

SiC/GaN Power Semiconductor Devices Theoretical Comparison and Experimental Evaluation

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Abstract—SiC and GaN power transistors conduction loss and switching losses are compared in this paper. In order to compare performance of the same power rating device, a theoretical analysis is given to compare SiC device conduction loss and switching losses change when device maximal blocking voltage reduces by half. Then static and dynamic characteristics of commercial SiC and GaN power transistors are compared and it is shown that GaN-HEMT would still have smaller ON-state resistance and inter-electrode capacitance in comparison with a 600V SiC device. After that, switching losses E_{sw} of a GaN-HEMT is measured and compared with that of a 1200V SiC-JFET and a 600V SiC-MOSFET, in which it is shown that E_{sw} of a GaN-HEMT is smaller than a SiC power transistor with the same power rating.

Keywords—Wide bandgap power semiconductor device; GaN-HEMT; SiC-JFET; SiC-MOSFET; Conduction loss; Switching loss

I. INTRODUCTION

Power electronics systems are largely used in electrical vehicles for electrical energy conversion [1], where power semiconductor devices play an important role. Understanding the characteristics of power semiconductor devices could help engineers design high efficiency, high power density power converters so as to improve overall performance of electrical vehicles such as increase range and reliability.

Wide bandgap power semiconductor devices like silicon carbide (SiC) and gallium nitride (GaN) are becoming one research hot topic recently, because they could operate in higher temperature, higher frequency and realize higher energy conversion efficiency in comparison with traditional silicon (Si) power semiconductor devices. Commercial SiC transistors (JFET, MOSFET) are able to withstand blocking voltage above 1200V, while commercial GaN transistor (HEMT) can block a maximal voltage of 650V. Current rating of the above devices can be found from a few amperes to a few tens of amperes. Both of the SiC and GaN devices can be applied in electrical vehicle based battery charger or power converters. Power semiconductor devices produce losses when they convert energy, so how to compare SiC and GaN power devices characteristics such as conduction loss and switching losses would be helpful for engineers when designing power electronics systems using in electrical vehicles.

Experimental comparison between SiC and Si power semiconductor devices [2] or between GaN and Si power semiconductor devices [3] can be found in literature. However,

there are few publications about experimental comparison between SiC and GaN power semiconductor devices. One major reason is that voltage ratings of most commercial SiC and GaN devices do not match. The objective of this paper is at first to theoretically analyze how losses of SiC power devices change when blocking voltage reduces from 1200V to 600V and then experimentally compare switching losses of a commercial SiC-JFET, SiC-MOSFET and GaN-HEMT in different switching conditions.

The paper is structured with following sections: at first, theoretical comparison of conduction loss and switching losses of SiC power devices when reducing blocking voltage is analyzed. Then, commercial SiC, GaN power devices characteristics of their datasheet values are compared. Meanwhile, measurement methods are presented on how to experimentally measure those characteristics. After that, device switching energy of a SiC-JFET, a SiC-MOSFET and a GaN-HEMT is measured based on switching circuit of each. Conclusions are given at last.

II. THEORETICAL COMPARISON

A. Conduction loss comparison

The structure of a MOSFET is shown in Fig. 1a, where it is shown that device ON-state resistance R_{ON} is mainly constituted by device channel resistance R_{ch} and drift region resistance R_{drift} .

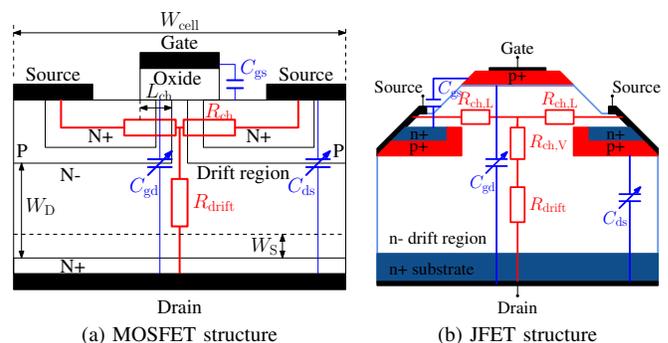


Fig. 1: Structure of different power transistors

Multiplying by device active area A , the relation of each specific resistance ($m\Omega \cdot mm^2$) is expressed by the following equation:

$$R_{ON,sp} = R_{ch,sp} + R_{drift,sp} \quad (1)$$

where device specific drift region resistance $R_{drift,sp}$ can be expressed by a function of device maximal blocking voltage V_{DSS} , material permittivity ϵ , carrier mobility in the drift region μ and critical electrical field E_c as given in [4]:

$$R_{drift,sp} = \frac{4V_{DSS}^2}{\epsilon\mu E_c^2} \quad (2)$$

Shown in [4], the minimal $R_{drift,sp}$ is a function of $V_{DSS}^{2.5}$, which means that for a 600V device, its $R_{drift,sp}$ value could decrease to a factor of 5.6 in comparison with a 1200V device. Device $R_{drift,sp}$ is also proportional to device drift region thickness W_D . Thus, device W_D would decrease for a maximal factor of 5.6 for a 600V device than a 1200V device.

Device specific channel resistance $R_{ch,sp}$ can be approximately expressed by a function of device channel length L_{ch} , unit cell width W_{cell} , channel mobility μ_{ch} and accumulated charge in the channel Q_{ch} as shown in [5]:

$$R_{ch,sp} = \frac{L_{ch} \cdot W_{cell}}{\mu_{ch} \cdot Q_{ch}} \quad (3)$$

According to the results presented by authors in [6], $R_{ch,sp}$ varies little on V_{DSS} voltage.

By applying the parameters given by authors in [7] for a SiC-MOSFET, $R_{ch,sp}$ is found to be about 40% of the total $R_{ON,sp}$ of a 1200V device. Thus, by combining the above equations, $R_{ON,sp}$ of a 600V device decreases to half of the value of a 1200V device.

The structure of one type of a commercial SiC-JFET (from Infineon) is shown in Fig. 1b, where device structure is quite similar to that of the MOSFET. For this device, $R_{ON,sp}$ equals to the sum of the specific lateral channel resistance $R_{ch,L}$, the specific vertical channel resistance $R_{ch,V}$ and the $R_{drift,sp}$. By applying parameters given by authors in [8], it is found that $R_{ch,sp}$ is about half of the $R_{ON,sp}$ value. Thus, for this type of SiC-JFET $R_{ON,sp}$ of a 600V device is about 60% of the value of a 1200V device. For another type of SiC-JFET where there is no lateral channel, by using the given doping concentration and thickness of both the drift region and device vertical channel in [9], it is found that $R_{ON,sp}$ of a 600V device could decrease by a factor of 2 than that of a 1200V device.

It can be summarized that according to the above analysis and calculation, $R_{ON,sp}$ of a 600V SiC device could decrease by a factor of 2 than a 1200V SiC device.

B. Switching loss comparison

It is illustrated in Fig. 1 the inter-electrode capacitances C_{gd} , C_{ds} and C_{gs} between each terminal. Different like C_{gs} , C_{gd} and C_{ds} are V_{DS} voltage dependent capacitances and their values can be approximately calculated by the following equation:

$$C_x = \frac{\epsilon \cdot A_x}{W_S} \quad (4)$$

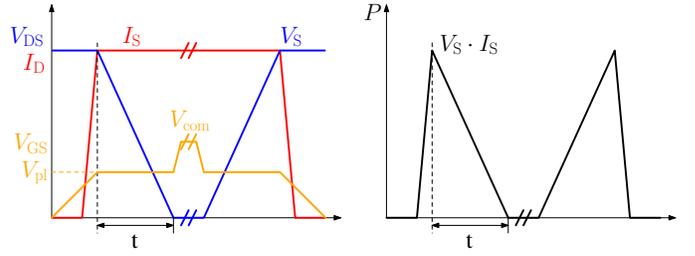


Fig. 2: Ideal switching waveforms and switching losses calculation

where C_x refers to either C_{gd} or C_{ds} , A_x refers to the active area of each capacitance and W_S is depletion region thickness, which is dependent on device switching voltage V_S .

Active area of C_{gd} and C_{ds} is obtained by multiplying a coefficient b to the device area A . The relation between W_D and W_S is obtained by the following equation given in [4]:

$$W_S = W_D \cdot \sqrt{\frac{V_S}{V_{DSS}}} \quad (5)$$

By combining eq.(4) and eq.(5), stored charge Q_x of each capacitor during switching can be obtained by:

$$\int_0^{Q_x} dq_x = \int_0^{V_S} C_x dq_x \quad (6)$$

$$Q_x = \frac{2b \cdot \epsilon \cdot A}{W_D} \cdot \sqrt{V_{DSS}} \cdot \sqrt{V_S}$$

Thus, the comparison of specific charge ($Q_{x,sp}$) between 600V and 1200V device can be obtained by following equation, which is shown that $Q_{x,600V}$ is bigger than $Q_{x,1200V}$.

$$\frac{Q_{x,600V}}{Q_{x,1200V}} = 0.7 \cdot \frac{W_{D,1200V}}{W_{D,600V}} \quad (7)$$

Power transistor ideal switching waveforms (device switching at voltage V_S and current I_S) is shown in Fig. 2, where transistor gate-drain charge Q_{gd} plays an important role in device switching, because its discharge and charge time t by gate current I_g influence on device switching losses. Thus, device switching losses E_{sw} of one period can be approximately calculated by the following equation:

$$E_{sw} = V_S \cdot I_S \cdot t = V_S \cdot I_S \cdot \frac{Q_{gd}}{I_g} = V_S \cdot I_S \cdot \frac{Q_{gd}}{V_{com} - V_{pl}} \cdot R_g \quad (8)$$

where R_g is gate resistor, V_{com} is controlled gate voltage and V_{pl} is Miller-plate voltage. It is to be noted that device output capacitance C_{oss} stored energy E_{oss} would be dissipated during turn-ON switching and E_{oss} would be recovered during turn-OFF switching. By adding E_{oss} in turn-ON switching and subtracting it from turn-OFF switching, eq.(8) can be still used to estimate device total switching loss.

It is shown in this equation that E_{sw} is proportional to Q_{gd} , thus it is proportional to the term $\sqrt{V_{DSS}} \cdot \frac{A}{W_D}$. In contrary

to the comparison result of $R_{ON,sp}$, it is found that device specific switching loss $E_{sw,sp}$ of 600V is bigger than 1200V device, because device specific capacitance of 600V device is bigger than 1200V device.

C. 600V/1200V device comparison

Device maximal conduction current I_D is limited by its heat dissipation, which is calculated by the following equation:

$$I_D^2 \cdot R_{ON} \cdot R_{th} = T_{j(max)} \quad (9)$$

Only device thermal resistance R_{th} of die is considered (without influence of packaging), which is determined by device length (which is supposed to be device drift region thickness W_D for a transistor), active area A and material thermal conductivity k . Thus,

$$R_{th} = \frac{W_D}{k \cdot A} \quad (10)$$

By combining eq.(9) and eq.(10), following equation can be obtained:

$$I_D = \sqrt{T_{j(max)} \cdot k \cdot \frac{A}{\sqrt{R_{ON,sp}} \cdot \sqrt{W_D}}} \quad (11)$$

As shown in section II-A, $R_{ON,sp}$ reduces half when V_{DSS} decreases to a half. Thus, for a 600V device of the same current rating, $\frac{A}{\sqrt{W_D}}$ should decrease to a factor of 1.4 of a 1200V device.

By combing with above E_{sw} analysis, following equation can be obtained in terms of the E_{sw} comparison between 1200V device and 600V device, which shows that E_{sw} is inversely proportional to the square root of device drift region thickness. According to eq.(12), switching loss of a 600V device might be superior to a 1200V with the same current rating.

$$\frac{E_{sw,1200V}}{E_{sw,600V}} = 2 \cdot \sqrt{\frac{W_{D,600V}}{W_{D,1200V}}} \quad (12)$$

SiC and GaN power devices will be experimentally compared in the next section in order to evaluate their performance.

III. EXPERIMENTAL VALIDATION

A. Device characteristics comparison and measurement

Device R_{ON} datasheet values of a SiC-JFET (IJW120R100T1, 1200V/26A, $V_{th} \approx -13.5V$), a 1200V SiC-MOSFET (CMF10120D, 1200V/24A, $V_{th} \approx 2.5V$), a 650V SiC-MOSFET (SCT2120AF, 650V/29A, $V_{th} \approx 2.8V$) and a GaN-HEMT (GS66508P, 650V/30A, $V_{th} \approx 1.4V$) are compared in Fig. 3, which shows that for a power device with the same current rating, R_{ON} of GaN-HEMT is about half of that of SiC device. R_{ON} of 650V SiC-MOSFET is about 75% of 1200V device, which confirms the theoretical study that in comparison with a 1200V SiC device with the same current rating, R_{ON} of a 600V SiC would decrease by a factor of 2ρ ($\rho = \frac{A_{(600V)}}{A_{(1200V)}} < 1$), which might be still superior to GaN

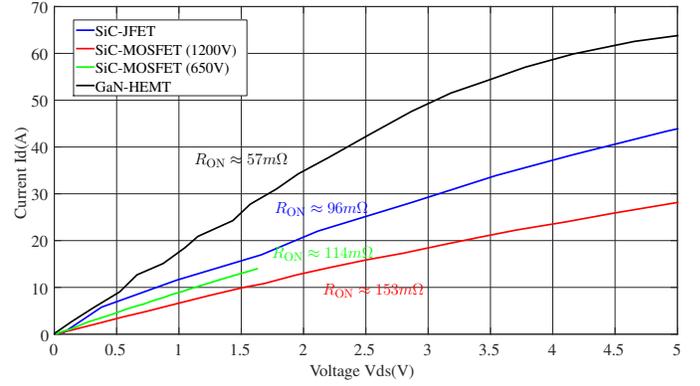


Fig. 3: Device R_{ON} comparison at 25°C

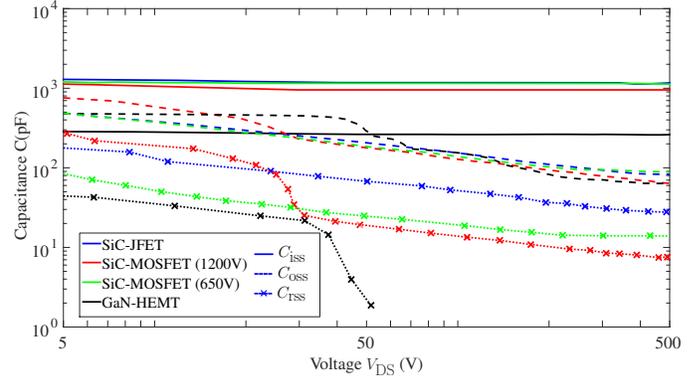


Fig. 4: Device inter-electrode capacitance comparison

device. Device datasheet of another 600V/40A SiC-MOSFET [10] (GP1T072A060B, 600V/40A, $V_{th} \approx 2.8V$) show that its R_{ON} is about 72mΩ, which is still bigger than GaN device.

Device R_{ON} values can be experimentally measured in a curve tracer or in any electrical circuit where device conduction current and voltage drop are measured.

Datasheet values of the inter-electrode capacitance comparison of the above devices is shown in Fig. 4, where device input capacitance $C_{iss} = C_{gs} + C_{gd}$, output capacitance $C_{oss} = C_{ds} + C_{gd}$ values of SiC-JFET and SiC-MOSFET are similar. Reverse transfer capacitance $C_{rss} = C_{gd}$ of GaN-HEMT is much smaller than that of SiC-JFET and SiC-MOSFET, which demonstrates a faster transition than SiC devices. Shown in Fig. 4, Q_{gd} of GaN-HEMT is about 5 times smaller than that of SiC-MOSFET and 10 times smaller than that of SiC-JFET if device switches from 300V.

It is also presented in Fig. 4 that 600V inter-electrode capacitances are bigger than 1200V device in some V_{DS} voltage range, which confirms the above theoretical analysis. If one compares the datasheet of the above 600V/40A SiC-MOSFET with a 1200V/32A SiC-MOSFET [11] (GP1T080A120B, $V_{th} \approx 2.8V$) of another manufacturer, it can be noted that inter-electrode capacitances of the former device are also bigger than the latter one.

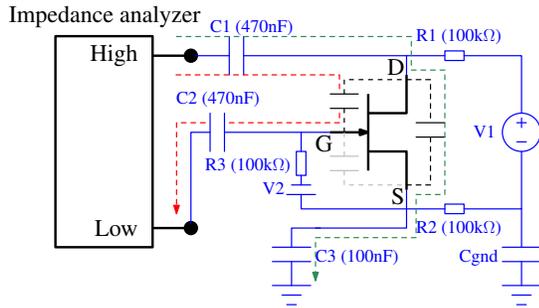


Fig. 5: Power transistor C_{gd} measurement by an impedance analyzer with ground connection

The inter-electrode capacitances values of the GaN-HEMT in Fig. 4 are given on a linear-linear scale in the device datasheet. Thus, it is difficult to extract C_{rss} value due to the strong non-linearity of its value. Power semiconductor device inter-electrode capacitances can be measured by small signal method, where device is biased by external DC voltage and small signal can be either generated by an impedance analyzer [12] or by a vector network analyzer [13].

One solution to measure device inter-electrode capacitance is shown in Fig. 5, where an impedance analyzer (IA) and ground connection is used. Device V_{DS} and V_{GS} are biased by external voltage sources. Three external capacitors are used to block the DC voltage between device terminals with IA connector and ground, while their impedance is neglected when passing high frequency (MHz range) AC current. High impedance branches are constituted by three big resistances, which guarantees that all the AC current flow through the transistor. In the electrical circuit shown in Fig. 5, only current flowing through C_{gd} is measured by IA, because current flowing through capacitance C_{ds} flows to the ground. By varying V_{DS} voltage, device C_{gd} values of different biased voltages are measured. Other measurement circuits can be used to measure C_{gs} and C_{ds} capacitance with similar measurement principle.

By knowing device inter-electrode capacitances, device switching losses can be measured and results will be presented in the next subsection.

B. Device switching losses measurement

The switching energy E_{sw} of above 1200V/26A SiC-JFET, 650V/29A SiC-MOSFET and 650V/30A GaN-HEMT are compared.

The electrical circuit of the switching mesh is shown in Fig. 6a, in which it is constituted by a bus capacitor C_{bus} , a half bridge circuit with two power semiconductor devices S1 and S2 together with their drivers. Lower device drain switching current I_D and drain source switching voltage V_{DS} are measured to calculate the device switching energy.

For the SiC-MOSFET, the realization circuit is shown in Fig. 6b, in which the device is in TO-220 package. The device is switched with a gate voltage from -5V to 20V and the external gate resistance is 0Ω. A hall-effect current

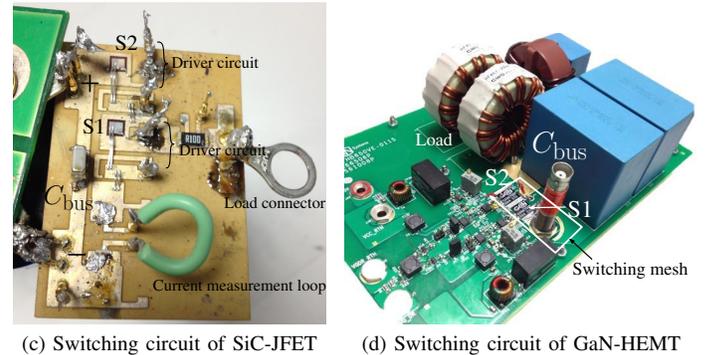
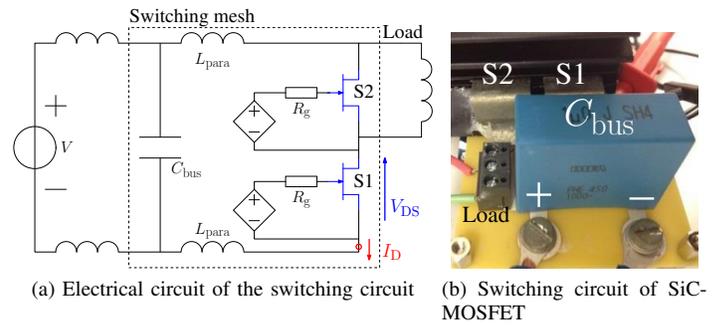


Fig. 6: Electrical circuit of the switching circuit and their realization

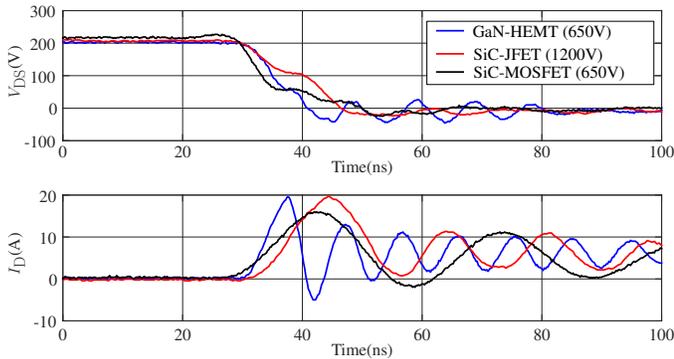
probe (TCP312, 100MHz) is used to measure I_D and an active differential voltage probe (TA043, 100MHz) is used to measure V_{DS} .

For the SiC-JFET, the realization circuit is shown in Fig. 6c, in which the die of the device is mounted in a copper substrate. The device is switched with a gate voltage from -18V to 0V and the external gate resistance is 0Ω. An AC current probe (P6022, 1kHz-120MHz) is used to measure I_D and the same active differential voltage probe is used to measure V_{DS} .

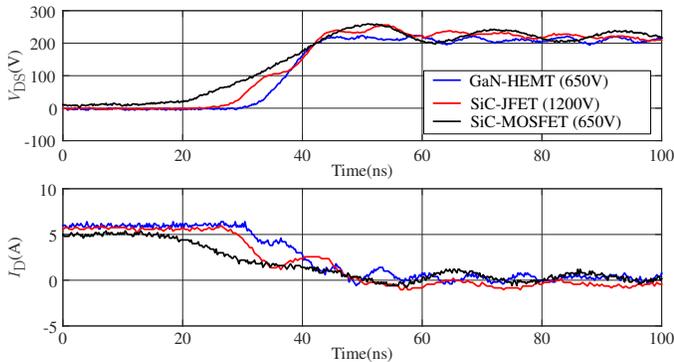
For the GaN-HEMT, the realization circuit is shown in Fig. 6d. The device is switched with a gate voltage from 0V to 7V and the gate resistance is 20Ω for device turn-ON switching. A current shunt (SSDN-10, 0.1Ω, 2GHz) is used to measure I_D and a high voltage passive voltage probe (PPE4kV, 400MHz) is used to measure V_{DS} . Switching mesh is kept as small as possible in all designs so as to minimize parasitic inductance L_{para} in the switching loop.

All devices are tested in double-pulse test in order to keep device junction temperature constant at 25°C. The switching waveforms comparison when devices switch at $V_{DS} = 200V$ and $I_D = 5A$ is shown in Fig. 7 while the results when devices switch at $V_{DS} = 300V$ and $I_D = 10A$ is shown in Fig. 8. It is shown in the results that GaN-HEMT switches faster than both SiC-JFET and SiC-MOSFET in those switching conditions, which give rise to a higher di/dt and dv/dt . Device E_{sw} can be calculated based on the measured switching waveforms and they are compared in Fig. 9 of different switching conditions.

As shown in the results, when device switches at 200V, E_{sw} of GaN-HEMT is about 1/3 smaller than that of SiC-



(a) Device ON



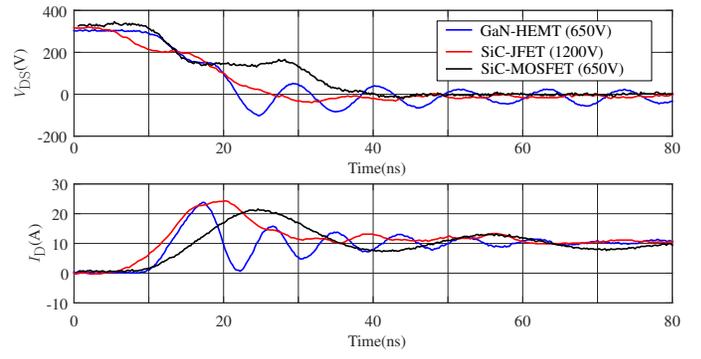
(b) Device OFF

Fig. 7: Switching waveforms comparison when device switches at $V_{DS} = 200V$ and $I_D = 5A$

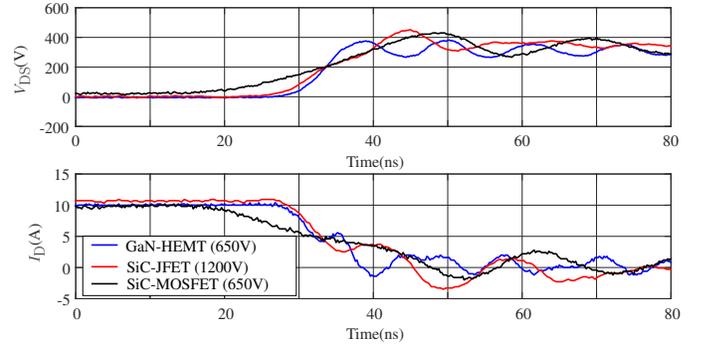
JFET and about half of SiC-MOSFET; while when device switches at 300V, E_{sw} of GaN-HEMT is about 40% smaller than that of SiC-JFET and about half of SiC-MOSFET. It is to be noted that as device package of the above devices is not the same, device internal gate resistance and switching loop inductance are not the same, which might slightly influence on obtained E_{sw} values based on the results presented by authors in [14]. However, according to eq.(8) and in eq.(12), E_{sw} of GaN-HEMT can be further decreased by using a smaller gate resistance.

In order to validate above theoretical analysis on device switching loss, switching waveforms of a 1200V/60A SiC-MOSFET (C2M0040120D) is compared with the above 650V/30A SiC-MOSFET. The comparison results when device switches at 300V and 10A are shown in Fig. 10, where it is shown that 1200V/60A device switches faster than 650V/30A device in terms of di/dt and dv/dt . It is to be noted that 1200V/60A MOSFET has bigger current conduction capability than 1200V/30A MOSFET, thus has bigger capacitance values as well. It suggests that even one compares the E_{sw} between 650V/30A device and 1200V/30A device with the same current rating, the former device has bigger E_{sw} than the latter one, which confirms the above analysis that 650V SiC device might produce bigger switching losses than 1200V device.

By combining all the above measurement results, it is shown



(a) Device ON



(b) Device OFF

Fig. 8: Switching waveforms comparison when device switches at $V_{DS} = 300V$ and $I_D = 10A$

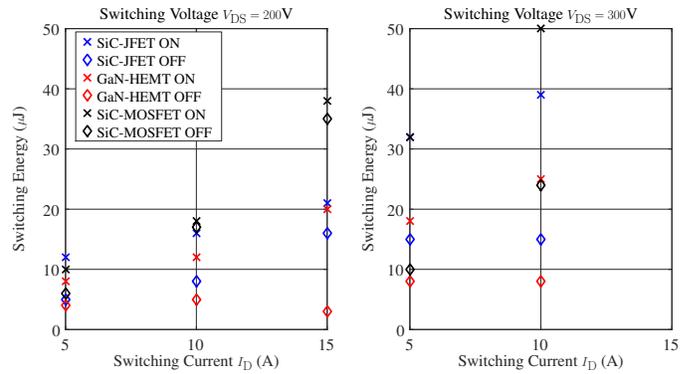


Fig. 9: Device switching energy comparison of different switching conditions

that GaN device produces less switching loss in comparison with a 600V or 1200V SiC device with the same current rating and it is more suitable than SiC device to be applied in below 300V energy conversion.

IV. CONCLUSION

SiC and GaN power semiconductor devices conduction loss and switching losses are compared in the paper. In order to compare losses of devices with the same power rating, a theoretical analysis is given, where it is shown that specific ON-state resistance of SiC power transistors will reduce half

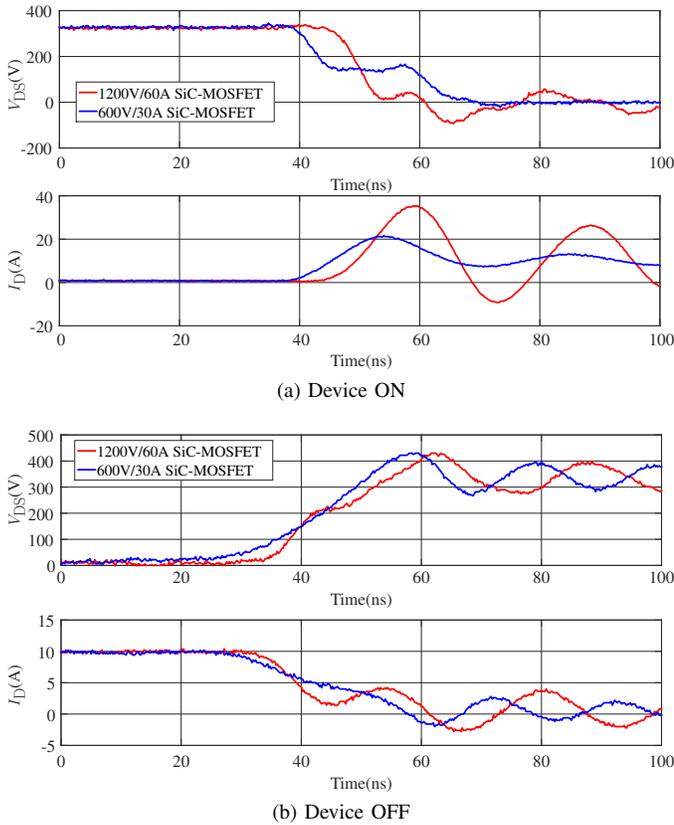


Fig. 10: Switching waveforms comparison between 1200V and 600V SiC-MOSFET switching at $V_{DS} = 300V$ and $I_D = 10A$

if device maximal blocking voltage decreases half. In contrary to that, device specific capacitance value would increase. Thus, for device with same current rating, switching losses E_{sw} is inversely proportional to the square root of device drift region thickness, which illustrates that switching loss would increase in a 600V SiC device.

Static and dynamic characteristics of 1200V and 600V SiC power transistors are compared with 600V GaN-HEMT, in which it is found that GaN-HEMT has a half smaller R_{ON} and about at least five times smaller gate drain capacitance charge Q_{gd} . Inter-electrode capacitances values of a 600V SiC-MOSFET is even bigger than a 1200V device in some voltage range, which helps to validate the presented theoretical analysis.

By comparing E_{sw} in the switching test, it is found that GaN-HEMT produce from a third to 40% less switching loss than 1200V SiC-JFET and only a half E_{sw} as 600V SiC-MOSFET in different switching conditions. It is also shown in the results that 1200V SiC-MOSFET switches faster than 600V device, which confirms the theoretical analysis of device switching losses. By using a smaller gate resistor, E_{sw} of GaN-HEMT will be further decreased, and it is more suitable than SiC device to be applied in below 300V energy conversion.

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