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RESEARCH INTO PROPERTIES OF POWER ELECTRONICS DEVICES MADE OF SILICON CARBIDE SIC, IN CONDITIONS OF COMMUTATING CURRENT WITH HIGH FREQUENCY

ABSTRACT *The paper presents results of measurements of the reverse recovery current and dynamic forward voltage of the SiC Schottky diodes at a current variation slope in a device, of 500 A/μs. These data were compared with the corresponding parameters determined for ultrafast silicon diodes. Results of tests of power losses in diodes made of silicon carbide, at a current commutation frequency of (10 $\div$ 200) kHz are presented, comparing them with corresponding data determined for ultrafast silicon diodes. Test results of power losses in transistors constituting elements of d.c. voltage controllers are also shown. Investigations were conducted with an ultrafast SiC diode and with an ultrafast silicon diode at the transistor switching frequency of 100 kHz.*

Keywords: *semiconductor devices, silicon carbide, high frequency converters.*

1. INTRODUCTION

Research work performed in the 90thies of the foregoing century on new technological materials lead to introducing into production semiconductor

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evices with properties essentially more advantageous than the corresponding devices based on silicon. This concerns especially the dynamic parameters, being particularly essential for converting electrical energy in power electronics systems, with high switching frequency and high operation temperature. One of the materials used presently in the semiconductor technology is the silicone carbide. Power electronics devices (Schottky diodes), produced on the basis of that material, are characterized by voltage and current parameters of 1200 V and some tens amperes. Basing on these devices it is already possible to build converters with power values of several, and in case of parallel connection, of above a dozen of kilowatts. These converters can operate at frequencies higher than those allowed by corresponding devices basing on silicon.

As these devices are relatively new, it is important to learn their properties, especially by experimental tests performed with converters with high operation frequency.

This paper present experimental results of investigations into dynamic parameters of Schottky diodes and ultrafast silicon diodes. The power losses generated in these diodes and in cooperating transistors at high frequency conditions are also presented.

2. POWER LOSSES IN DIODES AND TRANSISTORS DURING CURRENT COMMUTATION

In diodes operating in converter systems with current commutation, there occur power losses resulting from static characteristics in forward direction and power losses related to current commutation, when a diode goes over from forward to reverse operation and conversely from reverse to forward operation. Power losses related to current commutation depends of course on switching frequency. If the energy released in a device at switching-on and switching-off amounts to $E_{on} + E_{off}$ then the power loss generated in this device at a switching frequency of f will amount to $(E_{on} + E_{off}) \times f$.

Values of energy released in diodes in transient states at given values of voltage, current and the slope of its change, depend on the properties of those devices. These properties are determined by the values of the dynamic forward voltage and of the reverse recovery current. The dynamic properties of diodes co-operating with transistors in the commutation process have essential effect on the energy loss generated in the transistor at its switching-on.

In practice almost every topology of a transistorized converter contains diodes connected in counter-parallel with respect to transistors, e.g. in transistor module blocks for bridge systems of inverters, and as independent elements shorting with magnetic subassemblies, e.g. in the output circuit of a d.c. voltage controller. In the converter systems mentioned above the phenomena of current commutation in diodes effect the processes of switching-on currents by transistors and they generate additional power losses in transistors. In the process of taking over the main current by the transistor being switched-on, the diode goes over from the forward state into the reverse state and its reverse recovery current flows through this transistor. The variations of voltage and current of a transistor are shown in Figure 1.

The area denoted in the figure as E1 represents energy losses in the transistor, generated by the reverse recovery current of the diode co-operating with the transistor in the commutation process. The area E2 determines energy losses in the transistor originating from the load current of the main circuit.

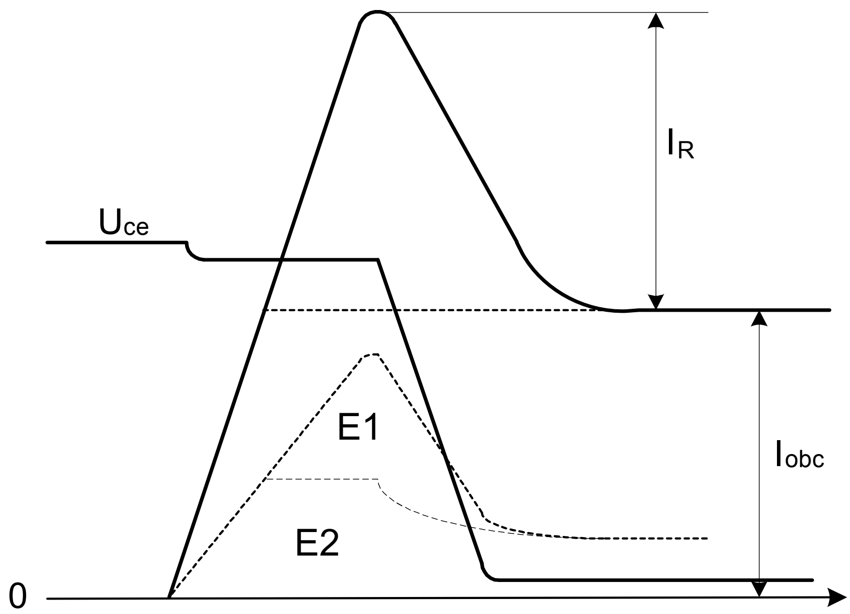

Fig. 1. Voltage and current of the transistor in the switching-on process
U_{CE} – voltage collector-emitter, I_{obc} – load current in steady state, I_R – peak value of the diode backward current

Thus the power (energy) loss generated in the transistor in the process of its switching-on depends on the current and voltage in the circuit, on transistor properties and on the reverse recovery current of the diode co-operating with the transistor during its switching-on.

3. INVESTIGATIONS INTO DYNAMIC PROPERTIES OF DIODES

Measurements of the dynamic forward voltage and of the reverse recovery current of a ultrafast silicone diode and of a Schottky diode made of silicone carbide were performed in the system shown in Figure 2. The parameters of those diodes are presented in Table 1.

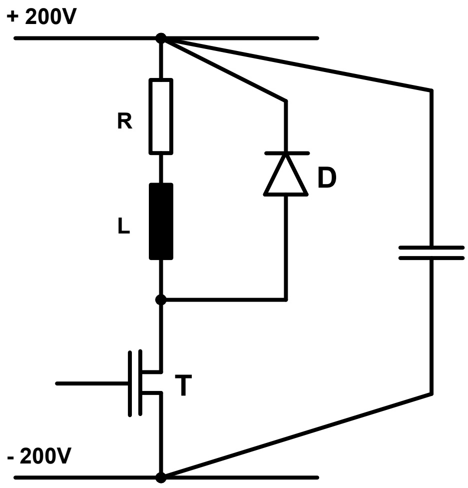

Fig. 2. Schematic diagram of the test system
D – dioda under test, T – switching transistor

The tests were conducted in the system of a d.c. voltage controller, whose schematic diagram is shown in Figure 2. The system was supplied with a d.c. voltage of 200 V, the current amounted to 10 A and the slope of its change was about 500 A/μs. An IGBT transistor of the type +IGTG12N60A4D of the firm Fairchild, with a current of 60 A and voltage of U_{CE} = 600 V was used as the switching element.

TABLE 1
*S*et of parameters of the diodes tested

Parameter		Diode type	
		IDT 16S60C (SiC)	**DSEP15-06A (Si)**
Backward voltage	V_{RRM}	600 V	600 V
Forward current	I_F	24 A, T_c < 100°C	15 A, T_c < 140°C
Voltage drop forward	V_F	1,5 V, I_F = 16 A, T_j = 25°C 1,7 V, I_F = 16 A, T_j = 155°C	2,04 V, I_F = 15 A, T_j = 25°C 1,35 V, I_F = 16 A, T_j = 150°C
Max. temperature of junction	T_j, T_{tg}	175°C	175°C
Type of casing		TO220	TO220
Thermal resistance	R_{thJC}	1.1 K/W	1.6 K/W
Total capacitive load	Q_e	38 nC	
Switching-off time	t_e	≥ 10 ns, 400 V, I = max, 200 A/μs, 150°C	35 ns, 30 V, 1 A, 100 A/μs, 25°C

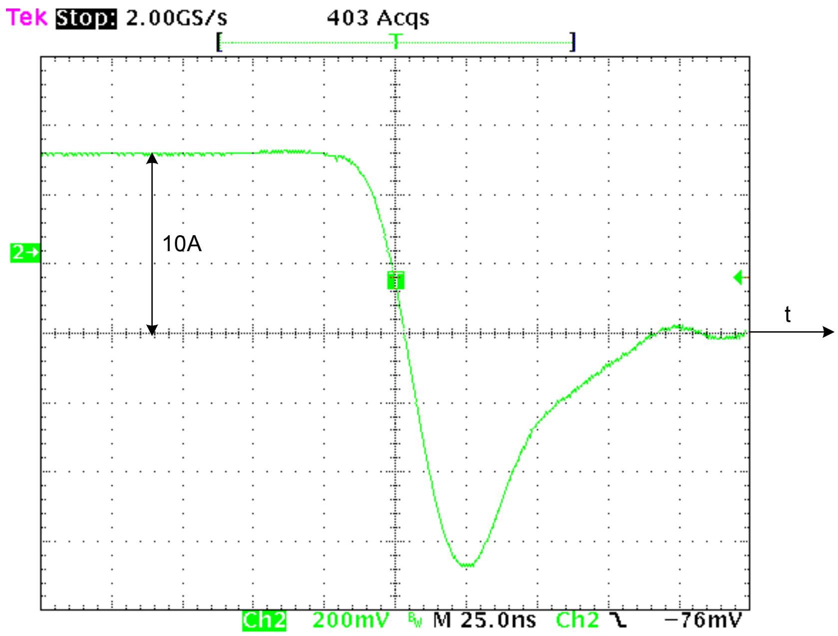

Fig. 3. Current of the silicon diode DSEP15-06A in the commutation process

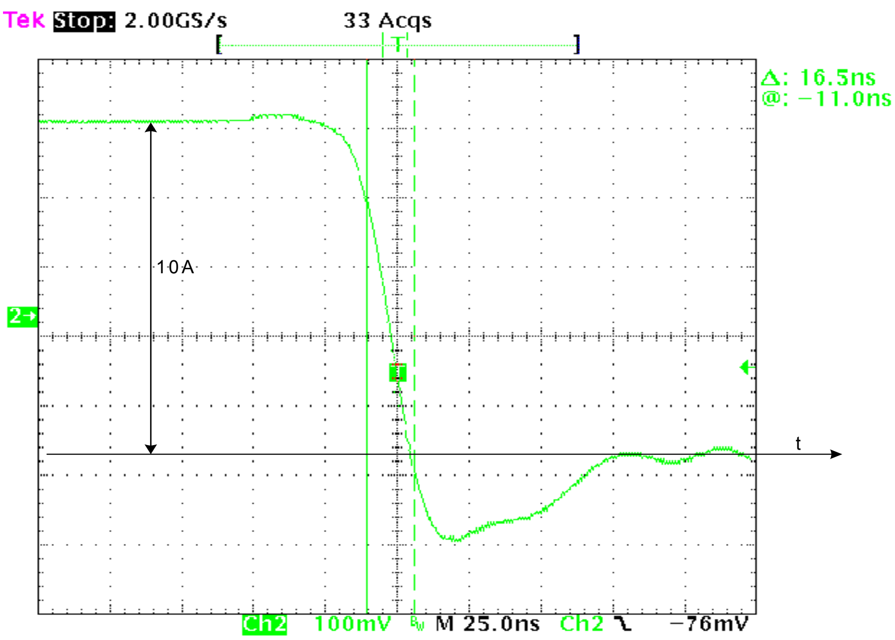

Fig. 4. Current of the silicone carbide diode IDT16S60C in the commutation process

The peak value of the reverse recovery current of the silicon diode is 13.6 A. Correspondingly, the value determined for the SiC diode is 2.5 A.

The parameter of diodes characterizing the properties of those devices in the process of coming into the steady state voltage is the dynamic forward voltage. The value of this parameter, similarly as that of the reverse recovery current effects the power losses generated in the device, particularly in conditions of converting energy with high frequency and at high variation slope of the diode forward current. The measurements of the dynamic forward voltage of the silicon diode and the SiC Schottky diode were performed at a forward current variation slope of 500 A/μs.

Oscillations in the voltage variation are the result of the resonance of junction capacitance and the inductance of the internal connections of diodes. The broken line presents the averaged variation of the forward voltage which can be interpreted as the component depending on the physical properties of the semiconductor material. The highest initial averaged value of the dynamic forward voltage of the silicone diode amounted to 11 V and the time which passed to gaining the stationary value of the voltage across the transistor was determined as 200 ns. The corresponding values for the SiC diode amounted to 4 V and 100 ns. Thus also at switching-in the SiC Schottky diode shows more advantageous properties than the ultrafast, silicone diode.
The measurement results are shown in Figures. 5 and 6.

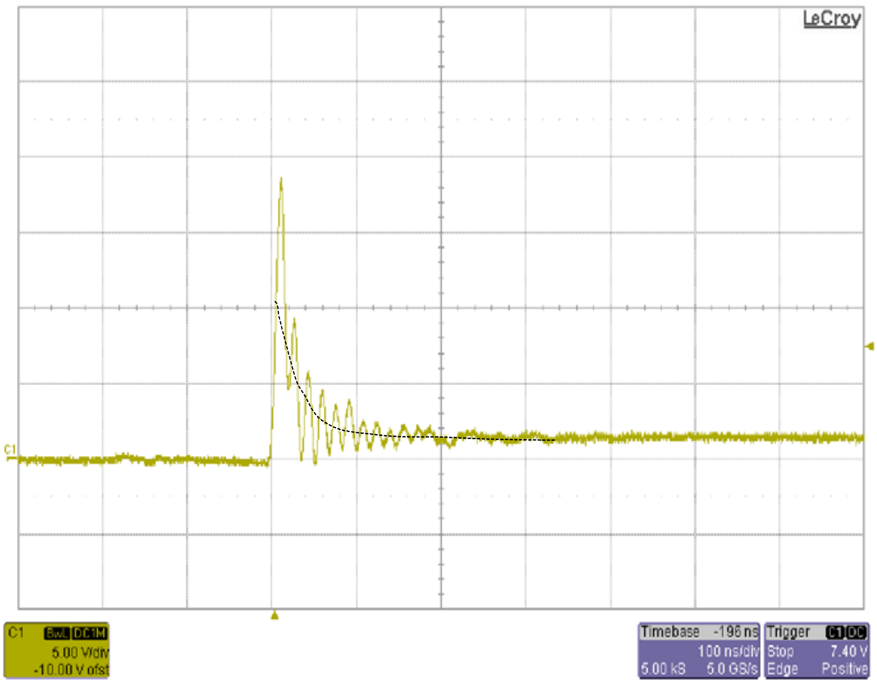

Fig. 5. Dynamic voltage drop in the forward direction of a silicone (Si) diode

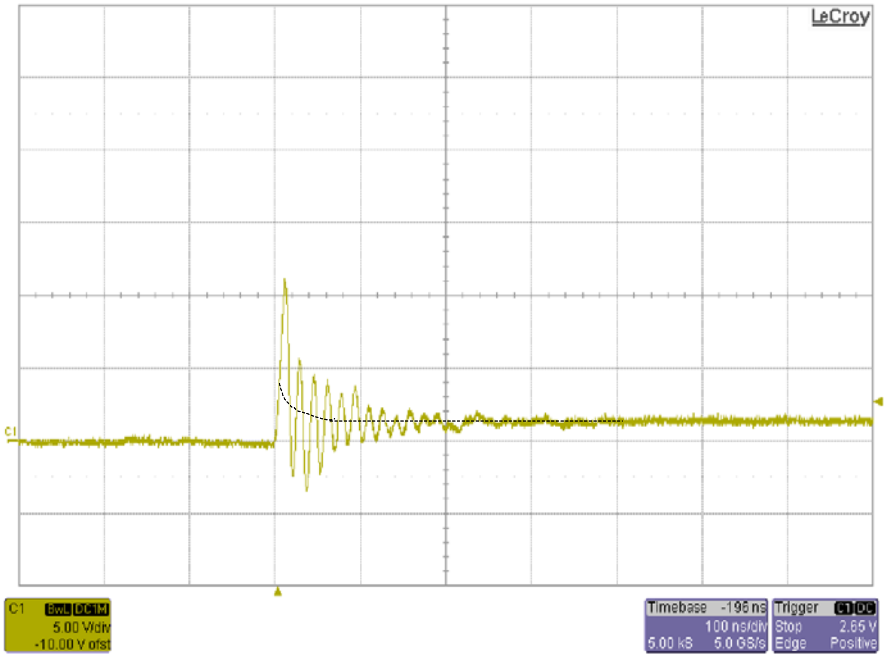

Fig. 6. Dynamic voltage drop in the forward direction of a silicon carbide (SiC) diode

4. MEASUREMENTS OF POWER LOSSES IN DIODES

Investigations were conducted in the system of a d.c. voltage controller whose schematic diagram is shown in Figure 2. The system was supplied with d.c. voltage of 200 V.

The switching frequency of the transistor was varied within (10 ÷ 200) kHz. The peak value of current pulses during tests was retained at the level of 10 A at a filling factor of 0.5, independent of frequency.

For determining the total power losses in semiconductor devices the thermal method was applied, consisting in making use of the thermal resistance of the radiator on which the tested devices were fixed. The tests were conducted in thermally stationary conditions. In the opinion of the Authors, the thermal method gives the most credible results of power loss measurements in conditions of high frequency, because it is not sensitive to electromagnetic interferences generated in such kind of systems.

Table 2 presents results of power loss measurements in Si and SiC diodes.

TABLE 2
Power losses in diodes

Conditions of loading		Power losses [W]	
Current	**Frequency**	**SiC diode**	**Si diode**
10 A	DC (continuous conduction)	13.10	11.95
10 A peak at a filling factor 1/2	10 kHz	6..55	6..90
	60 kHz	6..58	6..80
	100 kHz	6..62	14.70
	200 kHz	6.70	– [1)]

[1)] measurement given up because of exceeding the permissible temperatures of junction.

In conditions of d.c. loading, the losses in the SiC diode are by about 10% higher than in the Si diode. Comparable power losses in those diodes occur at a transistor switching frequency of 10 kHz whereby the power losses evolved in the diode of silicon carbide increase by only about 2% as the frequency increases from 10 kHz to 200 kHz. However power losses in the ultrafast silicone diode increase with frequency, and at a frequency of 100 kHz they reach a value over two times higher than at a frequency of 10 kHz. This frequency was assessed as the limit for a silicone diode at the given cooling conditions. Thus the measurement results presented above confirm the utilitarian advantages of Schottky diodes, made of silicone carbide, and the development perspectives of that technology in the high frequency converter technology.

5. MEASUREMENTS OF POWER LOSSES IN THE TRANSISTOR

Power losses in the switching transistor of the type IXKR40N60C produced in the technology CoolMOS were determined in the measuring system presented above for operation conditions with a Schottky diode of silicon carbide of the type IDT16S60C and with a silicone diode of the type DSEP15-06A. The voltage-current conditions in the system corresponded to those presented above. Measurements of power losses were conducted at a frequency of 100 kHz.

The power loss determined in those conditions amounted to:

- with a silicone diode 16.2 W,
- with a diode of silicon carbide 8.3 W.

The above measurement results present to how a high degree the dynamic properties of a diode affect the power losses, generated in the transistor, in the current commutation process especially in conditions of high switching frequency.

6. CONCLUSIONS

1. Measurements of reverse recovery current performed at the same values of forward current and of the slope of decay of this current at crossing the zero (I_F = 10 A, di_A/dt = 500 A/μs) for a diode of silicon carbide and for an ultrafast silicone diode showed that the peak value of that current is for a SiC device lower by several times than in case of an Si diode.
2. Values of dynamic forward voltage measured in conditions of current variation slope of 500 A/μs were, for a diode of silicone carbide, two times lower than the corresponding values determined for a silicone diode. This relationship concerns both the peak value of that voltage oscillations (caused by own capacitance and inductance of the diode) as well as the averaged value of that parameter.
3. The tested types of the SiC and Si diodes at loading by d.c. current of 10 A showed similar values of power losses. Power losses in an SiC diode determined at current commutation frequencies varied within (10 ÷ 200) kHz, showed an only insignificant rise in the whole frequency range. However the corresponding values of power losses determined in the same conditions of current commutation and frequency range for a silicone diode showed distinct rise with rising frequency. At a frequency of 100 kHz the power losses in that silicone diode were over two times higher than in a device of silicone carbide. This frequency is being determined as a limit value in given cooling conditions. As the SiC diode with frequency rising within (10 ÷ 200) kHz shows only a not high rise in power losses, it can be assessed that it will satisfy requirements also at current commutation frequencies higher than 200 kHz.
4. Using an SiC diode as a diode co-operating with the transistor in the current commutating process, essentially decreases the power losses in the device as compared with the corresponding Si diode. For example at the commutation frequency of the transistor forward current of 10 A and a frequency of 100 kHz,

the power losses in the switching transistor of the type IXKR40N60C produced in the CoolMOS technology using an ultrafast silicone diode were approximately two times higher than the corresponding losses generated with the SiC diode. Summarizing, it can be stated that in converters with high frequency current commutation using diodes made of silicone carbide causes generating essentially lower losses in the diodes themselves as well as in the transistors cooperating with them than, it finds place using even very fast silicone diodes.

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Manuscript submitted 29.11.2011

BADANIA WŁAŚCIWOŚCI PRZYRZĄDÓW ENERGOELEKTRONICZNYCH WYKONANYCH NA BAZIE WĘGLIKA KRZEMU W WARUNKACH KOMUTACJI PRĄDU Z WYSOKĄ CZĘSTOTLIWOŚCIĄ”

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STRESZCZENIE *W artykule przedstawiono wyniki pomiarów przejściowego prądu wstecznego oraz dynamicznego napięcia przewodzenia diod Schottky`ego wykonanych na bazie węglika krzemu – SiC. Pomiary przeprowadzono przy stromości zmian prądu wynoszącej 500 A/µs. Wyniki te porównano z odpowiednimi rezultatami uzyskanymi dla ultraszybkiej diody krzemowej o takich samych parametrach napięciowo-prądowych. Przedstawiono także wyniki pomiarów strat mocy generowanych w tych diodach w warunkach komutacji prądu z częstotliwością zmienianą w granicach (10 ÷ 200) kHz. Artykuł zawiera również wyniki badań strat mocy wydzielanych w tranzystorze kluczującym z częstotliwością 100 kHz. Wyniki te dotyczą przypadków współpracy tranzystora w procesie komutacji prądu z ultraszybką diodą krzemową oraz z diodą SiC.*