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AN EXPERIMENTAL STUDY IN FINDING THE SILICON CARBIDE ELECTRONICS PROPERTIES IN ELECTRONIC CIRCUIT

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ABSTRACT:

Silicon carbide (SiC) based power semiconductor switches, with their superior features compared with silicon- (Si-) based switches, has resulted in substantial improvement in the performance of power electronics converter systems. SiC devices are finding more applications where the benefits of SiC technology can offer system advantages, which are significant enough to offset the increased device cost. Even though several SiC-based power devices have been successfully commercialized recently, the SiC device market is still in its early stage and its potential users (power supply designers) are not familiar with this new technology. Silicon carbide materials, with its high mechanical strength, high thermal conductivity, ability to operate at high temperatures, and extreme chemical inertness to most of the electrolytes, are very attractive for high-power applications. This article, the pros and cons of commercially available SiC power devices will be discussed along with a comparison. In this paper, properties, advantages, and limitations of SiC and conventional Si materials are compared. Various applications, where SiC power devices are attractive, are discussed.

Keywords: *Silicon carbide (SiC), SiC properties, high-voltage, wide energy band-gap semiconductors.*

1.0 INTRODUCTION:

Silicon carbide (SiC) based semiconductor electronic devices and circuits are presently being developed for use in high-temperature, high-power, and 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. SiC power devices, with their close-to-ideal characteristics, bring great performance improvement to power converter applications. Power semiconductor devices constitute the heart of power electronics systems, and silicon (Si)- based power devices have been the dominant choice for this system. However, as the needs and requirements for electrical energy continuously grow, Si-based power devices have limited performance related to inherent material characteristics, which make them unable to meet future demands, especially in high-voltage, high-efficiency, and high-power density applications. SiC has become the material of choice for next generation power semiconductor devices to replace existing Si technology. The wider band gap, higher thermal conductivity, and larger critical electric field allow SiC devices to operate at higher temperatures, higher current density, and higher blocking voltages than Si power devices.

2.0 LITERATURE REVIEW:

Magnus Willander (2017) The physical and chemical properties of wide band gap semiconductors silicon carbide and diamond make these materials an ideal choice for device fabrication for applications in many different areas, e.g. light emitters, high temperature and high power electronics, high power microwave devices, micro-electromechanical system (MEMS) technology, and substrates.

Hangseok Choi, (2016), Silicon Carbide (SiC) power devices have evolved from immature prototypes in laboratories to a viable alternative to Si-based power devices in high-efficiency and high-power density applications. In this article, the pros and cons of commercially available SiC power devices will be discussed along with a comparison to their Si counterparts to help power supply designers learn more about this new technology and select the right SiC devices suitable for their applications.

Ahmed Elasser et al (2015) Silicon-based power semiconductor devices, ranging from diodes, thyristors, gate turn-off thyristors, metal–oxide–semiconductor field-effect transistors, and, more recently, insulated-gate bipolar transistors, integrated gate-commutated thyristors, and metal–oxide–semiconductor turn-off thyristors, are the workhorse of power electronic systems and circuits.

Burak Ozpineci et al (2014) The emergence of silicon carbide- (SiC-) based power semiconductor switches, with their superior features compared with silicon- (Si-) based switches, has resulted in substantial improvement in the performance of power electronics converter systems.

Nisha Kondrath et al (2010) Silicon carbide materials, with its high mechanical strength, high thermal conductivity, ability to operate at high temperatures, and extreme chemical inertness to most of the electrolytes, are very attractive for high-power applications. In this paper, properties, advantages, and limitations of SiC and conventional Si materials are compared. Various applications, where SiC power devices are attractive, are discussed.

3.0 RESEARCH METHODOGY:

Electronic properties:

While the possibility to crystallize in different poly types, being chemically inert, hard, and temperature resistant are all important properties, the aspect of SiC that has attracted so much attention concerns the unique electronic properties.

Due to the unstable nature on most poly types, only three of them are commonly produced. They are called 6H-SiC, 4H-SiC and 3C-SiC. Most of the physical properties of these polytypes are identical, except the electronic ones. The main parameters of 6H, 4H and 3C SiC polytypes are listed in table 1. For electronic devices, each polytype has its specific advantages. For example, 4H is better suited for high power (e.g. high voltage electricity distribution) and high temperature (e.g. car or plane engines), while 3C should be better for high frequency applications (e.g. radar).

Band gap:

The wide band gap is what enables the use of SiC for very high temperature operation. Thermal ionization of electrons from the valence band to the conduction band, which is the primary limitation of Si-based devices during high temperature operation, is not a problem for SiC-based devices because of this wide band gap.

Critical electric breakdown field:

One of the most important properties for power-device applications is the critical electric breakdown field, EC. This property determines maximum electric field that the material can support before suffering physical breakdown. Normally, wide band gap materials have a high breakdown electric field because the wide band gap leads to high impact ionization energy. Silicon carbide can withstand an electric field about ten times greater than GaAs or Si without undergoing avalanche breakdown. This high breakdown electric field enables the fabrication of very high-voltage, high-power devices such as diodes, power transistors or high power microwave devices. In addition, it allows close distances between adjacent devices, allowing high device packing density for integrated circuits. The breakdown voltage at a p-n junction is given by:

$$V_B = \frac{E_C W_d}{2}$$

Thermal conductivity:

The second most important parameter for high power and high-frequency device applications is the material's thermal conductivity. An increase in temperature generally leads to a change in the physical properties of the device, which normally affects the device in a negative way. Most important is the carrier mobility, which decreases with increasing temperature. Heat generated through various resistive losses during operation must thus be conducted away from the device and into the package. At room temperature, SiC has a higher thermal conductivity than any metal. The thermal conductivity of copper is 4.0 W/(cm-K). That of silver is 4.18 W/(cm-K). There is dependence on the purity of the crystal as well as on the crystal direction. High-purity semi-insulating SiC material has the highest reported thermal conductivity with a value of 4.9 W/(cm-K).

Saturated drift velocity and carrier mobility:

For high-frequency devices, a very important parameter is the saturated drift velocity vs. It is one of the key material and device properties that determine the ultimate limit of speed of response and frequency of a device, such as a transistor. In a semiconductor, carrier velocity cannot indefinitely increase with the applied electric field. Carriers speed up in response to a stronger field until the saturation drift velocity is reached. At this point, higher fields do not result in any increase.

Figures of merit for high power and high frequency devices:

Owing to its wide band gap, high heat conductivity and pronounced thermal, chemical and radiation stability, SiC has been regarded primarily for applications in the field of power electronics. The device potential of a semiconductor material is often estimated in terms of figures of merit. Johnson"s figure of merit (JFOM) addresses the potential of a material for high frequency, voltage and power discrete amplifiers, according to

$$JFOM = \frac{\left(E_B^2 v_s^2\right)}{4\pi^2}$$

where EB is the breakdown electric field and vs is the electron saturation velocity. The JFOM of 4H-SiC is up to 400 times better than Si and is only inferior to diamond.

SIC CHARACTERISTICS:

SiC is a compound semiconductor material that has many properties, which makes it suitable for different applications. The primary characteristic is the wide energy band gap, which determines the amount of energy required to raise an electron from the valence bond into the conduction band. The wide energy band gap, 3.0-3.2 eV, facilitates the operation of SiC in higher temperatures and higher radiation levels. A wide energy band gap results is reduced intrinsic carrier concentrations for higher temperature operation and reduced leakage current. Radiation does not degrade the electrical properties of SiC devices. SiC also operates at very high power levels for the same reason.

4.0 RESULTS:

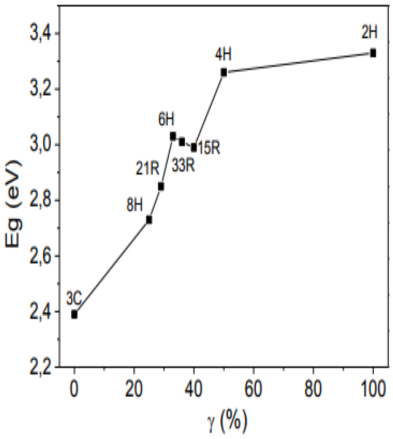

Figure shows Energies of the indirect band gap of several SiC poly types as a function of the 'hexagonality' percentage

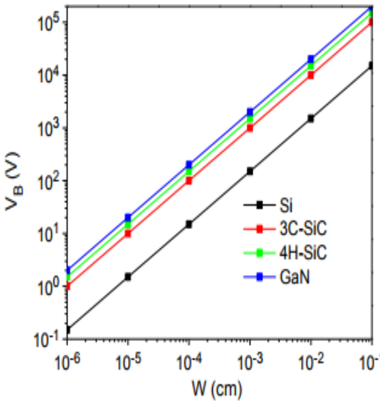

Figure shows Breakdown voltage as a function of drift region width for Si, 3C-SiC, 4H-SiC and GaN.

The relative strength of EC for SiC compared to Si of ten times refers to devices designed for the same blocking voltage. For a doping of approximately 1016 cm−3 , EC for 4H-SiC is 2.49 MV/cm [26]. For Si, the value of EC is about 0.401 MV/cm for the same doping [27]. In this comparison, the difference between SiC and Si is only about a factor of six and not the often advertized factor of ten. However, if one compares the critical strengths of devices made for the same blocking voltage, then a Si device constructed for a blocking voltage of 1 kV would have a critical field strength of about 0.2 MV/cm, which, when compared with the 2.49 MV/cm of SiC, amounts to the factor of ten.

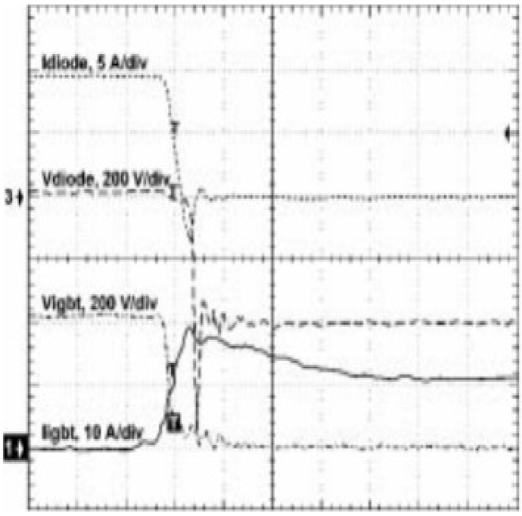

Fig. source Voltage and current waveforms at 150 C when a SiC diode is used as DUT, 50 ns/div, 480 A/ s

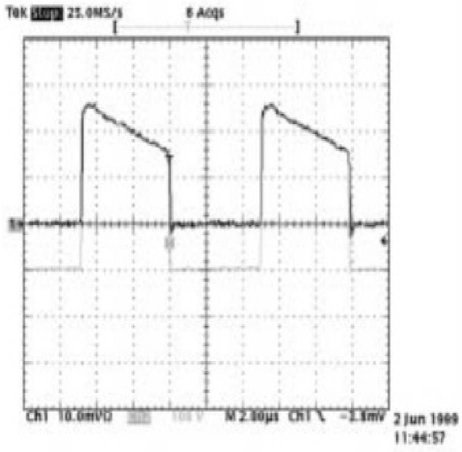

Fig. shows SiC diode voltage and current at 200-W load, 100-kHz switching frequency, 2 s/div, 2 A/div, 100 V/div. Top: Waveform current. Bottom: Waveform voltage.

Table shows Relative figures of merit of different materials

	JFOM	KFOM	BFOM
Si	1	1	1
3C-SiC	324	4.83	163
4H-SiC	400	4.17	464
GaAs	1.78	0.32	14.6
GaN	1600	3.04	1507
Diamond	8,100	32.2	23,000

Table shows Comparison of Electronic and Physical Properties of 4H-SIC, 6-H-SIC, GAAS, AND SI

Property	4H-SiC	6H-SiC	GaAs	Si
Band gap energy (eV)	3.26	3.03	1.43	1.12
Breakdown electric field, Emax (V/cm)	2.2×10^6	2.4×10^6	3×10^5	2×10^5
Thermal conductivity, Gth (W/cmK)	3.45	3.45	0.5	1.5
Saturation electron drift velocity (cm/sec)	2×10^7	2×10^7	1×10^7	1×10^7
Electron mobility, μe (cm2 /V-s)	800 ⊥ to c-axis 800 k to c-axis	400 ⊥ to c-axis 60 k to c-axis	6500	1200
Figure-of-merit, FM (MW/cm2)	2000	-	-	5
Dielectric constant, εr	9.7	9.7	12.8	12.8
Commercial wafers	1.375 ″	1.375 ″	6 ″	12″

5.0 CONCLUSION:

SiC power devices appear bright. The continued reduction of defect density, including micropipes, and the increase of wafer diameter are two important factors for increasing the chip size and consequently the current rating. The increase of epitaxial layer thickness for both nand p-type lightly doped layers will lead to higher voltage rating for – - diodes. The attractive characteristics of SiC and its advantages and limitations in comparison with Si have been discussed. SiC devices exhibit many electrical and thermal benefits. Though there are so many characteristics that makes SiC preferable to Si, the availability and easier processing techniques of Si, makes it challenging to fully exploit the physical and chemical properties of SiC as of todays technology. The various applications, where SiC devices could be attractive have been explored. SiC Schottky diodes are on the market and are used in many applications such as PFCs.

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