1. **INTRODUCTION**

Silicon carbide (SiC), also known as carborundum, is a [compound](http://en.wikipedia.org/wiki/Chemical_compound) of [silicon](http://en.wikipedia.org/wiki/Silicon) and [carbon](http://en.wikipedia.org/wiki/Carbon) with chemical formula SiC. SiC is widely used in high-temperature/high-voltage semiconductor electronics. SiC is now being seen as a more ideal material than Si. The dramatic quality improvement of the SiC material in combination with excellent research and development efforts on the design and fabrication of SiC devices by several research groups has recently resulted in a strong commercialization of SiC switch-mode devices .Nevertheless, the SiC device market is still in an early stage, and today the only available SiC switches are the JFET, BJT, and MOSFET .Commercially available SiC devices are not still in mass production .The components available are significantly higher than their Si counterparts. On the other hand, because of the low voltage and current ratings of these SiC devices, they are currently not suitable for power ratings above several hundred kilowatts. In particular,voltage ratings in the range of1,200 V and current ratings of few tens of amperes are available. Regardless of the type of SiC device, the driverfor each device counts as a vital part when the SiC devices operate in a power electronics converter. The driver requirements differ among the devices, and they should be designed in such a way that they ensure reliable operation. Finally, it is also worth mentioning the progress of the research on the SiC IGBT . To start with, an overview of the currently available SiC devices is given followed by the driver aspects for each device. It is found that available 1,200-V SiC BJTs behave as unipolar devices in the sense that there are practically no dynamic effects associated with build up or removal of excess charges. The reason for this is that the doping levels of 1,200-V SiC transistors are so high that any considerable carrier injection is superfluous for the conduction mechanism .For voltage ratings beyond 4.5 kV ,true bipolar devices will probably be necessary. In high-voltage high power applications such as high-voltage direct current transmission (HVdc), insulated gate bipolar transistors(IGBTs), and BJTs in SiC may seem as the ideal switch candidates as very high numbers of series-connected devices would be necessary to withstand system voltages. However since the trend in voltage in voltage source converter (VSC)-based HVdc is to build modular converters, the need for voltage ratings in excess of 10 kV may be questionable, since such a device in SiC would have a voltage drop with a built-in potential of more than 3 V. Since the fabrication of SiC IGBTs is far more complex than, for instance, that of an SiC JFET or a BJT, it makes sense first to fully exploit the benefits of these devices. Today, it is possible to build switch mode inverters in the 10–100 kW range with efficiencies well above 99.5%. A successful example is a 40- kVA three-phase SiC inverter with ten parallel-connected JFETs in each switch position. This inverter has an efficiency of approximately 99.7% . Truly, a new era in power electronics has begun.

**2. SILICON CARBIDE**

**S**iC is now being seen as a more ideal material than Si for power electronics. For an optimum power semiconductor switch, SiC offers a higher thermal conductivity, higher breakdown electric field (EM), larger band gap (EG), and higher saturation velocity (VD) then Si. In addition, SiC is an extremely rugged and stable material. Having the same native oxide as Si, it can be used to develop a number of devices as follows:

• Schottky Barrier Diode (SBD)

• PIN Diode

• Junction Field Effect Transistor(JFET)

• Metal Semiconductor Field Effect Transistor (MOSFET)

• Bipolar Junction Transistor (BJT)

• Metal Oxide Semiconductor Field Effect Transistor (MOSFET)

• Insulated Gate Bipolar Transistor (IGBT)

Silicon Carbide is available in a family of different crystal formations (known as polytypes) with wide band gaps similar to Gallium Nitride (GaN). Though there are more than 200 different SiC .

Because of the higher band gap energy, the semiconductor properties of SiC are less sensitive to increased temperatures than Si. This benefit results from SiC’s lower intrinsic carrier concentration (ηi). The intrinsic carrier concentration (ηi) defines when the device starts to behave as a bulk resistor (around 1 x 1015cm-3) and fails to operate in a normal semiconductor fashion . SiC does not approach this critical intrinsic carrier concentration until temperature.SiC can handle much higher field strengths.SiC MOSFETs exhibit lower conduction losses.

SiC devices can handle considerably higher temperatures.

**3. SILICON CARBIDE TRANSISTORS**

**3.1 SILICON CARBIDE JFET**

The first attempts to design and fabricate an SiC JFET were made in the early 1990s when the main research issues were dealing with the design optimization to realize high-power and high-frequency SiC devices .It was during these years that a few research groups had started mentioning the advantageous characteristics of the SiC material compared with Si .However, from the structure design point of view, the early-year SiC JFET was suffering from relatively low transconductance values, low channel mobilities, and difficulties in the fabrication process .During the last decade, the improvement on the SiC material and the development of 3- and 4-in wavers have both contributed to the fabrication of the modern SiC JFETs, and it was around 2005 when the first prototype samples of SiC JFETs were released to the market. One of the modern designs of the SiC JFET is the so called lateral channel JFET (LCJFET). The load current through the device can flow in both directions depending on the circuit conditions, and it is controlled by a buried p+ gate and an n+ source p-n junction. must be applied to turn the device off. By applying a negative gate source voltage, the channel width is decreased because of the creation of a certain space-charge region, and a reduction in current is obtained. There is a specific value of the negative gate-source voltage, which is called ‘‘pinch-off voltage,’’ and under this voltage, the device current equals zero. The typical range of the pinch-off voltages of this device is between \_16 and \_26 V. An important feature of this structure is the antiparallel body diode, which is formed by the p+ source side, the n- drift region, and the n++ drain. However, the forward voltage drop of the body diode is higher compared with the on-state voltage of the channel at rated (or lower) current densities. Thus, for providing the antiparallel diode function, the channel should be used to minimize the on-state losses. The body diode may be used for safety only for short-time transitions .This type of SiC JFET has been released by SiCED (Infineon) a few years ago, and it is going to be commercial in the near future. The second commercially available SiC JFET is the vertical trench (VTJFET), which was released in 2008 by Semisouth Laboratories. The VTJFET SiC JFET can be either a normally off (enhancement-mode VTJFET-EMVTJFET) or a normally on (depletion-mode VTJFET-DMVTJFET) device, depending on the thickness of the vertical channel and the doping levels of the structure. As other normally on JFET designs, a negative gate-source voltage is necessary to keep it in the off state. On the other hand, a significant gate current (approximately 200 mA for a 30-A device) is necessary for the normally off JFET to keep it in the conductionstate. The pinch-off voltage for the DMVJFET equals whereas the positive pinch-off voltage for the normally off one is slightly higher than 1 V. Comparing this type of SiC JFETs to the LCJFET, the absence of the antiparallel body diode in the DMVTJFET makes the LCJFET design more attractive for numerous applications. However, a SiC Schottky diode can be connected as the antiparallel diode for the VTJFET. This diode may be used for short-time transients in the same way as the body diode of the LCJFET. Except during these short-time transients, the reverse current should flow through the channel .The additional SiC Schottky diode is especially attractive if several VTJFETs are connected in parallel, and the voltage across the transistors is lower than the threshold voltage of the diode. In this case, only one diode would be necessary for all parallel JFETs because of the short (<500 ns) conduction interval of the diode. Two additional SiC JFET designs have been presented . The buried grid JFET (BGJFET), makes use of a small cell pitch, which contributes to the low specific on state resistance and high saturation current densities. The absence of the antiparallel body diode and the difficulties in the fabrication process compared with the LCJFET count as two basic drawbacks of this design. shows the double gate vertical channel trench JFET (DGVTJFET), which is actually a combination of the LCJFET and the BGJFET designs, and it has been proposed by DENSO . This design combines fast switching capability due to the low gate-drain capacitance with low specific on-state resistance because of the small cell pitch and double gate control. The commercially available SiC JFETs are mainly rated at 1,200 V, while 1,700 V devices are also available on the market. The current rating of normally on JFETs is up to 48 A, and devices having on-state resistances of 100, 85, and 45 mX at room temperature can be found**.**



**Fig 3.1: Cross section of the normally on SiC LCJFET**

**3.2 SILICON CARBIDE BJT**

The SiC BJT is a bipolar normally off device, which combines both a low on-state voltage drop (0.32 V at 100 A/cm2) and a quite fast switching performance. It has been deeply investigated, designed, and fabricated by TranSiC. A cross section of this device is shown in Figure 5, where it is obvious that this is an NPN BJT. The low on-state voltage drop is obtained because of the cancellation of the base-emitter and base-collector junction voltages. The SiC BJT is a current-driven device, which means that a substantial continuous base current is required as long as it conducts a collector current. The available SiC BJTs have a voltage rating of 1.2 kV and current ratings in the range of 6–40 A, while current gains of more than 70 have been reported at room temperature for a 6-A device . The fabrication of the SiC BJTs with improved surface passivation leads to current ratings of 50 A at 100 degree C and gains higher than 100. However, the current gain is strongly temperature dependent, and in particular, it drops by more than 50% at 250 \_C compared with room temperature. The development of SiC BJTs has been successful, and in spite of the need for the base current, SiC BJTs having competitive performance in the kilovolt range are expected in future.



**Fig 3.2: Cross section of the SiC BJT**

**3.2.2 SILICON CARBIDE BJT BASE DRIVER**

The SiC BJT is a current-driven device, which requires a substantial base current during the on state. The simplest base-drive unit for SiC BJTs consists of a series-connected resistor with the base, which is supplied by a voltage source. However, the switching performance of such a driver is poor when it is optimized for low power consumption. Considering this base driver, the switching performance can be improved by connecting a speed-up capacitor, CB, in parallel to the resistor . Hence, the switching performance might be improved, but this improvement depends on the supply voltage, Vcc. The higher the supply voltage, the faster the switching transients, but at the same time, the power consumption is increased. Therefore, it seems that the switching performance and the power consumption in this case is a tradeoff. To combine fast switching performance and low power consumption a base driver consisting of two voltage sources can be employed . A turn on process using this driver is shown . The high-voltage supply contributes to the high switching speed, while the power consumption of the driver is optimized by using the low-voltage supply connected to a carefully chosen base resistor. When the turn-on process starts, high-current peaks are provided to the base so that the SiC BJT is turned on rapidly. During the conduction state, the base current is determined by the current gain. Since this continuous base current is supplied from a low voltage source, the losses during the on-state can be kept fairly low.

**3.3 SILICON CARBIDE MOSFET**

Several years have been spent on the research and development of the SiC MOSFET. Specifically, the fabrication and stability of the oxide layer has been challenging. A cross section of a typical SiC MOSFET structure is shown in Figure 6. The normally off behavior of the SiC MOSFET makes it attractive to the designers of power electronic converters. Unfortunately, the low channel mobilities cause additional on-state resistance of the device and thus increased on-state power losses. Additionally, the reliability and the stability of the gate oxide layer, especially over have not been confirmed yet. Fabrication issues also contribute to the deceleration of SiC MOSFET development. However, the currently presented results regarding the SiC MOSFETs are quite promising, and it is believed that such devices will be available for mass production within a few years. The SiC MOSFET is the most recent SiC switch, which was released during the end of 2010 from Cree, while other manufacturers (e.g., ST Microelectronics) are very close to releasing their own MOSFET in SiC . At present, 1.2-kV SiC with current ratings of 10–20 A and on-state resistances of 80 and 160 mX are available on the market. Furthermore, SiC MOSFET chips rated at 10 A and 10 kV have also been investigated by Cree as a part of a 120-A half-bridge module . When compared with the state of- the-art 6.5-kV Si IGBT, the 10-kV SiC MOSFETs have a better performance .However, the commercialization of such a unipolar SiC device is not foreseen in the near future.



**Fig 3.3: Cross section of the SiC MOSFET**

**3.4 SILICON CARBIDE IGBT**

The Si-based IGBT has shown an excellent performance for a wide range of voltage and current ratings during the last two decades. The fabrication of a Si n-type IGBT started on a p-type substrate. Such substrates are also available in SiC, but their resistivity is unacceptably high and prevents these components from being used in power electronics applications. Furthermore, the performance of the gate oxide layer is also poor, resulting in high channel resistivities. These issues have already been investigated by many highly qualified scientists, and it is believed that such SiC devices will not be commercialized within the next ten years . On the contrary, even if high-voltage SiC IGBTs will be commercially available in the future, it is not obvious that they will give low-power losses as a high-voltage SiC JFET (e.g., 3.3-kV SiC JFET) if modularized circuits such as modular multilevel converter (M2C) are used for high-voltage high-power applications .

**4. GATE AND BASE DRIVERS FOR SILICON CARBIDE**

**DEVICES**

To use the advantageous performance of SiC devices compared with the Si counterparts, special driver designs are required. Such gate and drivers should be able to provide rapid switching for the SiC devices but should also have the lowest possible power consumption. Additionally, high-temperature operation is also preferable for these drivers because of the high-temperature capability of the SiC devices. Various drivers for SiC JFETs and SiC BJTs have been proposed since these devices started to be available on the market. Drivers for SiC MOSFETs have been omitted in this presentation as they are essentially the same as those for Si MOSFETs, except that a higher gate voltage (more than 20 V) is required in the on state.

**4.1 PARALLEL CONNECTION OF SILICON CARBIDE DRIVERS**

In several power electronics applications, higher current ratings are required than those of the available SiC transistors. It is, therefore, necessary to build either rmultichip modules or to parallel-connect several single chip components. In both cases, it is essential to keep track of both steady state and transient current sharing of parallel-connected chips. Unless the transient current is not equally shared among the devices, the switching losses caused in the device that conducts the highest current will be higher, resulting in an increased temperature. Similarly, a non uniform steady-state current sharing due to the spread of the on-state voltage drops or resistances will also result in unequal temperature distribution. The problems that are faced when normally off SiC JFETs are connected in parallel have been shown in . A similar investigation regarding SiC BJTs has also been presented by the same authors. In particular, it has been shown that the transient currents of these devices might suffer from mismatches, especially at high switching . But, on the contrary, during steady-state operation, they have shown excellent current sharing. An investigation of parallel-connected normally on SiC JFETs has been presented in . The two most critical parameters when parallel-connecting SiC JFETs are the pinch-off voltage and the reverse breakdown voltage of the gate. It was found that differences of approximately 25% in switching losses could result from a difference in the pinch-off voltage of 0.5 V. Additionally, the transient current may not be equally shared because of differences in the static transfer characteristics.

One solution to the parallel connection of SiC devices could be sorting with respect to the most critical parameters, which affect their switching performance. However, as it was shown in [22], this is not always sufficient. Thus, development of new drivers is essential to handle parallel connection reliably. A successful example of the parallel connection of ten JFETs in each switch position is the 40-kVA inverter shown in Figure . Despite the high number of parallel-connected devices, the total semiconductor cost is approximately US$37.5/kW of rated power, which is higher compared with the corresponding cost when Si IGBTs are employed. However, the outstanding switching performance of SiC JFETs and the outstandingly high efficiency (more than 99.5%) constitute the two driving factors to invest in such a converter.

**5.DESIGN DIRECTIONS OF SILICON CARBIDE**

Based on the brief analysis of the available SiC power devices presented earlier, it is clearly shown that their features are moving power electronics into new areas. When it comes to the design stage of power electronic converters with SiC devices instead of classic Si counterparts, three different design directions may be chosen .Since switching times in the range of nanoseconds have been reported, the most obvious direction is the increase of the switching frequency up to a few hundred kilohertz. In the case of the available Si devices for voltage ratings above 600 V, such high switching frequencies can be only reached when soft switching is employed . From a system perspective, the design advantages are reduction of size and weight of passive elements (e.g., inductors, capacitors) . This results in better compactness of the converter, especially in dc/dc converters and inverters with passive filters. Last but not least, as the switching speeds are higher and the harmonics are shifted up to higher frequencies, the size of electromagnetic interference (EMI) filters also will be reduced . Both short switching times and low voltage drops across SiC devices result in significant reductions in power losses. Therefore, in applications where the increase of switching frequency is not crucial, one of the other two possible design directions might be chosen. Since the reduction of the power losses is equivalent to an efficiency increase, a direct benefit is the reduction of size and weight of the cooling equipment. Furthermore, water cooling or air-forced cooling systems could be unnecessary as the amount of dissipated heat is a few times lower. High efficiency is also important in power delivery and distribution systems as well as photovoltaic applications because the lower power loss is directly recalculated into profit.

The third design direction is high temperature applications, as SiC devices are capable of being operated at junction temperatures above 450 degree C. This is a totally new area of power electronics aiming for automotive, space, or drill-hole applications. However, the main deceleration factor at elevated temperatures is not the device itself, but rather a lack of suitable packaging technology, high temperature passive components, and control electronics. Before real high-temperature converters will be released, small steps could be done with the existing SiC transistors. For instance, with junction temperatures in the range of 200–250 degree C, the thermal resistance of the heat sink the technology of high-temperature power modules packaging have been presented The SiC devices were operating at 250 degree C while the case temperature was below 200 degree C, but reliability and long-term stability also need to be investigated. The development of high-temperature gate drivers has been accelerated by the introduction of the silicon-on-insulator technology but the development of SiC control electronics is also promising could be higher, which leads to a reduction in volume and weight. During recent years, promising results regarding the technology of high-temperature power modules packaging have been presented.. The SiC devices were operating at 250 degree C while the case temperature was below 200degree C, but reliability and long-term stability also need to be investigated. The development of high-temperature gate drivers has been accelerated by the introduction of the silicon-on-insulator technology, but the development of SiC control electronics is also promising .

**6. ADVANTAGES**

There are advantages to the use of SiC over Si, there are still many challenges

1. The material quality is lower and the cost is higher than is needed for broad commercialization. While both of these are improving year by year, SiC substrates and epi layers are still far from the level of maturity that silicon has obtained.

2. Primary material defects are: a. Micro pipes, which are tornado like micron-sized holes through the wafer, also called an open core screw dislocation with a large Burghers vector.. These are killer defects for all devices.

b. Basal plane dislocations, which can cause VF drift in conductivity modulated devices (PIN diodes, BJT’s, etc), but are not harmful to majority carrier devices (MES FETs, MOSFETs, JFETs, Schottky diodes).

c. Screw dislocations, which are caused by rotational lattice mismatches that can be closed core or open-core .

d. Edge dislocations, which are extended defect lines or planes not aligned with neighbors .

3. MOSFETs, though under development, have not been brought to the point where they are used in military or commercial applications. Primary challenges are:

a. MOS interface quality, where inter face state and fixed oxide charge densities need further reduction for adequate control of Threshold Voltage (Vth) and Forward Voltage (VF).

b. Reliability issues associated with a smaller barrier height at the oxide/SiC interface due to the large band gap of SiC. This can result in increased Fowler- Nordheim current injection into the gate oxide at moder ate field strengths, which in turn can reduce the lifetime of the gate oxide.

4. In order to take full advantage of the much higher operating temperatures and power densities obtainable with SiC devices, significant packaging development is required. While SiC power devices can provide significant system performance advantages using conventional packaging, even greater improvements (and hence broader commercial utilization) will occur with enabling improvements in packaging.

SiC has advantages over Si Si in the high voltage (500V to >10KV), high power density, and high temperature operation end of the RF Power and Power Switching markets. The characteristics of SiC allows higher doping levels along with the use of thinner drift layers as compared with Si in high electric field (>500V) applications. With the higher doping and thinner drift layers in SiC, the on-resistance of the device can be reduced by more than an order of magnitude compared to Si. Additional benefits, including higher thermal conductivity (the ability to transfer heat), higher electric field strength, and higher drift velocity, will have major impacts on the size, efficiency, and applications of power electronics in the years ahead. Even though SiC has been around for some time, the development of high quality material has only recently allowed it to be used in power electronic applications. With this in mind, there are still many hurdles to overcome in order for this technology to become main stream. As time moves forward these challenges will be met; power systems will become more efficient and smaller. SiC devices will have a profound impact on the “Greening” of our world

**7. APPLICATIONS**

It cannot be denied that SiC power device technology is currently in bloom, not to say in an explosion stage as new things such as new devices, driver concepts, or application examples appear continuously. Undoubtedly, only a fraction of all new developments is published. Probably some of the most interesting examples are not revealed. This means that it is hard to give a true overview of the current SiC technology, but it is still possible to give an overview of

has been presented previously. In contrast to the well-established and mass-produced SiC Schottky diodes, the real application of SiC transistors in the field is still in the early stage. However, using the data for the four available transistor types, it is possible to make reasonable forecasts about the performance of future SiC converters. That is why a number of laboratory prototypes and demonstrators have been built and experimentally tested by several research group around the world.

**7.1PHOTOVOLTAIC**

The advantageous features of the SiC transistor perfectly match to meet the two basic requirements of the photovoltaic industry: increase in efficiency and integration of the inverter with the photovoltaic panel [31]. In the power range of a single kilowatt, efficiencies more than 99% can be reached by replacing Si with SiC components, and even if the device cost is higher, the overall system benefits are significant. The SiC transistors can also be used in future integration of small inverters on the backside of photovoltaic panels. Here, harsh environmental conditions are faced, and it is not possible to meet high reliability and lifetime requirements with Si technology. However, again the main argument against SiC devices is the cost, but the overall system benefits as well as the expected reduction of the device prices should solve this problem in the future.

**7.2 AC DRIVES**

As the state-of-the-art Si devices almost fulfill the requirements for inverter-fed ac drives and the cost of SiC device cost will always be higher, there are very small chances for mass introduction of SiC electronics in this area. Nevertheless, it is very likely that features of the SiC devices could be utilized in many niches, especially when high efficiencies and high power densities are required or when a high switching frequency is necessary to feed a high-speed motor.

**7.3 HYBRID ELECTRIC VEHICLES**

The gains when employing SiC transistors in inverters for hybrid electric vehicles are extremely high. The current trend deals with the integration of power electronic converters with the combustion engine using the same coolant at a temperature above 100 \_C. It is not likely that the associated requirements can be fulfilled by Si electronics. Thus, SiC electronics with much higher temperature limits is the best choice, and at the same time, very high efficiencies are possible. However, the lack of reliable high-temperature packaging still counts as a serious problem. Finally, the auxiliary components, such as gate drivers and capacitors, have to high temperature operations, which is a great challenge.

**7.4 HIGH-POWER APPLICATION**

The high blocking voltage capability of the SiC devices makes them attractive in the area of high-power converters for grid applications such as HVdc. According to , unipolar devices such as JFETs will be the best choice in the voltage range up to 4.5 kV, while for higher voltages, bipolar devices (BJT, IGBTs) may be superior. However, the availability of SiC devices with high voltage ratings is currently limited, even if a few interesting examples could be found in the literature. The case of a 300-MVA modular multilevel converter for 300 kV HVdc transmission is discussed. As the switching frequency is only 150 Hz, the switching losses are very low. Together with the low on-state resistance of the SiC JFETs, it is possible to achieve an efficiency increase by 0.3% (900 kW) with respect to the Si IGBTs case . The benefit is not only the lower amount of heat that needs to be dissipated but also the lower energy cost. The possible application of 20-kV SiC gate turn-off thyristors (GTOs) in a 120-kV/1-kA HVdc interface has been discussed. These devices are compared with the 435 kV Si counterparts by using an analytical device model and by performing system simulations. Employing the 20-kV SiC GTOs, a significant efficiency increase is expected at higher junction temperatures. Another interesting example of the high voltage capability of SiC JFETs is shown in , where six 1.2-kV transistors connected in a super cascade configuration were tested up to 5 kV in a dc/dc converter. With 6.5-kV JFETs, this converter would be able to operate at a voltage level above 20 kV in a distribution system. Moreover, the 10-kV SiC MOSFET is often considered for high-voltage applications such as solid-state transformers . In this case, although the power losses are a few times lower than the 6.5-kV IGBTs, the switching frequency of such a converter is increased from 1 to 20 kHz to reduce the size of high-voltage transformers. The 15-kV n-channel SiC IGBT has been considered in a study regarding smart grid applications. Despite the promising simulation results of the n-channel SiC IGBT (low on-state voltage and switching energies lower than the 6.5 kV Si counterpart), experimental verification has only been done with a 12-kV/10-A SiC IGBT in the laboratory .

**8. CONCLUSION**

A new era in power electronics is entered as new SiC transistors are introduced in high-efficiency, high frequency, and high-temperature applications. Efficiencies well above 99.5% are possible in the 10–100 Kw power range. High quality samples of 1,200 V JFETs, BJTs, and MOSFETs are available, and within a few years, mass-produced products using these new devices will be on the market in several application areas. The benefits of the new devices are so overwhelming that it cannot be afforded from systems perspective to neglect the use of these devices.

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