-pull circuit, and another pulse, with pulses of 13.5 V amplitude (\( V_{32} \)), connected to the gates of both push-pull ignition transistors. Using a pulse source on the gates of the driver transistors, a pulse-width signal (PWM) with a frequency of 66 kHz was simulated, with a constant duty cycle of about 50%. The switching time of the pulse source was set to \( T_{\text{ON}} = 7.74 \mu\text{s} \), the time pause between the two pulses (“dead time”) to \( D_T = 120 \text{ ns} \), and the establishment times of the ascending and descending edges \( T_{\text{rise}} = T_{\text{fall}} = 10 \text{ ns} \).

Elementary SPICE models of silicon transistors with a gate width \( W = 5000 \mu\text{m} \) and a gate length \( L = 200 \mu\text{m} \) were used to model the MOSFET ignition transistors, both n-channel and p-channel. Resistors \( R_{g1} \) and \( R_{g2} \) are added in the gates of the transistor to suppress oscillations in transient modes, but their presence also affects the increase of switching losses. Detailed simulation models of transistor manufacturers, developed in simulation programs from the SPICE family [20], were used for both tested transistors.

Simulation models describing the operation of transistors at room temperature were used, without taking into account additional thermal effects. The output inductance, \( L_{11} \), during the simulations, was proportional to the current of the source (\( I_{19} \)) of the tested power transistor \( Q_1 \), according to (1) [21]:

\[
L_{11} = \frac{V_{\text{out}}(T_{\text{Out}}-2D_T)}{I_{19}}
\]

The capacitance of \( S_{11} \) was constant (2240 \( \mu\text{F} \)) [22]. The dissipated power in the MOSFET and HEMT transistor (P) can be calculated according to (2):

\[
P = I_D V_D + V_G I_G + V_S I_S
\]

Where: \( I_D \); drain current, \( I_G \); gate current, \( I_S \); source current, \( V_D \); drain ground voltage, \( V_G \); gate ground voltage, \( V_S \); voltage source.

Based on the dissipation energy, calculated by using (2), the energy of total dynamic losses during one operating cycle (\( W_{\text{dyn}} \)) can be obtained as the sum of energy losses during transient processes of switching off (\( W_{\text{off}} \)) and switching on (\( W_{\text{on}} \)) of transistors as [23]:

\[
W_{\text{dyn}} = W_{\text{off}} + W_{\text{on}} = \int_{t_1}^{t_2} P_{\text{off}} \, dt + \int_{t_1}^{t_2} P_{\text{on}} \, dt
\]

Figure 1. Electrical scheme of the model for testing power transistors by using the double pulse method
In order to reduce the possibility of error, the interruption and establishment currents are given in the form of a list, which automates the whole process. All calculations were performed for two values of resistors in the gate (R\text{g1}=5 \, \Omega \text{ and } R\text{g2}=15 \, \Omega). Transistor on and off currents of (0.4 A, 1 A, 4.5 A, 7 A, 10 A, 20 A and 30 A), were simulated. By using the current list, in the LTspice software package [24], a simple comparative display of voltage, current and power for all set current values is enabled. At the end of the calculation, all results were recorded in one ASCII file.

In order to separate the results by streams in separate files, a program written for this purpose in the Python software tool was used. A dedicated program, written in the MATLAB software package was used to calculate the loss energies as well as all other parameters. Table 1 shows the basic technical characteristics of the silicon "super junction" MOSFET transistor, "STMicroelectronics" STW57N65M, and the cascade gallium-nitride HEMT, "Transphorm" TP65H035WS.

<table>
<thead>
<tr>
<th>Power transistor type</th>
<th>Breakdown drain-source voltage V\text{ds (br)} [V]</th>
<th>Gate threshold voltage, V\text{th} [V]</th>
<th>Drain continuous current, I\text{d (at 25°C)} [A]</th>
<th>Maximum allowable dissipation P\text{diss (at 25°C)} [W]</th>
<th>Static resistance drain-source, r\text{ds(on)} [mΩ]</th>
<th>Inverse recovery charge, Q\text{rr} [nC]</th>
</tr>
</thead>
<tbody>
<tr>
<td>STW57N65M</td>
<td>650</td>
<td>3.3-4.8</td>
<td>46.5</td>
<td>165</td>
<td>35-41</td>
<td>8000</td>
</tr>
<tr>
<td>TP65H035WS</td>
<td>650</td>
<td>3-5</td>
<td>4.2</td>
<td>250</td>
<td>56-63</td>
<td>170</td>
</tr>
</tbody>
</table>

Both transistors are designed for maximum drain-source voltage of 650 V, as well as a continuous drain current of about 40 A (at room temperature of Θa=25°C; in both cases, at a high temperature of Θa=100°C, the maximum drain current falls below 30 A).

From Table 1, it can be seen that the key size, which distinguishes silicon MOSFET and cascade GaN HEMT electrification accumulated in capacitances due to the influence of the inverse polarization of the MOSFET or in other word the direct polarization of the parasitic return diode source-drain (reverse recovery charge; Q\text{rr}). This parameter, which crucially affects the operation of semiconductor switches at high frequencies, in the cascade transistor TP65H035WS is about 50 times smaller than the "super junction" MOSFET STW57N65M, similar nominal parameters. By the way, even such a small value of the charge of the inverse recovery of the transistor TP65H035WS is a consequence of the existence of low-voltage igniter silicon MOSFET in the cascade structure: in monolithic gallium-nitride HEMT, Q\text{rr},0S.

3. SIMULATION RESULTS AND DISCUSSION

Simulation results on switching energy losses of GaN HEMT and Si MOSFET are shown in Table 2 and Table 3, for seven different simulated drain current values. Table 2 shows the data obtained by simulating the presence of an additional gate resistor in a 5 Ω, while Table 3 shows the data generated with a 15 Ω resistor. The designations used in the Table have the following meaning:

- W\text{on,GaN}: total energy losses when switching on GaN HEMT
- W\text{off,GaN}: total energy losses when switching off GaN HEMT
- W\text{dyn,GaN}: total dynamic energy losses during one cycle of on and off GaN HEMT
- W\text{on,Si}, W\text{off,Si}, W\text{dyn,Si}: by analogy with the GaN transistor, energy losses in the silicon MOSFET transistor in the corresponding transients.

<table>
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<tbody>
<tr>
<td>0.4</td>
<td>80.3</td>
<td>116.4</td>
<td>29.1</td>
<td>118.4</td>
<td>109.4</td>
<td>234.8</td>
</tr>
<tr>
<td>1</td>
<td>79.8</td>
<td>130.2</td>
<td>25.9</td>
<td>66.2</td>
<td>105.7</td>
<td>196.4</td>
</tr>
<tr>
<td>4.5</td>
<td>86.5</td>
<td>160.7</td>
<td>21.3</td>
<td>7.4</td>
<td>107.8</td>
<td>168.1</td>
</tr>
<tr>
<td>7</td>
<td>95.5</td>
<td>177.3</td>
<td>20.1</td>
<td>13.6</td>
<td>115.1</td>
<td>190.9</td>
</tr>
<tr>
<td>10</td>
<td>105.2</td>
<td>232.8</td>
<td>20.5</td>
<td>29.4</td>
<td>125.7</td>
<td>292.2</td>
</tr>
<tr>
<td>20</td>
<td>136.7</td>
<td>604.3</td>
<td>21.4</td>
<td>113</td>
<td>158.1</td>
<td>717.3</td>
</tr>
</tbody>
</table>

From Table 2, it can be seen that, with low gate resistance (5Ω) and in the case of working with low drain current, the difference in energy losses between NEMT and MOSFET transistors is not too large. However, when the drain current start to rise and approach the nominal value, the difference in energy losses...
increases, which, for I_D=30 A, become five times higher in the silicon "super junction" MOSFET transistor compared to the cascade GaN HEMT. On the other hand, when there is an additional (15 \( \Omega \)) resistor in the gate, the energy losses in the STW57N65M5 MOSFET become 7-12 times higher than in the NEMT TP65H035WS as shown in Table 3.

Table 3. Comparative display of switching power losses during simulation of GaN HEMT "Transphorm" TP65H035WS and Si MOSFET "STMicroelectronics" STW57N65M5, with a resistor in the gate of (15 \( \Omega \))

<table>
<thead>
<tr>
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</tr>
</thead>
<tbody>
<tr>
<td>0.4</td>
<td>51.4</td>
<td>179.6</td>
<td>18.9</td>
<td>656.3</td>
<td>70.3</td>
<td>835.9</td>
</tr>
<tr>
<td>1</td>
<td>54.9</td>
<td>192.0</td>
<td>19.7</td>
<td>611.5</td>
<td>74.6</td>
<td>803.5</td>
</tr>
<tr>
<td>4.5</td>
<td>64.6</td>
<td>242.7</td>
<td>19.2</td>
<td>447.5</td>
<td>83.8</td>
<td>690.2</td>
</tr>
<tr>
<td>7</td>
<td>74.3</td>
<td>270.9</td>
<td>19.6</td>
<td>438.9</td>
<td>93.9</td>
<td>709.8</td>
</tr>
<tr>
<td>10</td>
<td>86.2</td>
<td>378.9</td>
<td>20.5</td>
<td>438.7</td>
<td>106.7</td>
<td>817.6</td>
</tr>
<tr>
<td>20</td>
<td>123.4</td>
<td>573.1</td>
<td>26.9</td>
<td>495.1</td>
<td>152.3</td>
<td>1086.2</td>
</tr>
<tr>
<td>30</td>
<td>167.9</td>
<td>1064.0</td>
<td>38.7</td>
<td>602.9</td>
<td>206.6</td>
<td>1666.9</td>
</tr>
</tbody>
</table>

From Tables 2 and 3, it can be seen that the switching losses of the STW57N65M transistor MOSFET are, as expected, significantly higher than the NEMT losses of the TP65H035WS. This statement is valid both for losses when switching on and off the transistor and, therefore, for the total operating losses, for both simulated resistances in the gate voltage and current waveforms. Based on the calculated energy losses illustrated in Tables 2 and 3, we can see that:

a. In both the transistors, NEMT and the MOSFET, the switch-off losses were significantly smaller compared to the switch-on losses.

b. Figures 2 and 3 show the waveforms of transient voltages and currents, simulated in transistors TP65H035WS and STW57N65M5 with (5\( \Omega \)) resistor in the gate during the switching off process.

c. Figures 4 and 5 show the waveforms obtained during the simulation of the switching process with (5\( \Omega \)) resistor in the gate during the switching on process.

d. Figures 6-9 show the waveforms of the same electrical quantities, but obtained when working with a resistor of (15 \( \Omega \)) in gates as; voltages (Figure 6) and currents (Figure 7) when switching off power translators, while voltages (Figure 8) and currents (Figure 9) recorded during the switching on of power transistors.

![Figure 2](image1.png)

Figure 2. Comparative representation of transient voltages of drain-source transistors TP65H035WS (left) and STW57N65M5 (right), during switching off, with resistor in gate of (5 \( \Omega \)), for simulated drain currents of (0.4 A, 1 A, 4.5 A, 7 A, 10 A, 20 A and 30 A). Working with the (15 \( \Omega \)) gate resistor significantly dampened the voltage and current oscillations of the GaN HEMT in cases of current interruption up to (1 A), when the transistors are switched off (Figures 2, 3, 6 and 7). However, with the tested MOSFET, the increase in resistance in the gate led to a significantly higher current transfer during the shutdown process, especially for currents up to (1 A). There is also a delay in the increasing of the drain-source voltage of the MOSFET by about (100 ns).
Figure 3. Comparative representation of transient drain currents of transistors TP65H035WS (left) and STW57N65M5 (right), during switching off, with resistor in gate of (5 Ω), for simulated drain currents of (0.4 A, 1 A, 4.5 A, 7 A, 10 A, 20 A and 30 A)

Figure 4. Comparative representation of transient voltages of drain-source transistors "Transphorm" TP65H035WS (left) and "STMicroelectronics" STW57N65M5 (right), during switching on process, with gate resistor of 5 Ω, for simulated drain currents of (0.4 A, 1 A, 4.5 A, 7 A, 10 A, 20 A and 30 A)

Figure 5. Comparative representation of transient drain currents of transistors "Transphorm" TP65H035WS (left) and "STMicroelectronics" STW57N65M5 (right), during switching on process, with (5 Ω) gate resistor, for simulated drain currents of (0.4 A, 1 A, 4.5 A, 7 A, 10 A, 20 A and 30 A)
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The analysis of waveforms shown in Figures 4, 5, 8 and 9, generated during the simulation of the process of establishing currents through transistors, shows very large current shifts. The addition of a larger resistor in the gate reduced the current transfer amplitudes in HEMTs by about 30–50%, but in MOSFETs there was an increase in the amplitude of the current transfer, and a delay in the drop in drain-source voltage by about 60 ns. However, as can be seen in Figures 5 and 9, the increase in the resistor in the gate of the MOSFET led to the suppression of high-frequency oscillations, superimposed on the current signal.

Transient powers, dissipated in transistors during transients, are obtained by multiplying the obtained values of voltages and currents. For simulated GaN HEMT currents, the observed maximum transient power during oscillations caused during interruption of very small currents (up to 1A) is 8 kW. When establishing currents in HEMT TP65H035WS, significantly higher transient power peaks were recorded: up to 22 kW (Rg=5 Ω). However, in both cases, the duration of these power transitions was very short: of the order of several ns. In the case of the tested MOSFET, the peak values of the transient powers were similar to those of GaN HEMT (for Rg=5 Ω off, 9 kW; on, 24 kW), but due to the significantly longer duration of these transients (up to 70 ns), the values of switching loss energy were many times higher.

Similar values of transient power were recorded in the case when the MOSFET “STW57N65M5” worked with Rg=15 Ω. With the HEMT “TP65H035WS”, slightly different values of transient power were calculated: up to 4.8 kW during power outages, and up to 20 kW, during their establishment. However, despite the high peak power values, in GaN HEMT-y the total power dissipation transient lasted up to (15 ns), while in the silicon MOSFET “STW57N65M5” transistor, the power transient (with a peak value of 24 kW) lasted up to (100 ns). Therefore, the losses of the simulated MOSFET activation were 4-6 times higher than with the cascade NEMT.

Figures 2-9 show a much more pronounced oscillatory response in GaN HEMT transistors compared to Si MOSFET, especially when interrupting small drain currents. The increase in resistance in the gate of the tested transistors partially suppressed the oscillations caused by low current interruptions, but also led to a significant increase in dynamic energy losses, primarily in MOSFET transistors.

4. CONCLUSION

The paper presents a simulation model which describes the analysis of switching energy losses in silicon MOSFET and GaN HEMT transistors. Voltage and current waveforms were analyzed during the transient processes of establishing and interrupting the drain current, for two different values of additional resistance (5 Ω) and (15 Ω) in the gate of these transistors.

Analysis of the simulation results showed that the silicon MOSFET transistor “STMicroelectronics” STW57N65M5 has several times higher switching losses compared to the GaN HEMT “Transphorm” TP65H035WS. The ratio of switching losses depends on the breaking current and the resistor in the gate. For currents greater than (10 A), with an additional resistor (5 Ω) in the gate, the losses in the silicon transistor are 100% to 400% higher than in GaN NEMT. When there is a (15 Ω) resistor in the gate, the losses in the Si MOSFET are as much as 600% to 700% higher compared to GaN NEMT. The increase in the resistor in the gate of the NEMT transistor TP65H035WS contributed to the suppression of the oscillatory current response.
However, although the application of the same measure to MOSFET transistors led to the suppression of superimposed high-frequency oscillations, the current transfer amplitudes were even higher than in the case of operation with a small additional gate resistance.

From the point of view of reducing energy losses, the GaN HEMT “TP65H035WS” transistor, in the applied simulation models, demonstrated superior characteristics compared to the top “superjunction” MOSFET transistor, with up to eight times lower total switching energy losses for drain current of 30 A. However, before deciding to replace silicon components with new GaN semiconductor switches, it is necessary to consider other important issues, such as suppressing current oscillations and achieving high reliability of applied transistors.

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