# WIDE BAND GAP SEMICONDUCTORS IN HIGH VOLTAGE AND HIGH FREQUENCY POWER ELECTRONIC APPLICATIONS.

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## Abstract

**Recentadvancesin the SiCtechnology shows great potential impact on society. An increasing demand for high-voltage, high frequency power electronic devices and the fact that traditional silicon technology has come close to its theoretical limits in high power applications gave birth to a new era of power electronics—an era of wide bandgap semiconductors. Siliconcarbide (SiC) is a wide bandgap semiconductor material with high breakdown electric field strength, high saturated drift velocity of electrons, and a high thermal conductivity. In addition, SiC, like silicon (Si), has SiO2 as its stable, native oxide which is key to any semiconductor technology from a processing perspective as well as opening up metal-oxide-semiconductor (MOS) device opportunities for SiC. Therefore, these properties make SiC ideally suited for a vast number of applications. Most promising applications of SiC technology are in Transport, Energy, Defence, Industry and Medical Field.**

**Realize the benefits of Silicon Carbide technology with offering of SiC transistors and diodes from such industry-leading suppliers as Infineon, Cree Wolfspeed, Microsemi, Powerex and Vincotech etc. These Industries introduces important content into SiC design such as higher efficiencies, smaller power electronic system size, higher operating temperature, higher voltage operation, higher switching frequency, higher power density, increased heat dissipation, larger cost savings on the passive components and larger cost savings on the cooling devices due to the higher switching frequency and increased efficiency. The technology of wide bandgap materials is rapidly becoming mature as a technology for mass-production of power semiconductor devices. In the higher voltage range, SiC transistors as well as Schottky diodes will be important. An overview of power-conversion applications using the latest generation of SiC semiconductor devices gives the motivations for applying SiC technology. The majority of discrete Si devices have been designed for voltages less than 2 kV. Wide bandgap devices, however, may operate in excess of 10 kV and at high temperature greater than 1500C. For high voltage applications, the devices of choice are the MOSFET and theIGBT. For applications ranging in voltage from 1 kV up to 4 kV, the Si IGBT is most often used, but SiC MOSFET competing Si IGBT upto 3kV. Also SiC MOSFEToperates at switching frequency more than 100kHz with greater efficiency and reliability.**

**Keywords: Wide Bandgap Semiconductors, SiC Technology, SiC MOSFET, Schottky diodes,Si IGBT, Efficiency and Reliability.**

## 1. Introduction:

Power electronic systems have greatly developed during the past three decades from the tremendous advances that have occurred in power semiconductor devices. Advances in power semiconductor technology introduce power metal–oxide–semiconductor field-effect transistors (MOSFET) in the 1970s and the insulated gate bipolar transistors (IGBTs) in the 1980s. These MOSFET and IGBTs enabled design of very compact high-efficiency systems due to their high input impedance and innovative vertical structures. Meanwhile, silicon IGBTs continue to dominate the medium and high voltage application and MOSFET in low and medium voltage application. On the longer term, silicon carbide Schottky rectifiers and silicon carbide power MOSFET offer at least another tenfold improvement in performance in terms of higher voltage, higher frequency and higher operating temperature [1].The social implications are as excellent as the economic considerations. The increasing utilization of these wide bandgap powersemiconductors devices for control of power and energy leads to conservation of fossil fuels and reduces urban environmental pollution.

## 2. Key Features of Wide Bandgap Semiconductor:

### Crystal Structure and Properties of Wide Bandgap Semiconductor:

Silicon carbide (SiC) is a compound semiconductor and is a crystalline structure existing in variety of polymorphic structures. Presently, 4H-SiC is preferred in practical device manufacturing. This is because the charge carrier mobilities in 4H-SiC are identical along the two planes of the semiconductor. The 4H-SiC have hexagonal frame with carbon(C) atom's position at the centre of the tetragonal structure outlined by 4 neighbouring Si atoms. And the distance between a C atom to each Si atom is the same. SiC is from IVth group of semiconductor family and has indirect bandgap. Energy bandgap strongly determines various properties of power semiconductor devices such as critical electrical field, intrinsic carrier concentration, electron mobility and Thermal conductivity [2]. Today single crystal 4H-SiC wafers of 3 to 6 inches in diameter are commercially available.

Table 1: Properties ofWide BandgapSemiconductor Si, SiC, GaN and Diamond:

| **Materials** | Bandgap energy (in eV) | Breakdown electric field (MV/cm) | Thermal conductivity ($x10^2$) (W/mK) | Melting Point ($x10^3$ K) | Dielectric constant (pu) | Electronmobility ( $u_n$ ) $cm^2$ Ns | Saturated Drift velocity ($x10^7$) cm/s |
|---|---|---|---|---|---|---|---|
| Si | 1.12 | 0.6 | 1.5 | 1.687 | 11.9 | 1400 | 1 |
| GaN | 3.39 | 3.3 | 1.3 | 2.77305 | 9 | 1000 | 2.5 |
| 4H-SiC | 3.26 | 3 | 4.9 | 3.103 | 10.1 | 900 | 2 |
| Diamond | 5.45 | 10 | 0.8 | Phase change at 2473.15 | 5.5 | 2200 | 2.7 |

Table 1 compares the physical properties of SiC to other important semiconductor materials such as Si, SiC, GaN, and diamond. This comparison is also shown in the figure 1, which indicates that physical properties of semiconductors can be useful to obtain high voltage, high frequency, and high temperature important in various applications. As SiC has wider energy bandgap and high electric field, it can be used in high voltage applications. Maximum frequency at which the semiconductor device can operate mainly depends on saturated drift velocity and dielectric constant, which is clearly advantageous for SiC to be used in high frequency applications. Also, SiC has higher thermalconductivity and melting point compared to Si, so it can be used in high temperature operations.

### Critical Electric Field ($E_c$), Energy Bandgap($E_g$) and Specific On-Resistance ($R_{sp-on}$):

The specific on-resistance ($R_{sp-on}$) is an important device parameter for determining breakdown voltage and power losses. It is based on the critical electric field of the material $E_c$ and breakdown voltage $V_b$ which is expressed as

$$R_{sp-on} = \frac{4V^{2}_{b}}{\varepsilon \mu E_c^{3}} ----------(1)$$

Knowing the energy bandgap of the material, the critical electric field can be calculated. An expression for the critical electric field as the function of the bandgap energy for the indirect bandgap material such as Si is

$$E_c = 2.5\times 10^5 E_g{}^{3/4} \text{-----------}(2)$$

And for indirect bandgap material SiC is

$$E_c = 2.38\times 10^5 E_g{}^{2} \text{-----------}(3)$$

The critical electric field of SiC material is high as compared with Si because SiC has wider bandgap more than ten times higher critical field for SiC compared with Si allows power devices to be designed with thinner, more highly doped drift regions to achieve higher blocking voltages. The specific on-resistance which is function of energy bandgap for silicon can be calculated as

$$R_{sp-on} = 1.716\times 10^{-6} V_b^{2.5} E_g^{-3} / \mu_n \text{----------}(4)$$

From above equations, it can be seen that for same blocking voltages, SiC devices offer specific on-resistance that is 350 times lower than Si [3]. Figure2presents a theoretical silicon limits for on-state resistance ($R_{sp\text{-}on}$) and breakdown voltages ($V_b$) in Si, 4H-SiC, GaN and diamond. It is seen that silicon power devices reached at its silicon limit of break down voltage but wide band gap semiconductor with higher break down voltage are useful for higher voltage applications. It is also to be noted that the value of the specific on-resistance is dependent also on other parameters such as power device drift region doping, electron mobility and energy bandgap.

### Figure of Merit of Power Semiconductors (FOM):

To compare the performance of power semiconductor devices, figure of merit (FOM) is used. FOMs are functions of material properties and device parameters. The Baliga high frequency FOM (BHFFOM) is derived to compare the performance of power semiconductor devices operating at high frequency[5]. Baliga relates the power losses of the device to the intrinsic material parameters and shows that the switching loss of a power semiconductor device depends on electron mobility $\mu_n$ and the critical electric field $E_c$.

The BHFFOM is given by following equation

$$BHFOM = \mu_n E_c{}^2 \left(\frac{V_g}{4V_b{}^2}\right)^{\frac{1}{2}} \text{-----------}(5)$$

Where, $V_g$ is a gate drive voltage

For high frequency operation, the power losses can be reduced by using larger mobility and higher critical field. For same breakdown voltage, BHFFOM for 4H-SiC is 81.6 times bigger than Si. Therefore, significant performance improvement can be achieved by replacing Si with SiC.

### 3.SiC Power Semiconductor Devices:

Power semiconductor devices used in systems can be broadly classified into two categories: Power Rectifiers and Power Switches

**Power Rectifiers:**

Silicon-based power rectifiers have been used in power electronic systems since the 1950s. Commercially available power rectifiers have been either the Schottky barrier rectifier or PiN rectifier. Silicon Schottky rectifiers are generally used for applications operating at below 100 V due to their lower on-state voltage drop and faster switching speed when compared with PiN rectifiers. PiN rectifiers are generally used in applications that require blocking voltages above 100V.Fig .3 shows structures of PiN rectifier diode and Schottky rectifier.Many high-voltages SiC-based two terminal rectifiers are expected to replace Si bipolar rectifiers in the 0.6-6.5kV range, and power switches higher than 1.2 kV in the future. SiC Schottky Barrier Diodes (SBD) offer extremely high switching speed, low on-state losses, higher blocking voltage and low leakage current.SiCSchottky Diodes are commercially available since 2001. The most remarkable advantage of SiC Schottky Diodes is the continuing increase in the blocking voltage. They range from the initial 300 V and 600 Vto the actual 0.6kV and 1.2-1.7 kV. In comparison with Si counterpart, a 10x increase in voltage blocking is possible with the same SiC drift layer thickness. The main difference between SiPiN diodes and SiC Schottky rectifier lies in the absence of reverse recovery charge in Schottky Rectifiers, which is shown in fig 4. Therefore, SiC Schottky Rectifiers are well suited for highswitching speed applications. 0.6kV-1.2 kV SiC Schottky Rectifiers match perfectly as freewheeling diodes with Si IGBTs, CoolMOSFETand SiC MOSFET.Power Factor Correction and High-

Voltage Secondary Side Rectification are applications of 0.6 kV SiC Schottky Rectifiers.

## 2. Power Semiconductor Switches:

Most of the commercially available power semiconductor switches were being manufactured with MOS structure as shown in Fig. 5, which includes DMOSFET, UMOSFET, CoolMOSFET and IGBT structure. SiC power switches in the 600 V range have two strong Si competitors- CoolMOSFET and the IGBT. SiC is better suited for switches operating at high-voltage and especially at high-temperature. A low on-resistance SiC switch able to operate at high junction temperatures has clear advantages in comparison to its Si counterparts. In addition, there is an increasing demand of SiC high-voltage controlled switches, which opens the possibility of facing new application fields. Concerning the blocking voltage range from 1.2 kV to 1.7kV, the Si MOSFET is not a realistic option and the Si IGBT shows high dynamic losses when requiring fast switching.SiC IGBT need conductivity modulation to achieve low on-resistance which generates tail currents. MOSFET generate no tail current. As a result, SiC MOSFET have much lower switching losses than IGBTs, which enables higher switching frequency, smaller passives, smaller and less expensive cooling system. Therefore, SiC MOSFET can have turn off loss (Eoff) that is approximately 90% smaller.IGBT’s tail current increases with temperature whereas switching characteristics of SiC MOSFET are nearly independent of temperature. IGBT’s high switching loss increases the chip’s junction temperature (Tj) limiting the switching frequency to 20 kHz or less. The much lower Eoff allows SiC-MOSFET to switch at much higher frequency greater than 100 kHz. Comparison of energy loss during turn-off in Si IGBT verses SiC MOSFET is shown in Fig.6.Compared to 600V-900V silicon MOSFET, SiC MOSFET have smaller chip area and an ultralow recovery loss of body diodes. For these reasons, SiC-MOSFET are increasingly being used in power supplies for industrial equipment and inverters/converters for high-efficiency power conditioners.

Figure7shows comparison of conventional VD-MOSFET,CoolMOSFET, SiC MOSFET and Si IGBT voltage Ratings. Due to breaking of silicon limit by CoolMOSFET (SJ-MOSFET) they are operated at higher voltage ratings (0.6 kV to 1 kV) as compared tolower voltage ratings (50V to 600V) of conventional VD-MOSFET [4]. SiC power switches in the 1-1.7 kV range has a strong Si competitor: IGBT. Comparison between performance parameters of high voltage power semiconductor devices CoolMOSFET, SiC MOSFET and Si IGBTare given in Table2

Table 2: comparison between performance parameters of High Voltage Power Semiconductor Devices.

| **SWITCHING DEVICE FEATURES** | **SiC MOSFET** | **Si IGBT** | **Si super-junction MOSFET** |
|---|---|---|---|
| Breakdown voltage | Up to 1700 V currently; higher in future | high | Up to 900 V |
| On resistance | Low (only 35% increase from 25$^o$C to 150$^o$C) | Low (but high at lower current due to threshold voltage) | Low (only 250% increase from 25$^o$C to 150$^o$C) |
| Switching frequency | High (>100 kHz) | Limited switching frequency due to tail current at turn-off <10 kHz | High (<1MHz) |

## Commercially available SiC Power MOSFET:

1200 V SiC MOSFET are commercially available from no of manufactures with trench and planer technology and lowRds(on) in mΩlow are given in Table3. ROHM, STMICOELECTRONICSandCree has recently incorporated to its catalogue the 1700 V SiC MOSFET.

Table3:Commercially available SiC Power MOSFET:

| Manufacturer and device | Voltage | Current | Rds(on) | Switching Energy | Technology & Package |
|---|---|---|---|---|---|
| ROHM<br>SCT3040KL | 1200 V | 55A | 40 mΩ | Eon=283 µJ<br>Eoff=118 µJ | Trench<br>T0-247 |
| INFINEON<br>IMW120R045M1 | 1200 V | 20A | | Eon=300 µJ<br>Eoff=170 µJ | Trench<br>T0-247 |
| CREE<br>C2M0025120D | 1200 V | 90A | 25mΩ | Eon= 3.5 mJ<br>Eoff= 1.4 mJ | Planer<br>T0-247 |
| MICROSEMI<br>APT40SM120B | 1200 V | 40 A | 80mΩ | Eon=438 µJ<br>Eoff=130 µJ | Planer<br>T0-247 |
| STMICROELECTRONICS<br>SCTWA50N 120 | 1200 V | 65A | 59 mΩ | Eon=530 µJ<br>Eoff=310 µJ | Planer<br>HiP247 ™ |

## 4.Types of Power Electronic Circuits and Applications:

Applications where SiC MOSFET are getting design wins include grid connected solar inverters, power factor correction (PFC) circuits, motor drives, or uninterruptable power systems. In all these applications, power electronic circuits namely rectifier (AC to DC converter), chopper (DC to DC converter) and inverter (DC to AC converter) are popularly used [6]. 0.65 kV –1.2kV SiC MOSFET has applications in Data centre (750W power supply), EVonboard charging (3/6.6–20kW) and EV traction.1.2 kV -1.7kV SiC MOSFEThas applications in PV inverter, traction (e.g. EV/PHEV and rail), grid-tied energy storage, heavy duty vehicles, electric aircraft, industrial motor drive and uninterruptable power systems (UPS).

## 5.Reliability of SiC-MOSFET:

Today reliability of power semiconductor devices is important topic in power electronics. According to study in power electronic industry significant power device failures arerelated to electro thermal stresses. Reliability testing and corresponding studies are critical to improving the understanding of degradation and failure mechanisms and their impact on the performance of wide bandgap semiconductors devices, packaging, and integrated systems. Today various Reliability Tests such as High Temperature Reverse Blocking (HTRB), High Temperature Gate Bias (HTGB), Sigle Event Burn Out (SEB) and Power Cycling are carried out on power semiconductor devices to test their failure rate. [7]

Following are some critical factors for which failure rate in SiC MOSFET is observed.

**Reliability of gate insulating layer:**

Oxide is used as gate insulating layer. Its reliability directly affects SiC MOSFET' reliability. Development of high-quality oxide has been a challenging problem for the industry.

**Stability of gate threshold voltage against positive gate voltage:**

As the current technology level, electron traps are formed at the interface between gate insulating layer and SiC body. Electrons can be trapped and consequently increase the threshold voltage if a continuous positive gate voltage is applied for an extended period of time.

**Reliability of body diodes:**

Another mechanism that affects SiC MOSFET's reliability is the degradation caused by its body diode's conduction. If forward current is continually applied to SiC P-N junction such as body diodes in MOSFET, a plane defect called stacking fault will be extended due to the hole-electron recombination energy. Such faults block the current pathway, thus increasing on-resistance and $V_f$ of the diode. Increasing the on-resistance by several times disrupts the thermal design.

**Short circuit safe operation area:**

Since SiC-MOSFET have smaller chip area and higher current density than Si devices, they tend to have lower short circuit withstand capability (thermal fracture mode) compared to the Si devices.

**dV/dt breakdown:**

Si-MOSFET involve a breakdown mode in which high dV/dt causes transient current to pass through the capacitance $C_{ds}$ and turn on the parasitic bipolar transistor, leading to device breakdown.

Since SiC-MOSFET generate exceptionally low recovery current, reverse recovery current also will not cause high dV/dt. Consequently, SiC-MOSFET are considered unlikely to cause this breakdown mode.

## 5.Conclusion:

The new generation of power devices for power converters will be based on Wide Band Gap semiconductorsto replace traditional silicon power devices. Currently the highest breakdown voltage capability of the commercial dominant power switch (Si IGBT) is 6.5 kV. In any case, a Silicon-based device could not operate over $200^0$C. These inevitable physical limits reduce drastically the efficiency of current power converters, which also requires complex and expensive cooling systems. The use of these new power semiconductor materials will allow increasing the efficiency of the electric energy transformations for a more rational use of electric energy, thus reducing carbon footprint. The most promising wide bandgap semiconductors semiconductor materials for higher voltages and higher frequency, this new generation of power semiconductor devices are SiC.

SiC Schottky diodes are commercially availableup to 1.2 kVand 17 kV. The potential candidates are the SiC MOSFET (<5 kV) and the SiC IGBT (>5 kV) [8]. Moreover, the high operating temperature of SiC power devices (demonstrated over $500^0$ C) will certainly contribute to the market growth and industrial utilization. however, to develop packages able to withstand high operating temperatures in the range of $300^0$ C. The silicon carbide can exhibit simultaneously high electrothermal conductivity and fast switching. This advantage allows Sic power devices to work well in hot and hostile environment, avoiding performance derating and increases reliability. Finally, reliabilityanalysis of these wide band gap power devicesisimportant.

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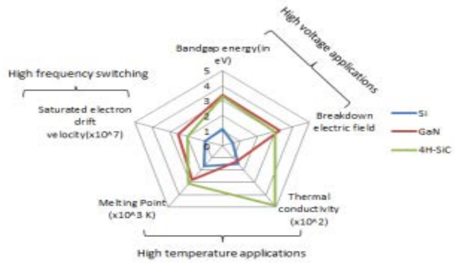


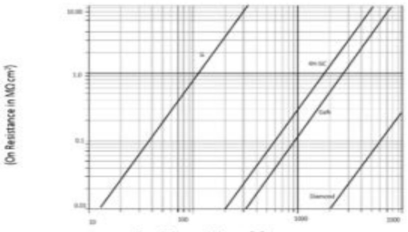
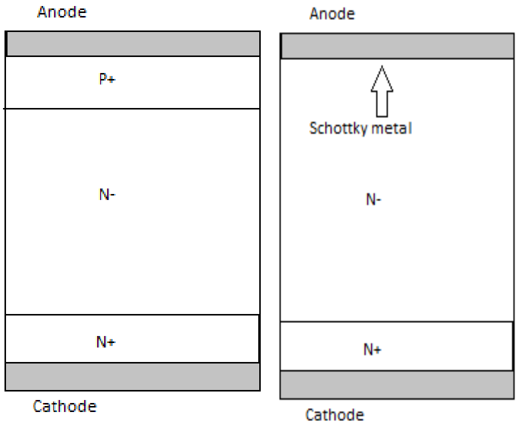


Fig1: Radar chart of Electrical Properties Fig2: Silicon Limit of Power Semiconductors
of Semiconductor Materials



**PiN Structure** **Planer Schottky Structure**

Fig .3: Power Rectifiers: PiN rectifier diode and Schottkyrectifierdiode

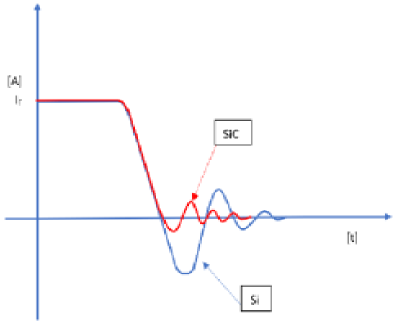
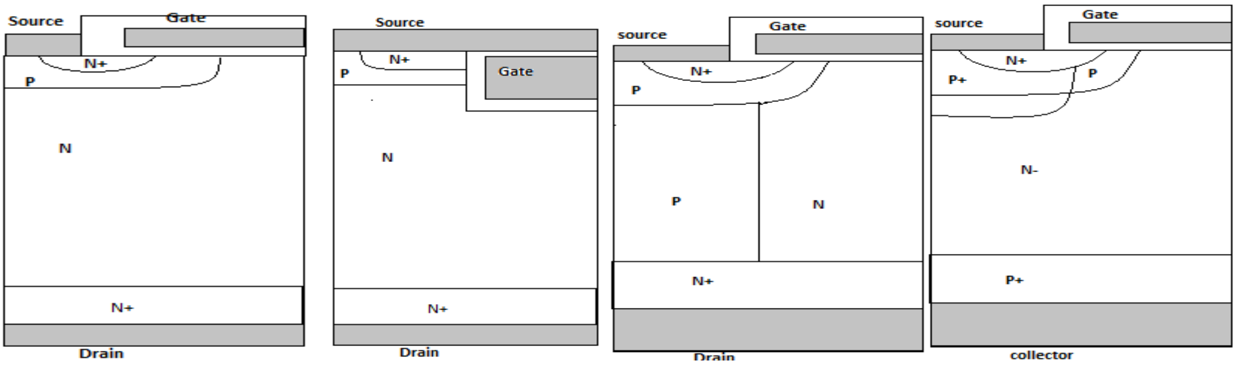


Fig.4: Reverse Recovery Characteristics of Si PiN diodes verses SiC Schottky diode



**DMOSFET Structure** **UMOSFET Structure** **CoolMOSFET Structure** **IGBT Structure**

Fig.5: Power Semiconductor Switches

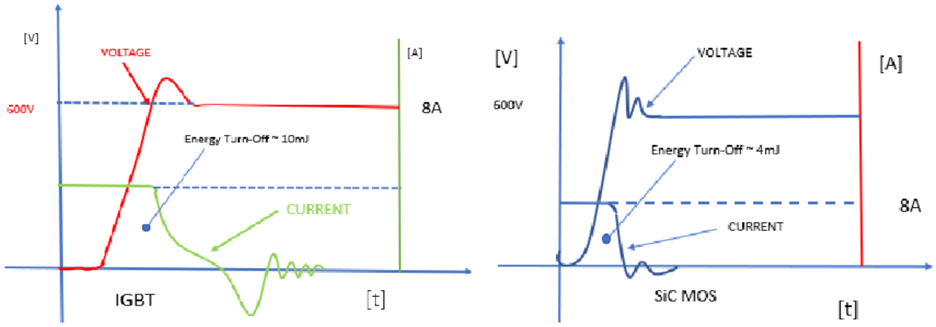


Fig.6:Comparison of Energy Loss ($E_{off}$) during turn-off in Si IGBT verses SiCMOSFET

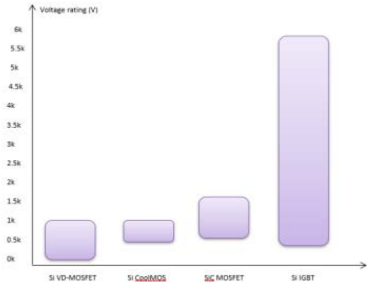


Fig.7: comparison between Voltage Rating of Power Semiconductor Devices