SiC and GaN Power Transistors Switching Energy Evaluation in Hard and Soft Switching Conditions

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Abstract*—SiC and GaN power transistors switching energy are compared in this paper. In order to compare switching energy E_{sw} 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. After that, E_{sw} of a 650V GaN-HEMT is measured in hard switching condition and is compared with that of a 1200V SiC-MOSFET and a 650V SiC-MOSFET with the same current rating, in which it is shown that E_{sw} of a GaN-HEMT is smaller than a 1200V SiC-MOSFET, which is smaller than 650V SiC-MOSFET. Following by that, in order to reduce device turn-ON switching energy, a zero voltage switching circuit is used to evaluate all the devices. Device output capacitance stored energy E_{oss} are measured and turn-OFF switching losses are obtained by subtracting E_{oss}, which shows that GaN-HEMT is sill better than SiC device in terms of switching losses and 1200V SiC-MOSFET has smaller switching losses than 650V SiC-MOSFET.

***Keywords*—Wide bandgap power semiconductor device; GaN-HEMT; SiC-MOSFET; Switching energy; hard switching; soft switching**

I. Introduction

Wide bandgap power semiconductor devices like silicon carbide (SiC) and gallium nitride (GaN) are able to operate in high temperature, high frequency and realize high energy conversion efficiency, so they are gradually applied in power electronics systems for electrical power conversion.

The ability of blocking voltage of the commercial SiC transistors such as JFET and MOSFET is bigger than 1.2kV, while that of commercial GaN transistors such as HEMT and GIT is smaller than 650V. Current ratings of both SiC and GaN devices can be found in a wide range from a few amperes to a few tens of amperes. Depending on electrical power requirements, SiC and GaN power devices can be applied in different power electronics systems such as battery charger, switching mode power supply, electrical motor drive. It is illustrated in Fig. 1 the reported application of SiC and GaN devices in power electronics systems in literature [1]–[6], where all devices are in hard switching mode when converting electrical power. SiC and GaN devices are compared in terms of power rating, efficiency and switching frequency. It is shown that both SiC and GaN devices can realize high efficiency power conversion. SiC devices are applied for above 1kW, below 500kHz power conversion while GaN devices are applied for below 1kW, above 500kHz conversion.

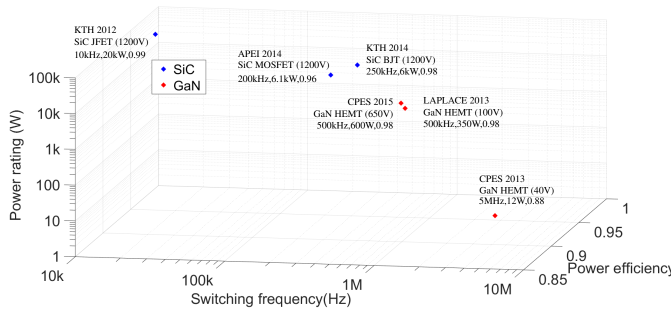


Fig. 1: Comparison of SiC and GaN devices in terms of switching frequency, power rating and efficiency

Due to the dismatch of device power rating, there are few publications about experimental comparison between SiC and GaN power semiconductor devices on switching energy. 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 1200V SiC-MOSFET (C2M0080120D, 1200V/36A), 650V SiC-MOSFET (SCT2120AF, 650V/29A) and 650V GaN-HEMT (GS66508P, 650V/30A) with similar current rating in different hard switching conditions, which would be helpful for engineers to choose wide bandgap power devices when designing power electronics systems. As shown in [6], [7], zero voltage switching (ZVS) is an efficient way to further reduce device switching losses, thus all the above devices are all evaluated in soft switching condition as well.

The paper is structured with following sections: at first, theoretical comparison of conduction loss and switching losses of SiC-MOSFET when reducing blocking voltage is analyzed. Afterwards, based on an optimized switching circuit of each device, switching energy of all the aforementioned devices is measured and compared in both hard and soft switching conditions. Conclusions are given at last.

II. Theoretical analysis

A. Conduction loss comparison

The structure of a MOSFET is shown in Fig. 2, 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}.

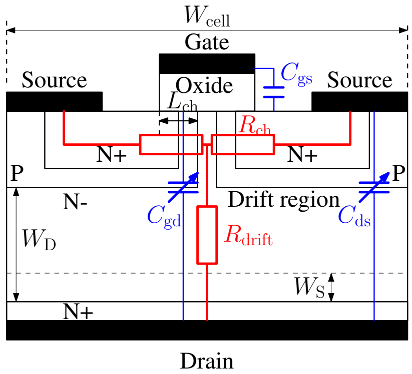


Fig. 2: Structure of a MOSFET

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

$$R_{\text{ON,sp}} = R_{\text{ch,sp}} + R_{\text{drift,sp}} \tag{1}$$

where device specific drift region resistance $R_{\text{drift,sp}}$ 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 [8]:

$$R_{\text{drift,sp}} = \frac{4{V_{\text{DSS}}}^2}{\epsilon \mu {E_{\text{c}}}^2} \tag{2}$$

Shown in [8], the minimal $R_{\text{drift,sp}}$ is a function of ${V_{\text{DSS}}}^{2.5}$. Following relation is obtained if one compares $R_{\text{drift,sp}}$ value of a 600V device and a 1200V device.

$$\frac{R_{\text{drift,sp,600V}}}{R_{\text{drift,sp,1200V}}} = \frac{W_{\text{D,600V}}}{W_{\text{D,1200V}}} \approx \frac{1}{5.6} \tag{3}$$

Device $R_{\text{drift,sp}}$ is also proportional to device drift region thickness W_{D}. Thus, device W_{D} ratio of a 600V device and a 1200V device follow the same relation as eq.(3).

Device specific channel resistance $R_{\text{ch,sp}}$ 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 [9]:

$$R_{\text{ch,sp}} = \frac{L_{\text{ch}} \cdot W_{\text{cell}}}{\mu_{\text{ch}} \cdot Q_{\text{ch}}} \tag{4}$$

According to the results presented by authors in [10], $R_{\text{ch,sp}}$ varies little on V_{DSS} voltage.

By applying the parameters given by authors in [11] for a 1200V SiC-MOSFET, $R_{\text{ch,sp}}$ is found to be about 40% of the total $R_{\text{ON,sp}}$ of a 1200V device. Thus, by combining the above equations, following equation can be obtained, which shows that $R_{\text{ON,sp}}$ of a 600V device is about a half of the value of a 1200V device.

$$\frac{R_{\text{ON,sp,600V}}}{R_{\text{ON,sp,1200V}}} \approx \frac{1}{2} \tag{5}$$

Afterwards, device switching losses are compared in the next subsection.

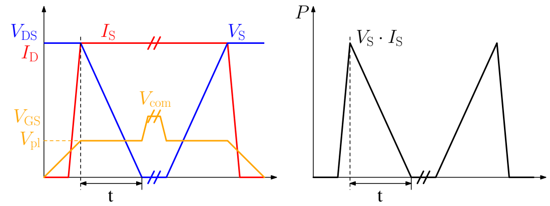


Fig. 3: Ideal switching waveforms and switching losses calculation

B. *Switching loss comparison*

It is illustrated in Fig. 2 the SiC-MOSFET 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:

$$C_{\text{x}} = \frac{\epsilon \cdot A_{\text{x}}}{W_{\text{S}}} \tag{6}$$

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 [8]:

$$W_{\text{S}} = W_{\text{D}} \cdot \sqrt{\frac{V_{\text{S}}}{V_{\text{DSS}}}} \tag{7}$$

By combining eq.(6) and eq.(7), stored charge Q_{x} of each capacitor during switching can be obtained by:

$$\begin{aligned} \int_0^{Q_{\text{x}}} \mathrm{d}_{q_{\text{x}}} &= \int_0^{V_{\text{S}}} C_{\text{x}} \mathrm{d}_{v_{\text{S}}} \\ Q_{\text{x}} &= \frac{2b \cdot \epsilon \cdot A}{W_{\text{D}}} \cdot \sqrt{V_{\text{DSS}}} \cdot \sqrt{V_{\text{S}}} \end{aligned} \tag{8}$$

Thus, the comparison of specific charge ($Q_{\text{x,sp}}$) between 600V and 1200V device can be obtained by following equation:

$$\frac{Q_{\text{x,sp,600V}}}{Q_{\text{x,sp,1200V}}} = 0.7 \cdot \frac{W_{\text{D,1200V}}}{W_{\text{D,600V}}} \tag{9}$$

By combining eq.(3) and eq.(9) together, it is shown in the following equation that in contrary to device $R_{\text{ON,sp}}$, 600V device $Q_{\text{x,sp}}$ is four times bigger than 1200V device.

$$\frac{Q_{\text{x,sp,600V}}}{Q_{\text{x,sp,1200V}}} \approx 4 \tag{10}$$

Power transistor ideal switching waveforms (device switching at voltage V_{S} and current I_{S}) is shown in Fig. 3, 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:

$$E_{sw} = V_S \cdot I_S \cdot t = V_S \cdot I_S \cdot \frac{Q_{gd}}{I_g} = V_S \cdot I_S \cdot \frac{Q_{gd}}{V_{com} - V_{pl}} \cdot R_g \quad (11)$$

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.(11) can be still used to estimate device total switching loss.

It is shown in this equation that E_{sw} is proportional to Q_{gd}. By dividing device surface, 600V and 1200V device specific switching loss $E_{sw,sp}$ can be compared by the following equation:

$$\frac{E_{sw,sp,600V}}{E_{sw,sp,1200V}} \approx 4 \quad (12)$$

Subsequently, switching losses of a 600V and a 1200V device with the same current rating are compared in the next subsection.

C. 600V/1200V device comparison

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

$$I_D{}^2 \cdot R_{ON} \cdot R_{th} = T_{j(max)} \quad (13)$$

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

$$R_{th} = \frac{W_D}{k \cdot A} \quad (14)$$

By combining eq.(13) and eq.(14), following equation can be obtained:

$$I_D = \sqrt{T_{j(max)} \cdot k} \cdot \frac{A}{\sqrt{R_{ON,sp}} \cdot \sqrt{W_D}} \quad (15)$$

If 600V and 1200V device has the same current conduction capability, the comparison of device area A can be expressed by the following equation by combining eq.(3) and eq.(5) together:

$$\frac{A_{600V}}{A_{1200V}} = \frac{\sqrt{R_{ON,sp,600V}} \cdot \sqrt{W_{D,600V}}}{\sqrt{R_{ON,sp,1200V}} \cdot \sqrt{W_{D,1200V}}} \approx 0.3 \quad (16)$$

By combing eq.(12) with eq.(16), following equation can be obtained if switching losses of a 1200V device and a 600V device are compared.

$$\frac{E_{sw,1200V}}{E_{sw,600V}} = 2 \cdot \sqrt{\frac{W_{D,600V}}{W_{D,1200V}}} \approx 0.83 \quad (17)$$

At second condition, if the influence of the packaging is considered, R_{th} is mainly dependent on device packaging type, where device area and thickness has little influence on R_{th} value [12]. Thus, R_{ON} of 600V and 1200V device should be the same if both devices have same current rating. It is then found that A_{1200V} should be twice as big as A_{600V}, so the following switching loss relation can be obtained.

$$\frac{E_{sw,1200V}}{E_{sw,600V}} \approx 0.5 \quad (18)$$

It is shown in eq.(17) and eq.(18) that switching loss of a 600V device can be superior to a 1200V device with the same current rating in both conditions.

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

III. Experimental validations

A. Switching circuit

Switching energy of a 1200V/36A SiC-MOSFET (C2M0080120D), a 650/29A SiC-MOSFET (SCT2120AF) and a 650V/30A GaN-HEMT (GS66508P) is evaluated and compared in this section. The switching circuit to test all the devices is shown in Fig. 4a. Gate loop and switching loop of each device is minimized in order to reduce gate loop inductance $L_{para,g}$ and switching loop inductance $L_{para,sw}$.

The realization prototype to test 1200V SiC-MOSFET is shown in Fig. 4b, where the package of the device is TO-247. Device is driven by a gate voltage from -5V to 20V. $L_{para,g}$ is obtained by measuring gate voltage resonance frequency, which is supposed to be resonated between $L_{para,g}$ and device input capacitance C_{iss}. $L_{para,g}$ in the prototype is about $2n$H.

The realization prototype to test 650V SiC-MOSFET is similar as that shown in Fig. 4b, except the package of the device is TO-220. Device is driven by the same gate voltage as 1200V SiC-MOSFET. The measured $L_{para,g}$ in the prototype is also about $2n$H.

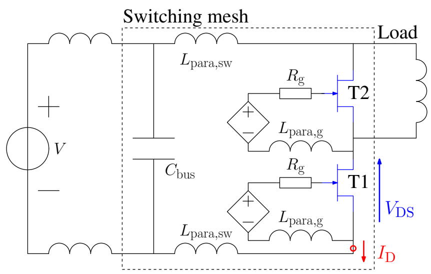
The realization prototype to test 650V GaN-HEMT is shown in Fig. 4c, where the package of the device is GaNPX. Device is driven by a gate voltage from 0V to 7V while the measured $L_{para,g}$ in the prototype is about $3n$H.

The used gate driver in all the above design is IXDN609SI and lumped gate resistance in all the measurements are about 4Ω including device internal gate resistance, external gate loop resistance and gate driver output resistance. Device T1 switching current I_D is measured by a current shunt (SSDN-414-025, 1.2GHz) while the switching voltage V_{DS} is measured by a differential voltage probe (TA043, 700V/100MHz). The bandwidth of the used oscilloscope is 1.5GHz. The device is at first tested in hard switching conditions by double pulse.

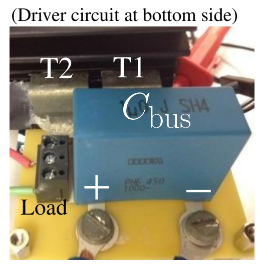
B. Comparison of device hard switching

The measured switching waveforms when all the device switching at $V_{DS} = 300$V, $I_D = 10$A are shown in Fig. 5.

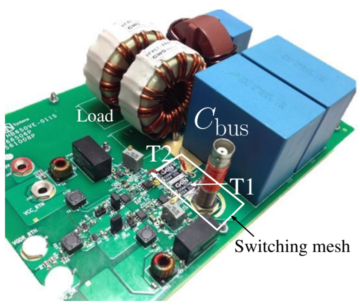
As shown in the results, 1200V SiC-MOSFET switches faster than 650V SiC-MOSFET in turn-off switching, which is supposed to be that transfer capacitance C_{rss} of 1200V device



(a) Electrical circuit of the switching circuit

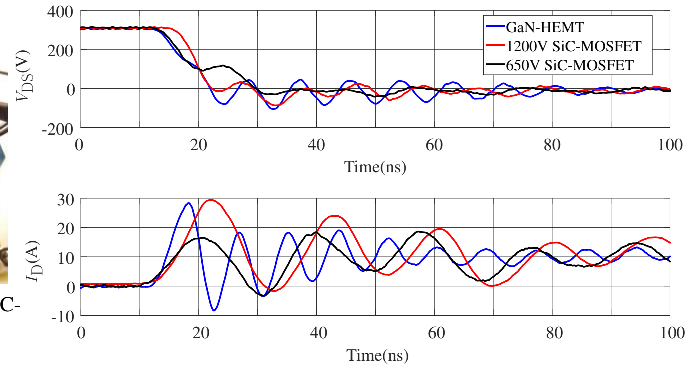


(b) Switching circuit of SiC-MOSFET

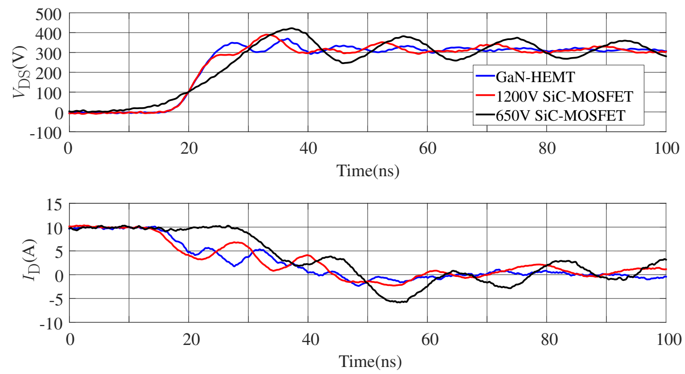


(c) Switching circuit of GaN-HEMT

Fig. 4: Electrical circuit of the switching circuit and their realization



(a) Turn-on



(b) Turn-off

Fig. 5: Switching waveforms comparison among 1200V SiC-JFET, 650V SiC-MOSFET and 650V GaN-HEMT in hard switching

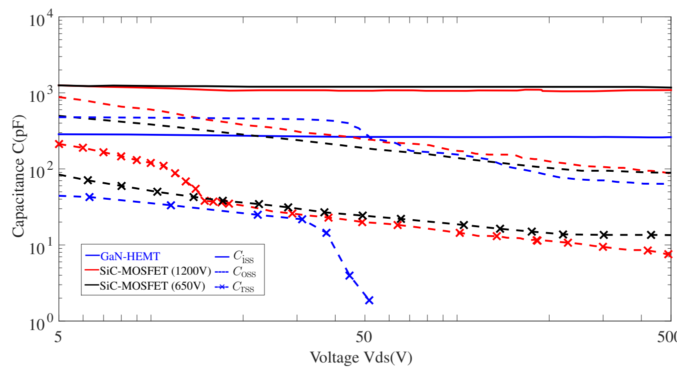


Fig. 6: Device inter-electrode capacitance comparison

is bigger than 650V device in high voltage. This can be also confirmed when comparing device inter-electrode capacitance datasheet values as illustrated in Fig. 6, where it is shown that C_{rss} of 1200V SiC-MOSFET is smaller than 600V SiC-MOSFET when blocking voltage superior to 20V. In terms of turn-ON switching, current transition time for both 1200V and 650V SiC-MOSFET is quite similar while measured $\mathrm{d}I/\mathrm{d}t$ of 1200V device is higher than 650V device, which suggests a similar input capacitance C_{iss} of both device. Again, it is found in the datasheet value that C_{iss} of both device is around $2n$F and that of 1200V device is slightly smaller than 650V device.

When comparing with 650V GaN-HEMT, it is shown that GaN-HEMT switches faster than 1200V SiC-MOSFET in turn-on switching, which confirms the datasheet value that C_{iss} of GaN-HEMT is only about one sixth of 1200V SiC-MOSFET. In terms of turn-off switching, no obvious difference observed between 1200V SiC-MOSFET and GaN-HEMT. This is supposed to be following two facts: one is that GaN-HEMT is turned OFF by 0V while SiC-MOSFET is turned OFF by -5V. If GaN-HEMT were turned OFF by negative voltage, the switching transition might be even shorter. Another fact is the fastest fall time of the gate driver is about 7ns shown in its datasheet. If a faster gate driver were used to drive GaN-HEMT, turn-OFF transition can be also accelerated because device has much smaller C_{rss} and C_{iss} values than 1200V SiC-MOSFET.

The switching energy comparison results of different switching conditions are shown in Fig. 7 for all the aforementioned devices. As it is in hard switching condition, measured I_{D} turn-ON current excludes C_{oss} discharge current and I_{D} turn-OFF current includes C_{oss} charge current. Thus, dissipated C_{oss} energy E_{oss} is not included in device turn-ON energy and E_{oss} is included in device turn-OFF energy. As shown in the results, 650V SiC-MOSFET has bigger switching energy than 1200V SiC-MOSFET, which confirms the analytical analysis. Thus, switching losses of a 1200V SiC-MOSFET is smaller than 650V device with the same current rating.

Switching energy of GaN-HEMT is smaller than that of 1200V SiC-MOSFET. However, at some switching conditions,

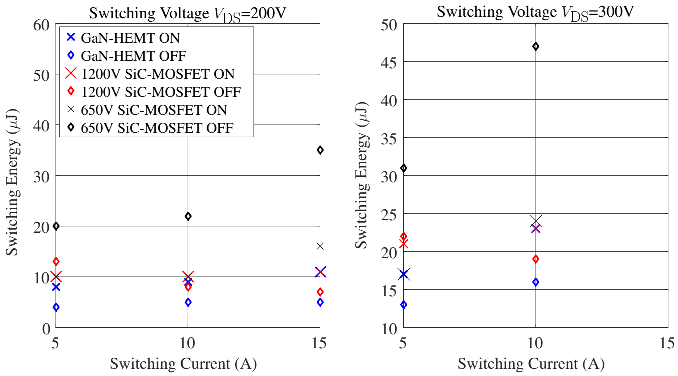


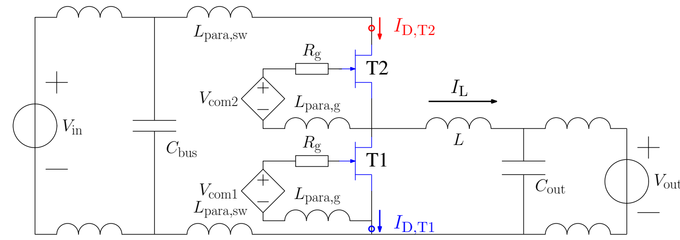
Fig. 7: Switching energy including C_{oss} stored energy comparison among 1200V SiC-JFET, 650V SiC-MOSFET and 650V GaN-HEMT in hard switching

measured switching energy for the two devices are quite close. This is because of the voltage drop across $L_{\text{para,sw}}$ during the rise of I_{D}, thus it helps to decrease I_{D} and V_{DS} overlapping time. Obtained apparent switching energy of SiC-MOSFET is decreased because of the snubber effect of $L_{\text{para,sw}}$. $L_{\text{para,sw}}$ can be estimated based on the observed LC resonance frequency of the switching waveform at the end of the switching, which is supposed to be the resonance between device C_{oss} and $L_{\text{para,sw}}$. It is thus found $L_{\text{para,sw}}$ of GaN-HEMT switching circuit is about 36nH while that of SiC-MOSFET is about 80nH, so V_{DS} voltage drop of SiC-MOSFET is twice than that of GaN-HEMT for the same $\mathrm{d}I/\mathrm{d}t$ turn-ON switching rate.

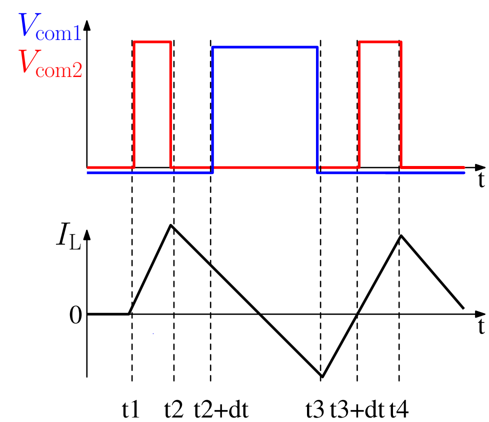
According to the switching energy comparison in this subsection, it is concluded that GaN-HEMT is more suitable than SiC-MOSFET for below 300V electrical energy conversion because of less switching losses. However, for both GaN-HEMT and 1200V SiC-MOSFET, it is found in Fig. 7 that device turn-ON loss is bigger than turn-OFF loss, thus it is helpful to apply these devices in soft switching to reduce turn-ON loss.

C. Comparison of device soft switching

The circuit using to analyse device soft switching is illustrated in Fig. 9a, where voltage of the output capacitor C_{out} is maintained constant by using an external power supply. At instant $t1$, device T2 is switched ON and load inductor starts to be charged by $V_{\text{in}} - V_{\text{out}}$. At instant $t2$, T2 is switched OFF in hard switching condition. Simultaneously, device T1 stored energy in its C_{oss} is transfered by load current I_{L} to C_{oss} of device T2. After deadtime dt, device T1 is switched ON at zero voltage switching (ZVS). Afterwards, Load inductor is reversely charged by V_{out} and it changes the direction. At instant $t3$, T1 is switched OFF in hard switching condition and simultaneously, device T2 stored energy in its C_{oss} is transfered by load current I_{L} to C_{oss} of T1. After deadtime, T2 is switched ON at ZVS and finally it is switched OFF at hard switching condition at instant $t4$.



(a) Electrical circuit



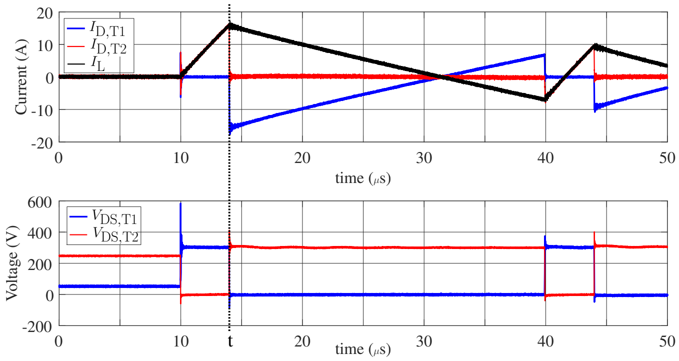
(b) Control signals with load current waveform

Fig. 8: Electrical circuit using to test device in soft switching and load current waveform

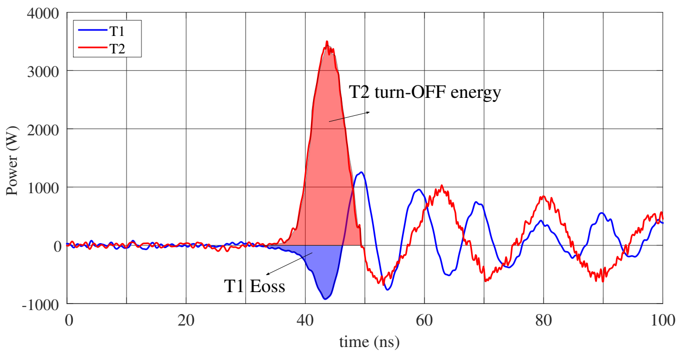
Thus, by changing I_{L} direction, device T1 and T2 turn-ON losses can be avoided and both device only have turn-OFF losses which is due to the overlapping of V_{DS} and I_{D}. Stored energy in T2 is transfered to T1 before switching ON and vice versa. Device total switching losses can be greatly reduced in this current mode.

When $V_{\text{in}} = 300\text{V}$ and $V_{\text{out}} = 50\text{V}$, the measured 1200V SiC-MOSFET switching waveforms are shown in Fig. 9a. At instant t, device T2 is switched OFF in hard switching and stored energy in C_{oss} of device T1 is transfered to T2. By multiplying measured current and voltage of each device, switching power waveforms are obtained and shown in Fig. 9b. Thus, T1 turn-OFF energy including E_{oss} and T2 E_{oss} can be obtained separately. Device turn-OFF switching loss due to the overlapping of current and voltage waveforms can be obtained. In the waveform shown, it is found that E_{oss} of 1200V device is about 4.4μJ when device is withstanding 300V V_{DS}.

Output capacitance stored energy E_{oss} of the aforementioned devices is then measured by this method and they are compared in Fig. 10. As shown in the results, the measured E_{oss} of all the devices is close to each other, which confirms that all devices have close C_{oss} values as shown in Fig. 6. According to these results, even though E_{oss} of 650V GaN-HEMT is only measured at 100V, its value would be close to that of 650V SiC-MOSFET when it switches at 200V, 250V and 300V. By subtracting E_{oss} from device turn-OFF energy as shown in Fig. 7, 650V SiC-MOSFET still has bigger switching losses than 1200V SiC-MOSFET and 650V GaN-HEMT is



(a) Device switching waveforms



(b) Device turn-OFF energy and stored energy when it switches at 300V/15A in soft switching

Fig. 9: Measured 1200V SiC-MOSFET switching waveforms and stored energy

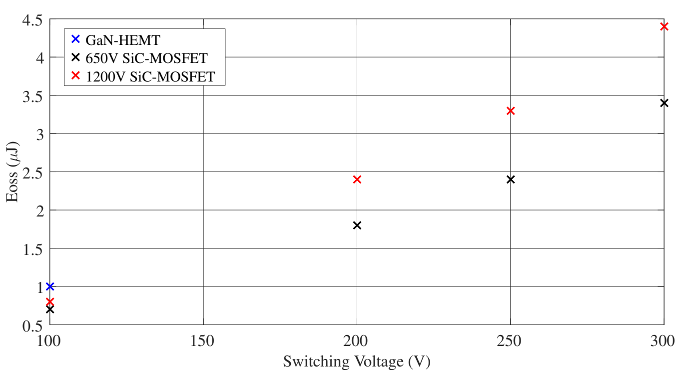


Fig. 10: Device stored energy E_{oss} comparison among 1200V SiC-JFET, 650V SiC-MOSFET and 650V GaN-HEMT

still more efficient than 1200V SiC-MOSFET in this switching mode.

IV. Conclusion

SiC and GaN power semiconductor devices switching energy are compared in the paper. In order to compare switching energy of devices with the same power rating, a theoretical analysis is given to show that specific ON-state resistance of SiC power transistors will reduce half if device maximal blocking voltage decreases half. In contrary to that, device specific capacitance value would increase. Thus, when comparing device with same current rating, switching losses would increase in a 600V SiC device than 1200V device.

In order to validate the theoretical analysis, switching energy of a 650V/29A SiC-MOSFET is compared with a 1200V/30A SiC-MOSFET in hard switching mode. Measurement results show that switching energy, especially turn-OFF energy of 650V SiC-MOSFET is bigger than 1200V device, which confirms the theoretical analysis. By comparing with a 650V/30A GaN-HEMT, it is found that switching energy of GaN-HEMT is smaller than 1200V SiC-MOSFET. It is also shown in the results that device turn-ON energy are bigger than turn-OFF energy for both 1200V SiC-MOSFET and 650V GaN-HEMT.

In order to reduce device turn-ON energy, a zero voltage switching circuit is used to evaluate device in soft switching mode. Device output capacitance stored energy E_{oss} can thus be measured, so device turn-OFF losses due to overlapping of switching current and voltage can be obtained. By subtracting E_{oss}, it is shown that GaN-HEMT is still better than 1200V SiC-MOSFET, which is better than 650V SiC-MOSFET in terms of the switching losses in this switching mode.

Based on all the results, it can be concluded that 1200V SiC-MOSFET has smaller switching losses than 600V device and GaN-HEMT is more suitable than SiC device to be applied in below 300V energy conversion.

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