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The Experience with SiC MOSFET and Buck Converter Snubber Design

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Abstract**—**The newest semiconductor devices on the market are MOSFET transistors based on the silicon carbide – SiC. This material has exclusive features thanks to which it becomes a better switch than Si – silicon semiconductor switch. There are some special features that need to be understood to enable the device's use to its full potential. The advantages and differences of SiC MOSFETs in comparison with Si IGBT transistors have been described in first part of this article. Second part describes driver for SiC MOSFET transistor and last part of article represents SiC MOSFET in the application of buck converter (step-down) and design of simple RC snubber.

Keywords**—**SiC, Si, MOSFET, IGBT, SBD, RC snubber.

I. INTRODUCTION

SiC material for semiconductor devices manufacturing has been known since the 1930s. The starting disadvantage of this material was quality (initially limited to material stability and pollution), size and cost. These disadvantageous properties were substantially improved over just the several years and a rival for silicon semiconductors devices was created [1].

II. MAIN FEATURES OF SIC

SiC material has the following key features that make it a superior semiconductor material in comparison with previous Si materials:

- The thermal conductivity in SiC is higher than in GaAs and more than three times higher than the conductivity of Si. At room temperature 4H SiC has a higher thermal conductivity than copper.
- This semiconductor material operates in an extreme junction temperature up to 800°C (theoretically) but experimental results were obtained at temperatures up to 600°C, verifying the dependence between temperature and motion minority carrier. Results are better for SiC than for its counterparts. Nowadays, the manufacturer faces a problem with case for these high temperature devices.
- The bandgap is defined as energy difference between valence and conduction band in a material. The width of this band depends on the motion of minority carrier, respectively on thermal generation of current flow. This current leakage is very low in comparison with silicon material.
- The higher breakdown field of SiC is almost nine times thinner than the breakdown field of silicon.

SiC diode technology has been in the market for more than one decade, and many switches have recently become available to enable "all-SiC" circuit solutions. SiC diode and transistor production on voltage type 600 V, 1200 V and 1700 V and current rates up to 100 A [1].

III. COMPARISON SIC MOSFET AND SI IGBT TRANSISTOR

The static and dynamic properties of SiC MOSFET transistor and Si IGBT transistor were compared in the sample with the same voltage and current levels. The comparison of SiC MOSFET (type CMF20120D - Fig. 1) to Si IGBT was chosen due to large popularity and frequency of IGBT transistor usage in power electronics solution and for new information on the properties of SiC semiconductor technology [1].

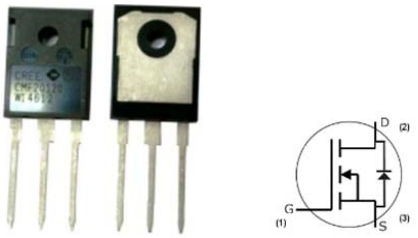

Fig. 1 SiC MOSFET transistor Cree CMF20120D in the general case TO-247 and schematic symbol

A. The Comparison of Static and Dynamic Characteristics of SiC MOSFET and Si IGBT

By the experimental measurements on SiC MOSFET transistor CMF20120D and Si IGBT transistor IRG4PH40UPbF the static and dynamic characteristics were obtained. Measurement was performed on the experimental stand for the measuring characteristics of transistors. Power transistors were mounted on an active air heat sink. Driver circuits of transistors have been placed in their immediate vicinity on the one PCB (Printed Circuit Board).

The results of static measurements of both transistors are shown on Fig. 2. The waveforms for the MOSFET and IGBT can occur in the typical form of curves, also a higher voltage drop V_{CE} is possible on IGBT. For better illustration and comparability both axes are placed in the same scale [1].

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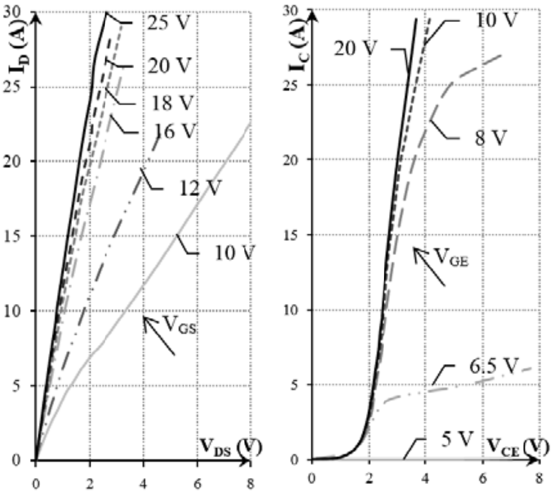

Fig. 2 Measured static characteristics $I_D = f(V_{DS})$ of SiC MOSFET transistor (left) and of Si IGBT $I_C = f(V_{CE})$ (right)

Measurement of dynamic characteristics was carried out at a switching frequency of 10 kHz, a limitation due to Si IGBT driver. For the tested SiC MOSFET driver, the frequency of the input signal was increased up to 1 MHz. Output square waveform was without any signal distortion.

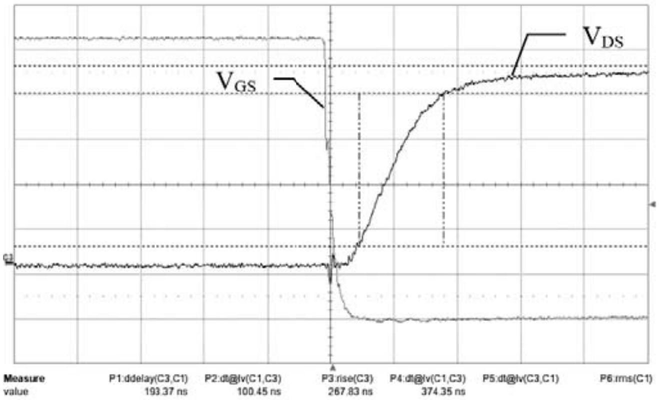

Fig. 3 Dynamic characteristics SiC MOSFET during turn-off (V_{GS} – 5 V/div, V_{DS} – 10 V/div, 200 ns/div)

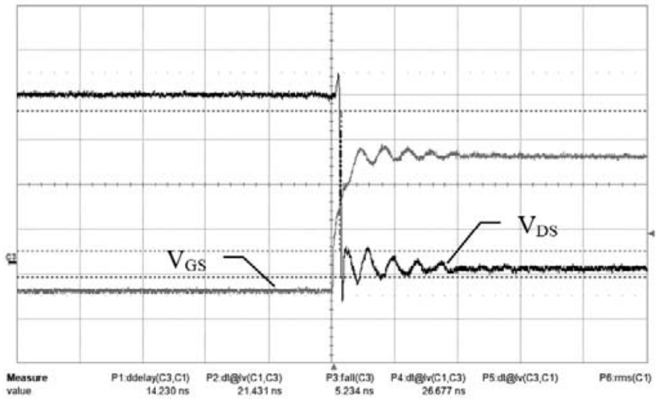

Fig. 4 Dynamic characteristics SiC MOSFET during turn-on (V_{GS} – 10 V/div, V_{DS} – 10 V/div, 200 ns/div)

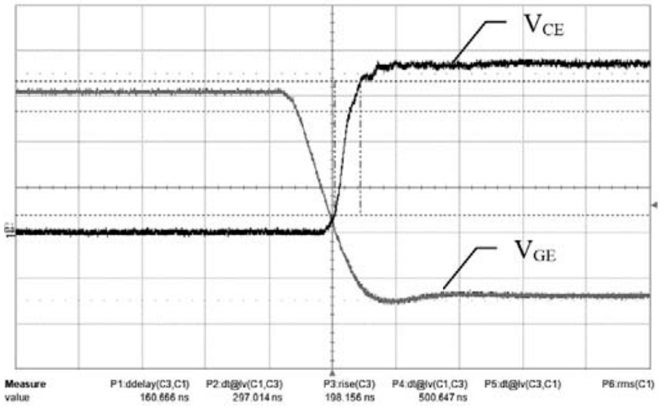

Fig. 5 Dynamic characteristics Si IGBT during turn-off (V_{GE} – 5 V/div, V_{CE} – 10 V/div, 500 ns/div)

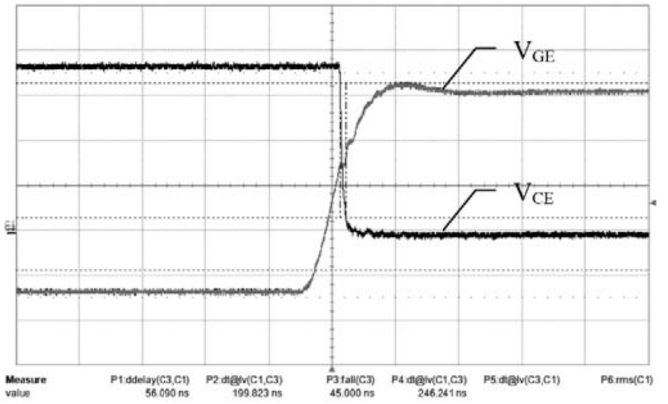

Fig. 6 Dynamic characteristics Si IGBT during turn-on (V_{GE} – 5 V/div, V_{CE} – 10 V/div, 500 ns/div)

After detailed analysis of oscilloscope waveforms (Figs. 3 to 6) were written down to dynamic parameters of the transistors shown in Table I.

TABLE I
DYNAMIC FEATURES SIC AND SI TRANSISTORS

Symbol	SiC MOSFET CMF20120D	Si IGBT IRG4PH40UPbF
$\mathbf{t_{d(off)}}$	100 ns	300 ns
$\mathbf{t_r}$	270 ns	200 ns
$\mathbf{t_{off}}$	370 ns	500 ns
$\mathbf{t_{d(on)}}$	22 ns	200 ns
$\mathbf{t_f}$	5 ns	45 ns
$\mathbf{t_{on}}$	27 ns	245 ns

IV. DRIVERS FOR SIC MOSFET TRANSISTORS

The SiC MOSFET transistor is in the same way as its forerunners based on the unipolar structure. Gate electrode is controlled by a voltage signal. However, the real transistor has many parasitic capacitances (C_{oss}, C_{iss}, C_{rss}) which significantly affect the speed of switching on and off. The transistor driver has to provide an impulse powerful enough to invoke fast current charging of these capacities. The SiC transistor driver in comparison with a classical Si driver is largely different.

- The gate voltage swing is almost 30 V_{pp} (+24 V to -5.5 V). The recommended on state V_{GS} is more than +20 V and the off state V_{GS} is between -2 V to -5 V.
- The SiC MOSFET transistor needs to be driven with a higher gate voltage swing.
- The gate voltage must have a fast dV/dt to achieve fast switching times which indicates that a very low impedance driver is necessary [1].

A. The Realization of SiC Driver

According to the requirements mentioned above, the driver was assembled in accordance with the recommendation of Cree, Inc. The driver is supplied by a single voltage +12 V DC which feeds two DC/DC converters. The first converter is for the positive polarity to the gate electrode and the second for the negative one. Input control signal is galvanically separated by fast optocoupler ACPL-4800-300E. The output signal from the optocoupler is amplified for high-speed gate driver IXDN609 (maximum output current 9 A, rise and fall times of less than 25 ns). For the experimental measurement of the SiC MOSFET transistor CMF20120D the single channel driver was realized (Fig. 7) on the two layers PCB with dimension 33 x 42 mm [2], [3].

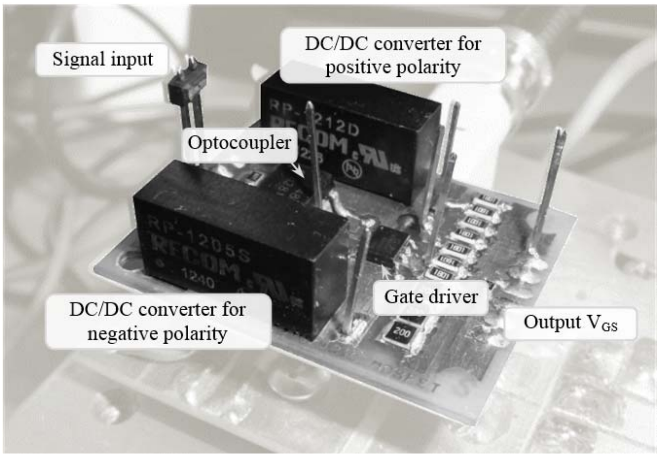

Fig. 7 Realized SiC MOSFET driver with test points

B. The Comparison of SiC and Si Driver

The differences between Si and SiC drivers are obvious from the previous paragraphs. The basic difference is based on switch-on and switch-off voltage level, which is higher in the case of the SiC driver. Similarly, the slope of voltage V_G is higher. The SiC and Si transistor driver features were compared by experimental measurements and by data from datasheets. The SiC MOSFET driver was built with high-speed gate driver IXDN609, Si IGBT transistor was driven by SKHI22AH4 by Semikron. The comparison of basic properties of both drivers is displayed in Table II.

TABLE II
MAIN FEATURE SIC AND SI DRIVERS

Symbol	**Conditions**	**SiC MOSFET driver IXDN609**	**Si IGBT driver SKHI22A Semikron**
V_S	Supply voltage primary side	12 V	15 V
I_{S0}	Supply current primary side (no load)	50 mA	80 mA
I_{SM}	Supply current primary side (max.)	350 mA	290 mA
V_i	Input signal voltage on/off	10 – 12V / 0V	15 V/ 0 V
R_{in}	Input resistance	1.2 MΩ	10 kΩ
$V_{G(on)}$	Turn on gate voltage output	+25 V	+15 V
$V_{G(off)}$	Turn off gate voltage output	-5 V	-7 V
R_{GE}	Internal gate-emitter resistance	47 kΩ	22 kΩ
$t_{d(on)IO}$	Input-output turn-on propagation time	160 ns	1.4 µs
$t_{d(off)IO}$	Input-output turn-off propagation time	180 ns	1.8 µs
$t_{d(err)}$	Error input-output propagation time	Not supported	0.6 µs
t_{pERR}	Error reset time	Not supported	9 µs
V_{CEsat}	Reference voltage for V_{CE} monitoring	Not supported	5 V
f_{SW}	Switching frequency	1 MHz	20 kHz

The comparison of the parameters of both drivers (Table II) shows major differences in the values of output voltage levels V_G, the length of delay of input-output signals, where SiC driver has more than six times smaller delays. The disadvantage of SiC transistor driver is the absence of over current or short-circuit protection of switching transistor.

V. APPLICATION OF SIC MOSFET - BUCK CONVERTER

Before the experimental measurement of SiC transistor a simulation scheme was created. The simulation model of the SiC MOSFET transistor and the SiC SBD diode was obtained on request from the manufacturer Cree, Inc. The simulation scheme of buck converter was created in LTspice program, which is freely available on the company website of Linear Technology [4]. The simulation scheme presents principal function of buck converter and function of RC snubber circuit (in Fig. 8 labeled as C1 and R1).

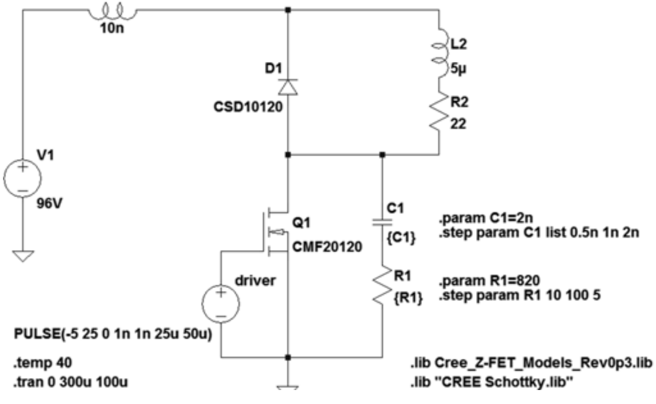

Fig. 8 The simulation scheme of buck converter with RC snubber circuit

VI. DESIGN OF A SIMPLE RC SNUBBER CIRCUIT

A. Buck Converter without Snubbers

Fig. 10 shows the basic one-quadrant buck converter circuit without snubbers. Output (load) voltage and transistor voltage V_{DS} has ideally square wave characteristics when turning on and off. But actually the turn-off of the transistor interrupts current through the leakage inductance of the load. This current cut-off causes a voltage spike on the drain (V_{DS}) of the transistor. The inductance will ring with stray capacitances in the circuit, producing very large amplitude (hundreds of volts) high-frequency (up to tens MHz) waveforms as shown in Fig. 9.

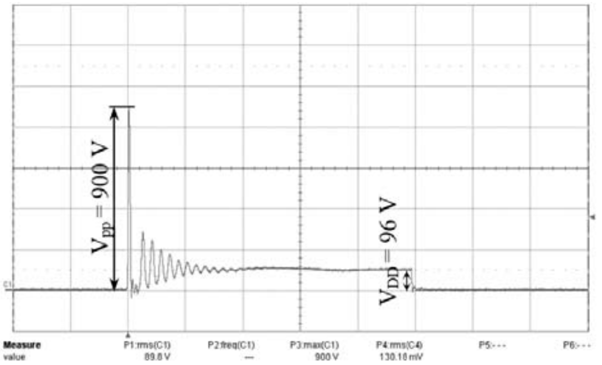

Fig. 9 900V high V_{DS} voltage peake during switching-off transistor (200V/div, 1µs/div)

Some designs of converter's circuit ignore the ringing waveforms and operate the converter without snubber. It brings problems with excessive voltage on the drain of the MOSFET which can result in an avalanche breakdown and failure of the device. Another problem is the ringing energy. This high frequency will be radiated throughout the load, power supply and electronic system and creating noise issues with can lead to logic errors. For the circuit reliability it is necessary to add a circuit to damp the ringing - using the RC snubber, or clamp the voltage - used RCD clamps, or both of them. In this article we will focus on RC snubber design.

B. Buck Converter with RC Snubber

Probably the simplest circuit is a buck converter as shown in Fig. 10.

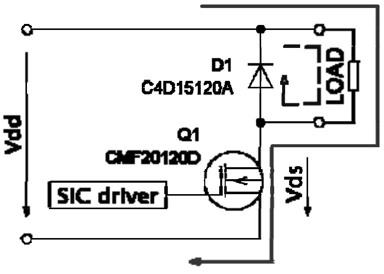

Fig. 10 Buck converter and direction of current

If the transistor Q1 is switched-on, current flows through load and MOSFET transistor (Fig. 10). If transistor Q1 is switched-off, current commutates from the main loop (solid line) to the SBD diode (dash line) and the reverse recovery effect occurs in transistor Q1 as a voltage peak on the V_{DS} waveform (Fig. 9) [5].

The problem of voltage overshoot is described in the equivalent circuit in the Fig. 11. First of all, it is necessary to take into account the parasitic elements in the circuit:

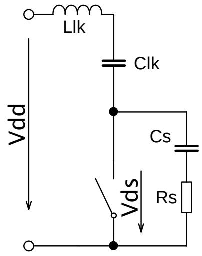

Fig. 11 Equivalent circuit of converter

- C_{LK} – the parasitic capacitance is mainly due to transistor output capacitance C_{OSS} and SBD diode capacitance.
- L_{LK} – the total stray or leakage inductance comprised of cable inductance, load inductance, device package inductance, connection inductance, etc.
- Q1 – equivalent switch.

The negative oscillation can be snubbed by connecting an RC circuit across transistor Q1 to drain-source [5].

Design Step 1: Determining C_{LK} and L_{LK}

There are many ways to determine the parasitic capacitance and inductance. A practical way to determine the value of the capacity C_{LK} is to look into data sheet of MOSFET transistors (C_{OSS}) and SBD diode.

By experimental measurements using RLC bridge meter it is possible to obtain parasitic inductance with some precision.

Design Step 2: Measure the Ringing Frequency

The waveform in Fig. 12 was captured from the measurement of a buck converter with no snubber. Caution! Peak voltage without damping circuit is up to ten times higher than the power supply voltage V_{DD}! The ringing frequency f_{RING} is estimated from this waveform [6].

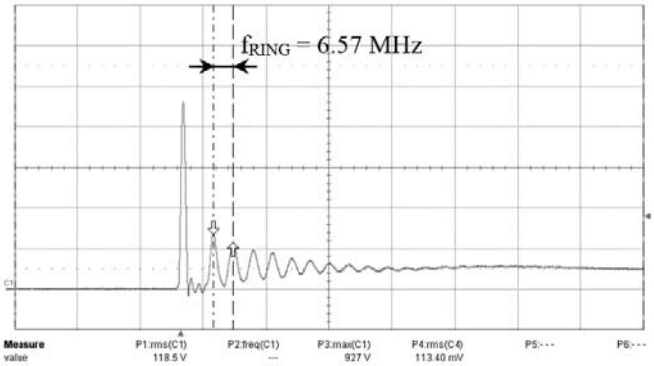

Fig. 12 The detail of ringing transistor V_{DS} voltage peake during switching-off (200 V/div, 500 ns/div, Vpp = 927 V)

Design Step 3: Calculation Rs and Cs

The circuit ringing is well-damped, if we use a snubber resistor corresponding to the characteristic impedance of the ringing. The response of this circuit to the voltage step change is usually called as degree of damping ζ in the circuit. For $\zeta = 0$ oscillates are undamped. The case $\zeta = 1$ is called as critically damped and this is the point at which oscillation just leaves off. For values greater than $\zeta = 1$ circuit is overdamped, it means that voltage response of the circuit becomes more sluggish. For this configuration of resonant circuit, the relationship between ζ, R_S, L_{LK} and C_{LK} is:

$$\zeta = \left(\frac{1}{2R_S}\right)\sqrt{\frac{L_{LK}}{C_{LK}}} \tag{1}$$

Rearranging (1) we have:

$$R_S = \left(\frac{1}{2\zeta}\right)\sqrt{\frac{L_{LK}}{C_{LK}}} \tag{2}$$

The snubber capacitor Cs is used to minimize dissipation at the switching frequency, while the resistor is allowed to be effective at the ringing frequency [6].

$$f_{RING} = \frac{1}{2\pi R_S C_S} \tag{3}$$

Rearranging (3) we have:

$$C_S = \frac{1}{2\pi R_S f_{RING}} \tag{4}$$

With substitution in the (2), (4) we calculate value of snubber capacitor Cs and resistor Rs:

$L_{LK} = 3.3\ \mu H$
$C_{LK} = 1.25$ nF
$f_{RING} = 6.57$ MHz
$\zeta = 1$

$$R_S = \left(\frac{1}{2\zeta}\right)\sqrt{\frac{L_{LK}}{C_{LK}}} = \frac{1}{2}\sqrt{\frac{3.3\cdot 10^{-6}}{1.25\cdot 10^{-9}}} = 25.7\Omega \sim 26\Omega \tag{5}$$

$$C_S = \frac{1}{2\pi R_S f_{RING}} = \frac{1}{2\pi\cdot 25.7\cdot 6.57\cdot 10^{6}} = 0.94\text{nF} \sim 1\text{nF} \tag{6}$$

[5], [6]

C. *Experimental Verification*

For experimental measurement a model of one quadrant buck converter with SiC MOSFET transistor was assembled.

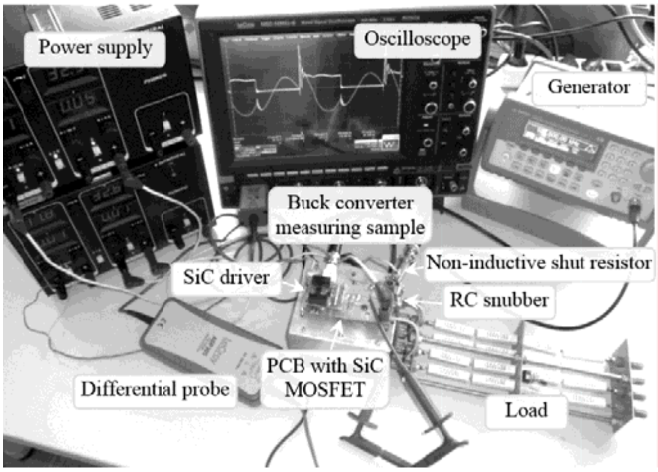

Fig. 13 Measuring stand od one quadrant buck converter with SiC MOSFET

RC snubber was determined by theoretical calculation:
$R_s = 26\ \Omega$
$C_s = 1$ nF

The measurement was performed for these R_s and C_S values: $R_s = 0.5\ \Omega$, $10\ \Omega$, $25\ \Omega$, $50\ \Omega$, $75\ \Omega$ and $100\ \Omega$

$C_S = 0.5$ nF, 1 nF, 2 nF

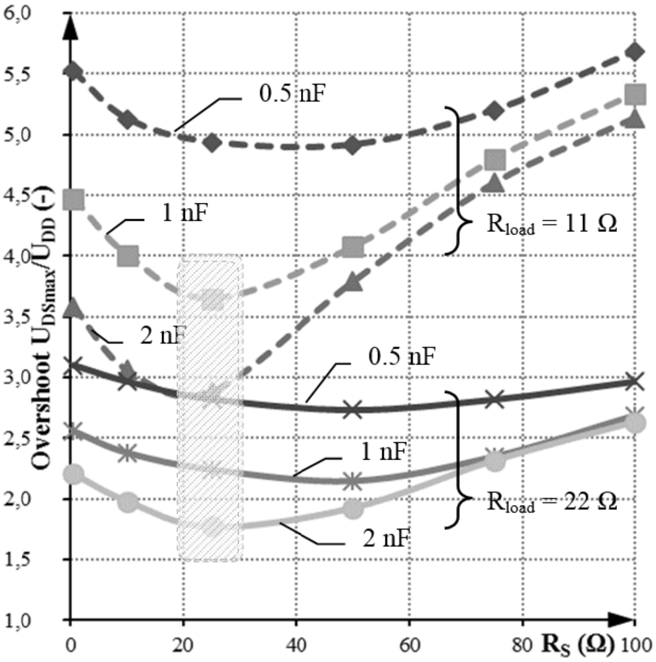

Fig. 14 The graph of voltage overshoot U_{DSmax}/U_{DD} (-) with diferent value R_S, C_S and for load resistor 11 Ω (8 A) and 22 Ω (13 A)

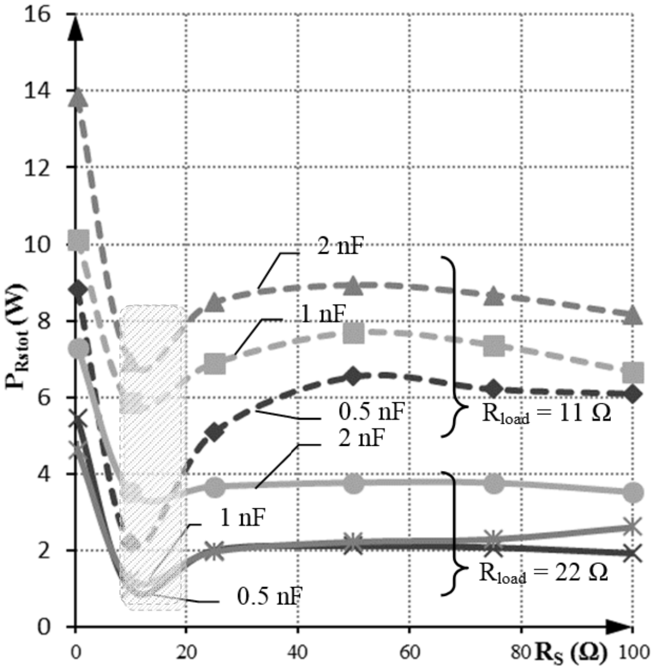

Fig. 15 The graph of power disipation of resistor R_S with diferent value R_S, C_S and for load resistor 11 Ω (8 A) and 22 Ω (13 A)

The results of experimental measurement are shown in the charts above, revealing that the requests of snubber circuit construction are different. High capacity of capacitor C_S (Figs. 14 and 15) has been chosen because of large damping of overvoltage peaks. Furthermore, the choice of high capacity causes high power loss in series resistor R_S. In the case of the resistor unplaced of into series circuit ($R_S \to 0$) to damped high voltage peak, however, capacitor was charged with high unlimited current. This case of circuit swings the device in switch-off and also in switch-on of MOSFET transistor. Optimal value of C_S or R_S is displayed in the charts in crosshatch areas, i.e. $R_S \sim 20\ \Omega \pm 5\ \Omega$ a $C_S \sim 1$ nF ± 0.1 nF.

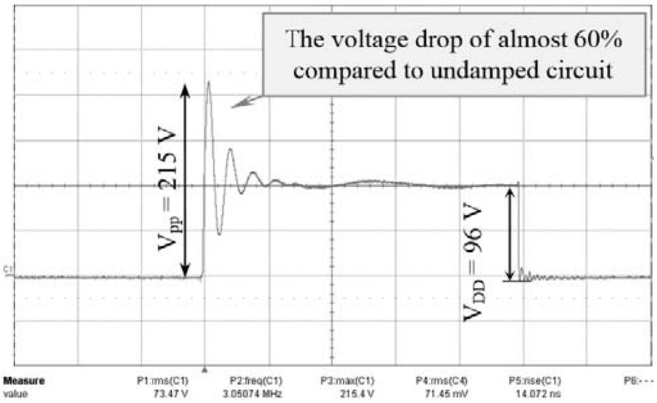

Fig. 16 The transistor voltage V_{DS} with RC snubber C_s = 1 nF, R_s = 25 Ω (100V/div, 1µs/div)

VII. CONCLUSION

This contribution aimed to present the properties of new semiconductor devices based on SiC semiconductor material. This article describes the main material properties of these semiconductor items and also compares their electric static and dynamic properties with well-known Si IGBT transistors. The comparison reveals (see Table I) that SiC MOSFET transistor is almost 10 times faster in switching-on and approximately by 30% faster in switching-off. These results confirm the producer Cree wording that this is the fastest switching device in the market. Different semiconductor structure of switching device requires the driver with relevant properties. Chapter 4 deals with basic properties demands applied on SiC driver. Basic differences of SiC and Si transistor drivers are demonstrated in Table II. The first difference of both drivers is higher switch-on voltage, higher switching frequency and lower input-output switching propagation time of SiC driver. The chapter V is aimed to the application of SiC devices (MOSFET transistor and SBD diode) in buck converter. The converter function or the construction does not fall in the field of this article. The Chapter VI deals with the design of RC snubber for the limitation of high peaks of voltage V_{DS} in MOSFET transistor. The theoretical calculation determined special values for circuits: snubber capacitance C_S = 1 nF and snubber resistor R_S = 26 Ω. The comparison as well as measurement results confirmed the correctness of calculated values. RC snubber limited voltage peaks of undamped circuit up to 60%. The high power losses in resistor R_S shows that it is not suitable to use this circuit in high efficiency circuits.

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