NEW POSSIBILITIES OF POWER ELECTRONIC STRUCTURES USING SiC TECHNOLOGY

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Summary This paper is dedicated to the recent unprecedented boom of SiC electronic technology. The contribution deals with brief survey of those properties. In particular, the differences (both good and bad) between SiC electronics technology and well-known silicon VLSI technology are highlighted. Projected performance benefits of SiC electronics are given for several large-scale applications on the end of the contribution. The basic properties of SiC material have been discussed already on the beginning of 80's, also at our university [1].

1. INTRODUCTION

Silicon carbide (SiC) based semiconductor electronic devices and circuits are presently being developed for use in high-temperature, high-power, and/or high-radiation conditions under which conventional semiconductors cannot adequately perform. Silicon carbide's ability to function under such extreme conditions is expected to enable significant improvements to a far-ranging variety of applications and systems. These range from greatly improved high-voltage switching for energy savings in public electric power distribution and electric motor drives to more powerful microwave electronics for radar and communications to sensors and controls for cleaner-burning more fuel-efficient jet aircraft and automobile engines. In the particular area of power devices, theoretical appraisals have indicated that SiC power JFET's and diode rectifiers would operate over higher voltage and temperature ranges, have superior switching characteristics, and yet have die sizes nearly 20 times smaller than correspondingly rated silicon-based devices. However, these tremendous theoretical advantages have yet to be realized in experimental SiC devices, primarily due to the fact that SiC's relatively immature crystal growth and device fabrication technologies are not yet sufficiently developed to the degree required for reliable incorporation into most electronic systems. The widely spread usage of power semiconductors manufactured of SiC is one of the most promising developments at this market today. Because of the outstanding performance of this new material high voltage blocking active switches are under investigation [1,2,4].

2. FUNDAMENTAL PROPIERTIES OF SEMICONDUCTOR MATERIALS

SiC is a material with outstanding properties for power semiconductor application. Beside research activities including different power semiconductor switch types, unipolar JFET devices for blocking voltage of more than 1200V are applicable as samples promising switching loss reduction above all [2].

Tab. 1. Key electronics properties of Si, GaAs & 4H-SiC

Property	Si	GaAs	4H-SiC
Bang gap, Eg [eV]	1.12	1.42	3.2
Electron mobility, μ_n [cm^2/Vs]	1400	9200	800
Hole mobility, μ_p [cm^2/Vs]	450	400	140
Intrinsic carrier concentration, n_i [cm^{-3}]:300K	1.5 x10^{10}	2.1 x10^6	5.0 x10^9
Electron saturated velocity, v_{nsat} [x10^7 cm/s]	1.0	1.2	2.0
Critical breakdown electric field, E_{crit} [MV/cm]	0.25	0.3	2.2
Thermal conductivity, Φ [W/cm.K]	1.5	0.5	3 to 5

In comparison with similar table in [1] one can see that, the new material 4H-SiC with energy band gap 3.2 eV has been developed and is mostly used in applications (see below in next chapters).

The wide band gap energy and low intrinsic carrier concentration of SiC allow SiC to maintain semiconductor behavior at much higher temperatures than silicon (Si), which in turn permits SiC semiconductor device functionality at much higher temperatures than silicon. As discussed in basic semiconductor semiconductors textbooks [1], semiconductor electronic devices function in the temperature range where intrinsic carriers are negligible so that conductivity is controlled by intentionally introduced dopant impurities. Furthermore, the intrinsic carrier concentration n_i is a fundamental prefactor to well-known equations governing undesired junction reverse-bias leakage currents.

As temperature increases, intrinsic carriers increase exponentially so that undesired leakage currents grow unacceptably large, and eventually at still higher temperatures, the semiconductor device operation is overcome by uncontrolled conductivity as intrinsic carriers exceed intentional device dopings. Depending upon specific device design, the intrinsic carrier concentration of silicon generally confines silicon device operation to junction temperatures less than 300 °C. SiC's much smaller

intrinsic carrier concentration theoretically permits device operation at junction temperatures exceeding 800 °C, and 600 °C SiC device operation has been experimentally demonstrated on a variety of SiC devices.

The structure of 6H-SiC new material is shown in Fig. 1.

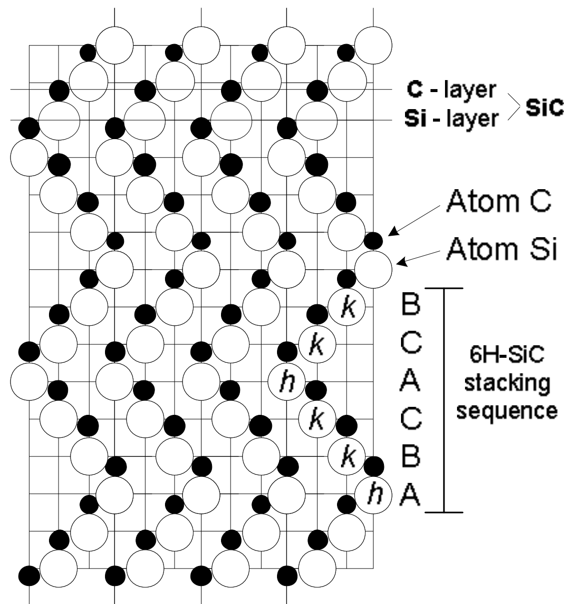

Fig. 1. Schematic cross-section of the 6H-SiC polytype [4]

3. ADVANTAGES OF SiC MATERIAL COMPARED WITH Si

Table 1 compares the key electronic properties of 4H-SiC to Si and GaAs. The higher breakdown electric field strength of SiC enables the potential use of SiC Schottky Barrier Diodes (SBD) in 600-2000 V range. Specific benefits of SiC electronic properties are:

The 5 to 30 x higher breakdown electric field strength of SiC reduces the specific on resistance r_{on} compared to the Si and GaAs SBDs. This is illustrated in Fig. 2. At 600 V, a SiC SBD offers a r_{on} of 1.4 mΩ/cm^2, which is considerably, less than 6.5 mΩ/cm^2 for a GaAs SBD and 73 mΩ/cm^2 for a Si SBD. This means that the SiC SBD will have a much smaller foot-print.

The higher band gap results in much higher Schottky metal-semiconductor barrier height as compared to Si, resulting in extremely low leakage currents at elevated junction temperatures due to reduced thermionic electron emission over the barrier.

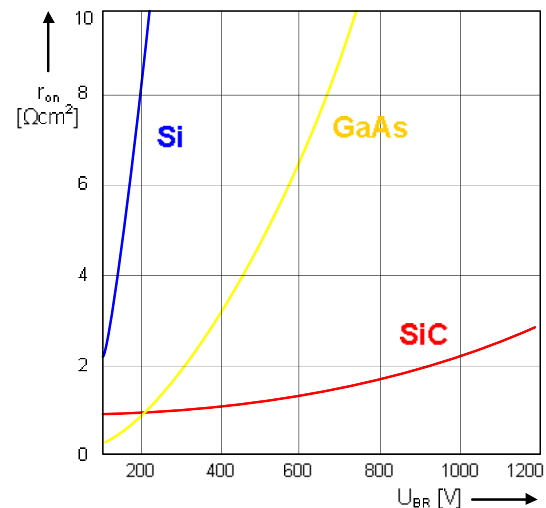

Fig. 2 Specific on Resistances Function of the Breakdown Voltage [5].

The very high thermal conductivity of SiC reduces the thermal resistance of the die. This means heat is more easily conducted away from the device junction, and thus the device temperature increase is slower.

SiC can operate at high temperatures because of its wider band gap. SiC device operation at up to 600 °C is mentioned in the literature. Most Si devices, on the other hand, can operate at a maximum junction temperature of only 180 °C.

Forward and reverse characteristics of SiC power devices vary only slightly with temperature and time; therefore, SiC devices are more reliable.

SiC-based devices have excellent reverse recovery characteristics. With less reverse recovery current, the switching losses and electromagnetic interference (EMI) are reduced and there is less or no need for snubbers.

SiC is extremely radiation hard; i.e., radiation does not degrade the electronic properties of SiC [6].

4. POSSIBILITIES OF APPLICATION SiC MATERIAL IN POWER SEMICONDUCTOR DEVICES

Schematic diagram of the SiC Schottky barrier diode structure, showing the field oxide, the overlapping metal electrode, and the epi-layer drift region (Fig. 3).

- Low-switch losses
- Very high switching speed
- Breakdown voltages of 600 to 1200 V
- High-Temperature Performance (over 300 °C)

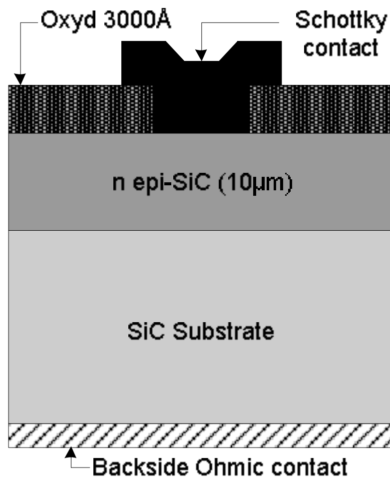

Fig. 3 Structure of SiC Schottky Barrier Diode

The structure of SiC Vertical Junction Field Effect Transistor (V-JFET) is given in Fig. 4. Properties of this structure are as follows:

- Very high switching speed
- High T capability (PN-isolation)
- Fast & robust PN body diode
- Volume mobility in the channel
- Doping: channel drift region
- Suitable up to 3 – 4 kV
- Lowest R_{ON} (today)
- No need for an external freewheeling diode

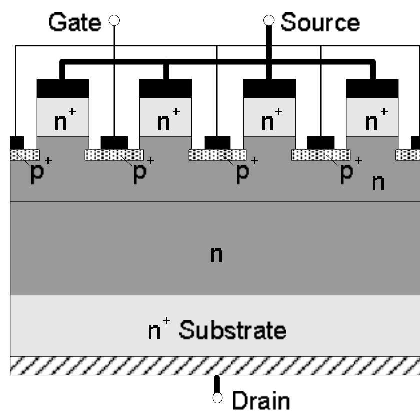

Fig. 4 Structure of SiC V-JFET

Cascode connection – is basic connection of V-JFET transistor couplet with low voltage power Si MOS FET transistor (Fig. 5). Properties of this structure are as follows:

- 80 mΩ on resistance (25 °C) includes low voltage power Si-MOSFET
- High short circuit capability
- Power almost totally on SiC V-JFET
- Suitable up to 3 – 4 kV
- High T capability

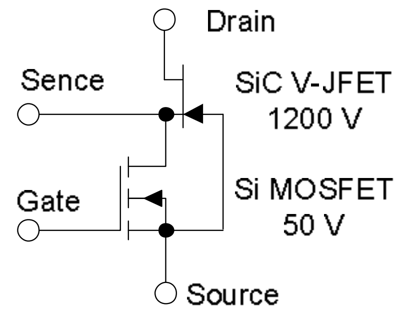

Fig. 5 Cascode SiC V-JFET + MOSFET

5. SIMULATION OF SCHOTTKY DIODE DYNAMIC PROPERTIES

The computer simulation was made in OrCAD®, PSpice Simulink®. The simulation circuit is given in Fig. 6.

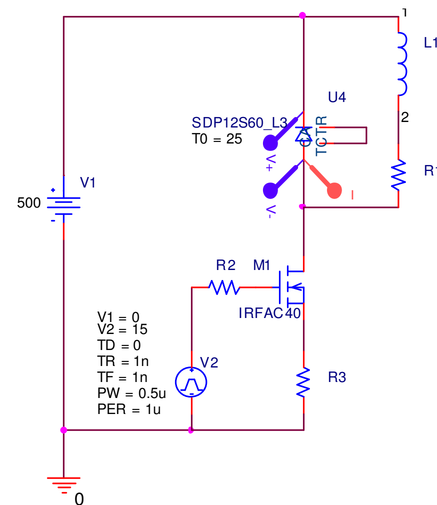

Fig. 6 Circuit for Simulation of Dynamic Properties of SBD

The oscillations of voltage and current SBD's, by turn on and turn off sequence, are given by properties of discharge circuit (serial R-L-C circuit). The capacitor in this circuit is the internal capacity of Schottky barrier.

The turn on and turn off sequence, the voltage and current SBD's, is given in Fig. 7 and Fig. 8.

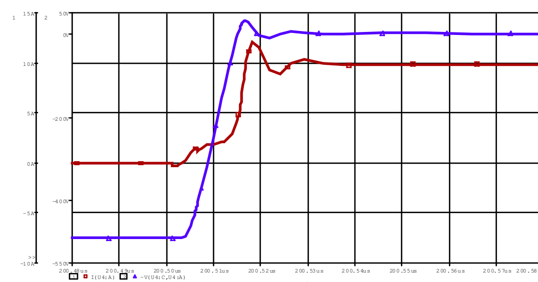

Fig. 7 Voltage and Current Waveforms of SiC Schottky Barrier Diode – Turn ON Process

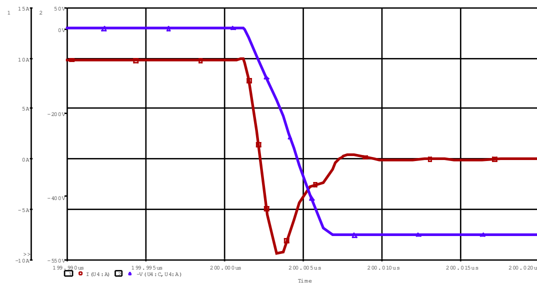

Fig. 8 Voltage and Current Waveforms of SiC Schottky Barrier Diode – Turn OFF Process

The turn off time is given by discharging the energy from Schottky capacity of Schottky barrier diode. In this simulation of SBD10S60 Schottky barrier diode is the turn off time 5 ns.

It means, the Schottky barrier diodes are suitable for high frequency circuits and their applications.

6. CONCLUSION

The new possibilities and characteristics of the SiC structure are discussed and reported in the paper. The new survey [9] forecasts that the world market for Schottky diodes and power transistors will grow from $13 million in 2004 to over $53 million in 2009 (see in Fig. 8). Schottky barrier diodes, supplied by US Cree Company and by Infineon in Europe, will penetrate the microelectronics market at a much higher rate than transistors, which are less mature. Rockwell Scientific and Cree supply SiC MOSFETs, and another 15 companies, mostly major chip manufacturers, are working on further development of these transistors.

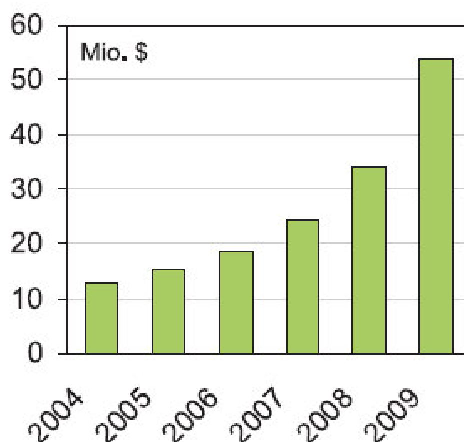

Fig.8 2004 –2009 World Market for SiC Devices

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