

## USING OF THE MODERN SEMICONDUCTOR DEVICES BASED ON THE SiC

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**Summary** This paper deals with possibility of application of the semiconductor devices based on the SiC (Silicon Carbide) in the power electronics. Basic synopsis of SiC based materials problems are presented, appreciation of their properties in comparison with current using power semiconductor devices ((IGBT, MOSFET, CoolFET transistors).

### 1. INTRODUCTION

Power semiconductor devices based on the SiC substrate is coming more and more popular used with increasing development of the power electronics. Due to the advantageous qualities discovered at the SiC this material becomes very interesting object for research and development and subsequent using in the all sorts of applications where bigger and bigger exigencies on efficiency, magnitudes, weight and impact on surroundings are set.

### 2. SiC PROPERTIES

Crystals of SiC have analogical crystalline structure as diamond and therefore they belong among the hardest known materials, in the Moh's scale of the hardness they reach levels 9-10. Primarily SiC finds use as material called "Carborundum" and it used to exploit for grinding and polishing. Later it was used in the fire-resistant fireclay brickworks and heating shells for industry furnaces or in the composite materials.

With development of the electrotechnics the semiconductor features of SiC were detected and it started to add to the semiconductor substrate of blue shining LED diodes, later in the high shining diodes and in the last few years it has also started to assert in the field of the power electronics.

Relatively high density of basic material failures was the highest problems of the SiC semiconductor devices development. Subsequently due to the improving technologies the wafers magnitudes increased and therefore failure density decreased. This fact get started decreasing of the SiC price and boost up next development. Fig. 1 shows development of the particular semiconductor wafers in the last period.

From the chart (Fig.1) it is evident that size of the SiC wafers expressively approximate GaAs (gallium arsenide) and mainly due to the price of the material. It stands to reason that bigger wafers diameter offers to create devices for higher nominal voltages and currents. In the present time there is production of devices (mainly diodes) for voltage

range 300, 600, 1200 and 1700 V (engineering samples of 6500V for traction vehicles of Siemens).

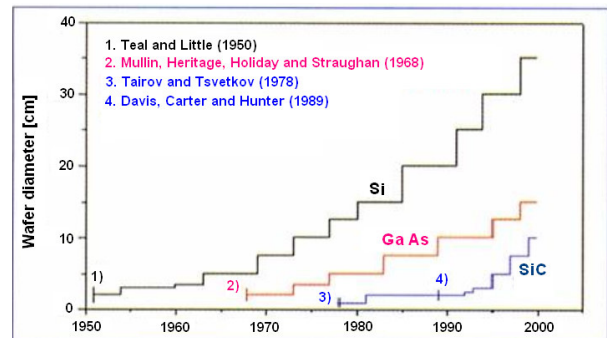


Fig. 1: Increase of the wafer diameter of various materials in the period of last 15 years

The Silicon Carbide as a crystalline material has many modifications caused by various form of crystalline lattice which determines semiconductor properties together with atom features. Especially number of the valence electrons, nucleus weight and dimensions of basic cells of crystalline lattice are parameters to determine character of the material. Also sort and lattice defect number can determine the character.

Different crystalline structures are called polytypes and they cause by various means of layers ordering. Individual polytypes of the same material are different in structure and often take part of various crystalline systems.

Each of the polytype SiC has unique electrical and optical properties due to the distinct arrangement of the silicon atom and carbon atom inside crystalline lattice. While over the 170 polytypes of the SiC are known, only few of them we can use in the area of semiconductor devices. Polytypes 3C-SiC, 4H-SiC, 15R-SiC a 6H-SiC are most common developed for power electronics.

3C-SiC also so-called  $\beta$ -SiC is the unique form of the SiC with cubic crystalline structure, it means the same features in all directions. This fact does not valid at other types so-called  $\alpha$ -SiC, their properties are dependent on the current direction or electric field orientation.

### 3. COMPARISON OF THE SIC WITH OTHER MATERIALS

SiC has several unique properties, which make SiC very interesting object for research and development, mainly in the area of high voltage applications. Fig.2 shows these features in comparison with commonly used semiconductor materials (Gallium Arsenide and Silicon).

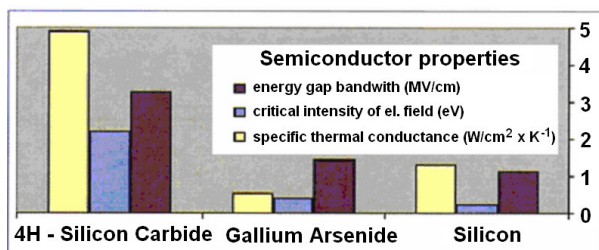


Fig.2 Comparison of individual semiconductor features

Much smaller intrinsic carrier concentration of SiC allows working at extreme temperature of the junction (theoretically more than 800°C), temperature 600°C was experimentally verified. Now it is difficult to imagine working at this temperature mainly according to the limitation of used cases. Polymer cases and current types of soldering are applicable for "lower" temperature. Cases LTCC (Low Temperature Co-fired Ceramic) are the one possibility of using SiC devices in the future. However cases LTCC can dramatically debase manipulation ability in comparison with current devices. Therefore the applications for very high have to abide for appropriate cases development.

High disruptive voltage and wide energy gap of SiC enable to made extremely fast power components. Therefore power electronic converters used devices based on the SiC can work at the higher switching frequencies with higher efficiency (low switching losses).

Using higher switching frequencies of the converters is very desirable to use smaller capacitances, inductances and transformers to decrease general size and weight.

The lower resistance at the on-state and faster switching frequency of SiC help to minimize energetic losses and therefore lower heat generation. Higher thermal conductivity enables more efficient heat removal from the component. It is very important to appreciate that heat radiation very escalate with increasing thermal difference between device and surrounding. So the higher working temperature of the device the more efficient cooling. Device ability (based on the SiC) worked at the higher temperatures allows much efficient cooling and then smaller cooling system or its total elimination.

Tab. 1 Comparison of electric features of semiconductors

Parameter	Si	GaAs	4H-SiC	6H-SiC	3C-SiC
Energy gap bandwidth [eV]	1,1	1,42	3,2	3	2,3
Relative dielectric constant	11,9	13,1	9,7	9,7	9,7
Breakdown electric field at $N_D=10^{17} \text{ cm}^{-3}$ [MV cm <sup>-1</sup> ]	0,6	0,6	with c-axis: 3	with c-axis: 3,2 ⊥ with c-axis: >1	>1,5
Thermal conductivity [W cm <sup>-1</sup> K <sup>-1</sup> ]	1,5	0,5	3-5	3-5	3-5
Intrinsic carrier concentration $n_i$ [cm <sup>-3</sup> ]	$10^{10}$	$1,8 \cdot 10^6$	$\approx 10^{-7}$	$\approx 10^{-5}$	10
Electron mobility at $N_D=10^{16} \text{ cm}^{-3}$ [cm <sup>2</sup> V <sup>-1</sup> s <sup>-1</sup> ]	1200	6500	with c-axis: 800 ⊥ with c-axis: 800	with c-axis: 60 ⊥ with c-axis: 400	780
Hole mobility at $N_D=10^{16} \text{ cm}^{-3}$ [cm <sup>2</sup> V <sup>-1</sup> s <sup>-1</sup> ]	420	320	115	90	40
Saturated electron velocity [10 <sup>7</sup> cm s <sup>-1</sup> ]	1	1,2	2	2	2,5
Donor type added	P,As	Si	N,P	N,P	N
Acceptor type added	B	Be,Mg,C	Al,B	Al,B	Al

One of the advantages of semiconductor based on the SiC is evident from the Figure 3. It is outstanding decrease of backward recovery current through the diode at the transition from on-state interval to the blocking state. Detailed description of this process is presented in [7]. This phenomenon has fundamental influence on the switching losses size.

Schottky construction is mainly used for SiC production, it exploits rectifier property of metal-semiconductor junction. The big advantage of this junction is absence of minority charge carriers. The current conduction is only realized by majority carriers which brings several advantages.

Schottky diodes are used in applications for very high frequencies to replace point contact diodes. Schottky diodes have better mechanical strength, produce reproducibility, lower signal noise and higher reverse blocking voltage. Low voltage drop on-state interval enables to use Schottky diodes for power electronic converters like rectifiers, inverters and switches with higher energetic efficiency, smaller dimensions and weight against using classical diodes. On-coming of the SiC removed one of the biggest negative of Schottky diodes – lower reverse blocking voltage (up to 150 V).

For example the company Cree produces high voltage diodes in range 300, 600, 1200V and etc. at current loading 1-30 A. Single-channel designed D-PaK, D2 Pak, TO – 220 and double-channel TO – 247 [2] are available.

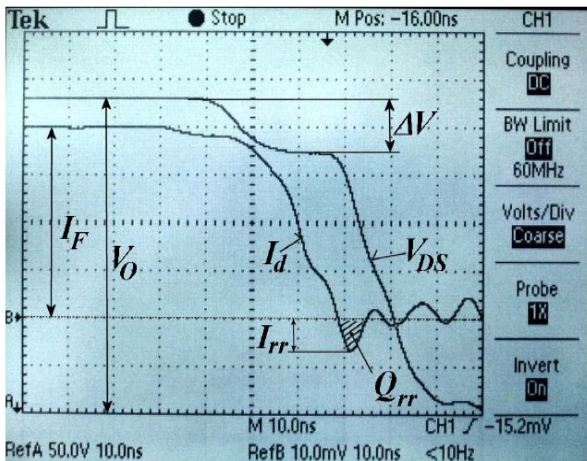
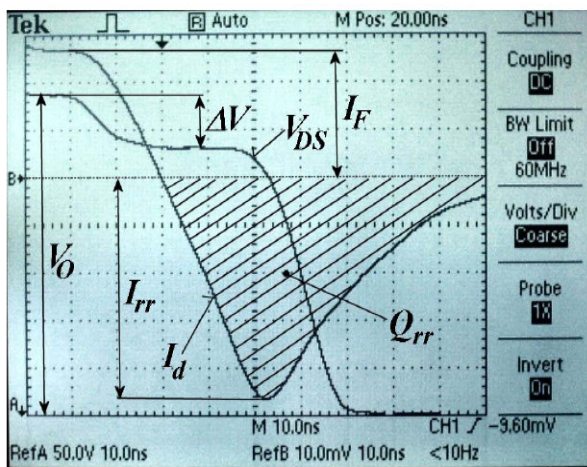


Fig.3. Current waveform of the ultrafast soft recovery epitaxial 15ETH06/600V (left) and thinQ! SiC Schottky SDT12S60/600V(right)

#### 4. PRACTICAL USING OF THE SIC

Meantime SiC diodes are the most used devices based on the Silicon Carbide. They are used in many applications. Blocking (freewheeling) diodes in the PFC applications has been the first example of using and it is still frequently used. Rectifying and

freewheeling diodes in the switching sources and freewheeling diodes in voltage inverters or active switching rectifiers are the next using of SiC. Further we will discuss possibility of other devices based on the SiC:

#### SiC V-JFET (vertical junction FET)

Unipolar power switches for voltage cca 1200 V and 30 A, engineering samples c. 3,5 kV.

#### SiC – MOSFET

It has expressively better dynamic properties of freewheeling diodes than the previous Si MOSFET.

Reached parameters: 3,3kV/2A;  $R_{DSon} = 3\Omega$  at 25°C; 4,8Ω at 150°C; the goal is to achieve  $R_{DSon} = 0,4\Omega$  and lower.

#### J-FET cascade

The next device in the development is so-called Si-MOSFET/SiC – JFET (cascade design). As it is evident from the label it consists of uniplar silicon MOSFET with blocking voltage 60V and SiC VJFET 1500V. The principal scheme is presented in the Fig.4.

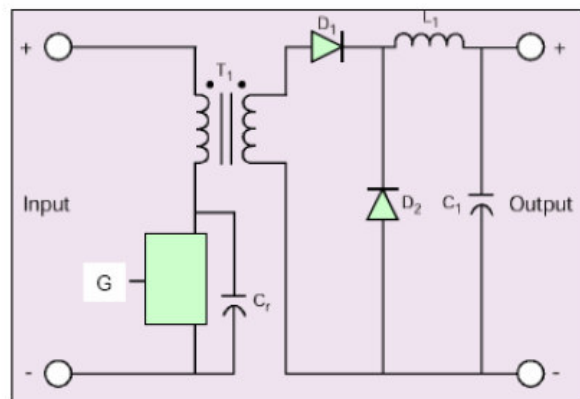
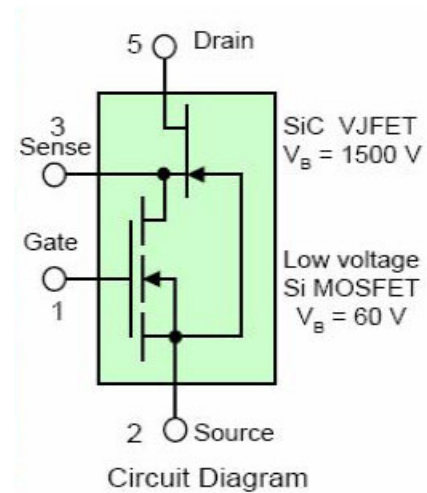


Fig. 4 Principal scheme of device J-FET (cascade)

Low total losses, high switching frequencies (till 200 kHz), high reverse voltage, resistivity of

avalanche breakdown and positive voltage switching are advantages of this design. There are additional inconsiderable ability – short circuit current limitation ( $t_{sc} > 85\text{ms}$ ) and working at higher thermal conditions ( $T_j > 200^\circ\text{C}$ ).

#### 4. CONCLUSION

Main reasons to give priority to SiC devices against classical Silicon:

- Roughly 3x larger energy gap bandwidth than Si – blocking ability also at higher temperature (chip c.  $400^\circ\text{C}$ , case  $300^\circ\text{C}$ ).
- 9x higher value of critical intensity than Silicon – possibility to realize applications of power components with high reverse voltage (unipolar devices up to 5 KV, bipolar devices up to 10 till 20 KV).
- 3,5x higher value of specific thermal conductance than Silicon – easier transfer of thermal power dissipation enabling higher current loading at the same cooling conditions.

However there are principle handicaps breaking the SiC development in the power electronics, mainly:

- Low quality of basic crystalline material, high fault density and small wafer diameter.
- High production expenses caused by very difficult technology.
- Improving quality of Silicon power devices (COOLMOSFET, FS-IGBT).
- Very small spectrum of mass producers, small choice of different types.
- EMC aspects – with increasing switching frequency the EMC interference rises and high quality filters have to be added to the converters.

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