Silicon carbide – the power semiconductor material of the future

Within the next decade silicon carbide (SiC) can be expected to join and possibly even supplant silicon as the material of choice for power semiconductor devices, especially for voltages from 500 V upwards. Losses are significantly lower with SiC-based power devices, while their operating temperatures can be higher than those of devices based on silicon.

Power semiconductor devices – diodes, thyristors, transistors and insulated gate bipolar transistors (IGBTs) – are key components of ABB's power electronics products. Main areas of application for the devices are industrial drives, power supplies and traction vehicles, such as trams and electric locomotives. At the top end of the spectrum are static var compensators (SVCs) and other equipment used for power conditioning, plus systems for HVDC transmission. In all, the power range for ABB power electronics products spans eight orders of magnitude – from hundreds of watts to several gigawatts.

ABB also produces its own power semiconductors, concentrating on devices with breakdown voltages of 1500 V and higher. The products that dominate in this business are gate turn-off (GTO) and high-power thyristors and diodes.

The ideal switch

Power electronics design engineers have searched for years for a device that is capable of blocking high voltages in the off-state, conducting large currents in the on-state and being switched from one state to the other with a minimum of energy – all without any unnecessary losses.

Although an ideal switch with this capability is not yet available, several types of switch are in use that come close to it. Often, the semiconductor switches' high power losses will force designers to choose a less than ideal type of switch. This problem is further aggravated at the higher system voltages 1.

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The MOSFET (for metal oxide semiconductor field effect transistor) is perhaps the device that best approximates the ideal switch described. Unfortunately, it has hitherto only been used for applications with relatively low voltages, since the losses for a given current density increase very rapidly with the blocking voltage.

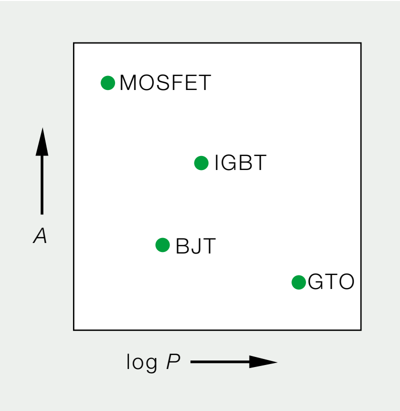
The IGBT is, in a sense, a MOSFET whose structure has been modified to circumvent that device's inherent disadvantages, though at the cost of higher switching losses. During the 1980s the IGBT deposed the bipolar junction transistor as the power semiconductor of choice for blocking voltages from a few hundred volts up to 2 kV. Above 2 kV, the GTO thyristor is still holding its own against the IGBT. While the GTO is able to handle very high powers per device, it requires a considerably more complex control circuit than that needed to drive a MOSFET or IGBT.

What the power electronics circuit designer wants is therefore a device with the ease of use of the MOSFET and the power handling capability of the IGBT and GTO (in 1, for example, it would be found in the top right-hand corner of the diagram). This is precisely what MOSFETs based on SiC offer.

Silicon carbide devices

SiC has a breakdown strength which is about ten times higher than the value for silicon, resulting in much lower losses for SiC-based devices. For example, MOSFET structures based on SiC should be able to handle breakdown voltages of several kilovolts, whereas the maximum value for corresponding Si devices is limited to between 500 to 1000 V.

Historically, new types of switch have more or less revolutionized the way power electronics systems are built. For example, the introduction of the GTO – the first really high-power device to have turn-off capability – changed the way



Subjective comparison of the relative benefits of different types of power semiconductor devices: ease of use A as a function of the power handling capability P **1**

locomotive drives are designed, allowing DC and synchronous machines driven by phase-commutated converters to be replaced by AC motors driven by force-commutated voltage source converters. In the industrial drive sector, the introduction of the IGBT has led to a substantial simplification of the power and control circuits, allowing improved performance as well as a reduction in costs.

SiC can handle much higher field strengths

To sustain a voltage U_b, the blocking pn-junction of a semiconductor has to have a certain thickness. This must ensure that the maximum electric field E_{max} that the material will withstand before breakdown is not exceeded. The minimum thickness W of the junction is given by:

$$W > \frac{2\,U_b}{E_{max}} \qquad (1)$$

(The factor 2 can be omitted under certain design conditions.)

The prime advantage of SiC is that its E_{max} value is about ten times the figure for Si[1]. For a given voltage, the required thickness of an SiC device will therefore be only one tenth the thickness required for a corresponding Si-based device.

In the following equation, more generally known as Maxwell's equation, account is also taken of the doping (ie, the controlled impurity content) of the material:

$$\frac{dE}{dx} = \frac{\rho}{\varepsilon\varepsilon_0} = \frac{qN_d^+}{\varepsilon\varepsilon_0} \qquad (2)$$

In this equation, ρ is the space charge density, ε the permittivity, ε_0 the electrical field constant, q the elementary charge, and N_d^+ the ionized donor concentration. It has been assumed that the voltage is sustained by a low-doped n-type layer, which is the case in most power devices (ie, Si as well as SiC).

Assuming a constant doping density and combining eqns (1) and (2), the following relationship is obtained:

$$N_d^+ < \frac{\varepsilon\varepsilon_0\,E_{max}^2}{2\,qU_b} \qquad (3)$$

Thus, for any given breakdown voltage and with the ten times stronger field that is possible with SiC, the doping in the low-doped n-layer can be around one hundred times higher than with Si.

SiC MOSFETs exhibit lower conduction losses

MOSFETs are the power switches with the most attractive properties for the circuit designer and end-user **2**. As mentioned, however, the MOSFET has hitherto been used only for breakdown voltages of up to a few hundred volts. One explanation of this is given by the following equation:

$$r_{ds,on} = \frac{4\,U_b^2}{\mu\varepsilon\varepsilon_0\,E_{max}^3} \qquad (4)$$

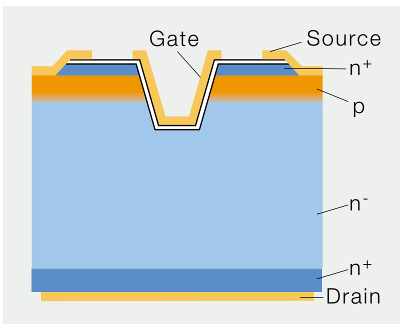
In this equation, $r_{ds,on}$ is the specific resistance (measured in Ωcm^2) of the blocking junction, also referred to in the case of a vertical MOSFET as the drift region. The resistance increases with the width of the drift region and decreases with increased doping, since this leads to a larger number of the charge carriers that carry the current. μ gives the mobility of these charge carriers, which are usually electrons.

According to eqn (4) the resistance of the drift region of the MOSFET increases as the square of the breakdown voltage. In the case of Si, intolerably high resistance values are reached with just a few hundred volts. In addition, it is observed that the resistance drops as the cube of the critical field. Since the critical field strength of SiC is some ten times that of Si, the conduction losses of an SiC MOSFET will be dramatically lower than for an Si device, at least in the breakdown voltage range where the conduction losses are dominated by the drift region. This applies to all so-called unipolar devices (ie, devices that rely on only one carrier type to pass current), including MOSFETs, junction field effect transistors (JFETs) and Schottky diodes.

Bipolar devices for higher breakdown voltages

Since the Si-based MOSFET cannot be used for applications with breakdown

Structure of a possible silicon-based MOSFET. The n⁻-region is the voltage-sustaining part of the device and has most influence on its conduction properties. **2**



[1] For the sake of simplicity, E_{max} is treated here as a constant, although it depends on factors such as doping and temperature. The errors introduced as a result of this are relatively small.

SiC test substrates (wafers) with diode structures of varying size **3**

(Photo: IMC)

Micrograph of a substrate showing micro-pipes (dark lines) penetrating the pn-junction. The defects have a diameter of about 1 µm. **4**

(Photo: University of Linköping)

voltages above a few hundred volts, the circuit designer has to resort to bipolar devices for the higher voltage ranges. As can be seen from eqn (3), the resistance is limited by the number of available charge carriers (N_d^+). In bipolar devices (eg, pn-diodes, IGBTs and GTOs) the number of carriers is increased by injection from the anode and cathode emitters when the device is switched on. This leads to a dramatic reduction in the conduction losses compared with MOSFET structures. Since electrons are injected by the cathode and holes by the anode, the current is carried by both negative electrons and positive holes – hence the term 'bipolar' devices.

The drawback of bipolar carrier injection is that the excess charge has to be removed from the device during turn-off before a return to the blocking state is possible. The removal takes place via a current in the reverse direction plus so-called recombination, (ie, mutual neutralization of the holes and electrons). The time required to remove the excess carriers is far from negligible, and during this interval both the voltage and current may have high values at the same time, leading to a sharp increase in the switching losses. The advantage of relatively low conduction losses is therefore traded off against relatively high switching losses.

Carrier removal is, of course, also necessary in MOSFETs and other unipolar devices, but the losses associated with them are normally much smaller than for the bipolar devices.

The total value of the injected specific charge q_{inj} is given by

$$q_{inj} = J\Downarrow \qquad (5)$$

In this equation, J is the current density and $\Downarrow$ the so-called minority carrier lifetime (ie, the average time it takes for an electron and a hole to recombine). The lifetime in power devices is determined by the concentration of certain defects (eg, impurities). The manufacturer seeks an appropriate trade-off between the conduction and switching losses for each type of device according to its intended application.

Bipolar SiC thyristors for voltages above 10 kV

As already mentioned, the circuit designer only resorts to bipolar devices when the system's voltage is too high for unipolar devices, such as MOSFETs and Schottky diodes. It has already been said that SiC will allow MOSFETs and Schottky diodes to be used which feature much higher breakdown voltages than are possible with Si. Thus, it can be expected in the future that MOSFETs will be used for most applications, including those requiring power devices for several kilovolts.

Some applications, such as static var compensation and HVDC transmission, feature system voltages that are much higher than the breakdown voltage which is possible with a power device based on either type of material. In such cases, the only solution is to connect the devices in series.

The breakdown voltage of the devices is chosen so as to obtain the best possible system performance and minimum losses. The thyristors used for these applications today typically feature a breakdown voltage of 6 to 7 kV, a value which constitutes a trade-off between cost, performance, conduction losses and switching losses. Such high breakdown voltages call for Si thicknesses approaching 1 mm and lifetimes in the region of 100 μs, resulting in considerable switching losses.

With SiC, the optimum breakdown voltage for these application areas are likely to be much higher, and devices with a breakdown voltage easily exceeding 10 kV are conceivable. The required minority carrier lifetimes would lie between 1 and 10μs, offering the possibility of an acceptable switching performance.

SiC devices can handle considerably higher temperatures

It is generally considered wise to operate bipolar power devices based on Si below 125 °C, whereas operation of unipolar devices, such as MOSFETs, is possible

Impurities are incorporated in SiC through epitaxial growth. This requires RF heating of the material to about 1500 °C. **5**

(Photo: IMC)

up to temperatures of 150 °C. These restrictions can be explained physically by the higher reverse leakage currents, which cause higher temperatures in the pn-junctions, leading to an increased risk of thermal runaway. Since the carrier lifetime increases, there is an increased risk of parasitic, destructive processes being triggered. Finally, the reduction in mobility leads to an increase in conduction losses in unipolar devices. A fundamental limitation is that the operating temperature must lie below the temperature at which the semiconductor material becomes intrinsic (ie, the point where the carrier density is no longer determined by the doping, but by the bandgap of the semiconductor). Above this limit, all current control and voltage blocking capability is lost. For Si, this limit occurs around 300 °C.

SiC, on the other hand, can be operated at much higher temperatures. The leakage currents in the pn-junctions are extremely small, permitting voltage blocking at temperatures considerably higher than 300 °C. The intrinsic limit is not reached until well over 1000 °C.

An SiC-based MOSFET has been operated by a US research team, for example, at a temperature of 650 °C. This high temperature capability is certain to have several benefits for the designers of power electronics systems. It should be emphasized, however, that the low losses described apply to operating temperatures and current densities similar to those usual for Si.

Using a microscope to measure the breakdown voltage of an SiC diode in SF_6 gas **6**

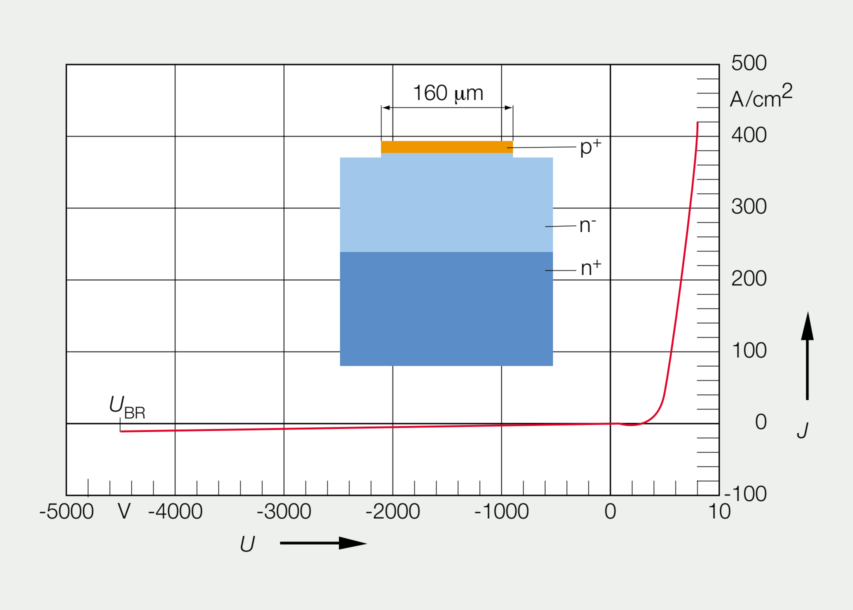
(Photo: IMC)

Why are SiC devices still not available?

The advantages of silicon carbide power devices have been known since the 1960s. The fact that they are still unavailable today can be put down to the technological difficulties involved in their manufacture. Up until now, the main industrial use for SiC has been as an abrasive (carborundum).

SiC cannot be melted under controllable pressures, instead changing directly to the gaseous state at its sublimation point of about 2500 °C. The crystal therefore has to be cultivated from the gas phase – a process which is considerably more complex than the cultivation of silicon, which melts at approximately 1400 °C.

One of the main obstacles to commercial success for SiC technology is the lack of a substrate of suitable quality for the industrial-scale fabrication of power semiconductor devices. As in the case of Si, a monocrystalline substrate, often referred to as a wafer, is a prerequisite for production. One method of growing large-area SiC substrates was developed during the late 1970s **3**. However, the



Current-voltage characteristic and schematic structure of an SiC test diode with a breakdown voltage of 4.5 kV – a world record **7**

J *Current density*
U *Voltage*
U_{BR} *Breakdown voltage*

p^+ *Emitter, 1.5 µm, 1 x 10^{18} cm^{-3}*
n^- *Base, 45 µm, 1 x 10^{15} cm^{-3}*
n^+ *Substrate*

substrates grown using this process, known as the modified Lely method, have been plagued by severe defects known as micro-pipes **4**.

It has been shown, for example, that a single micro-pipe penetrating a high-voltage pn-junction can destroy the junction's ability to block voltage. The density of such defects has come down from thousands per square centimeter to tens per square centimeter in the last three years. In spite of this improvement, a process yield of more than a few percent is still only possible when the maximum size of the devices is limited to a few square millimeters. This restricts the maximum rated current per device to a few amperes at most. Further improvements in substrate technology are therefore necessary before SiC power devices can become commercially viable.

Silicon carbide research

ABB is today one of the industry leaders in the development of silicon carbide technology. Research at ABB is focused on processes for device manufacture including etching, deposition of dielectrics, oxidation, metallization and contact formation. In contrast to Si technology, much of the SiC material for the semiconductor structure is grown by the device manufacturer rather than being provided by a substrate supplier. The reason for this is that doping – the controlled introduction of impurities by diffusion at high temperature – is not practical for SiC. Instead, the dopants (impurities) are incorporated during epitaxial growth of the material. For very shallow structures (including the contact layers) ion implantation can be used, as in the case of Si.

Working together with research partners at the University of Linköping, Sweden, and the Industrial Microelectronics Center (IMC) in Stockholm **5**, **6**, ABB has achieved some major results in the area of high-voltage SiC devices.

World record for an SiC diode

One result of the research work is the development of an SiC diode with a breakdown voltage of 4.5 kV **7** – a new world record. This figure improves the previously highest voltage level by more than a factor of 2.

A key contribution to this result was made by the quality of the epitaxial material. The growth technology, developed at the University of Linköping, has produced the thickest (up to 90 µm) and purest (residual doping below 10^{14} cm^{-3}) layers ever reported. As described above, the thickness and purity of the material are key factors in the production of high-voltage, high-power devices.

Until recently the minority carrier lifetime was believed by many specialists in the field to be limited to below 100 ns. The 4.5-kV diode mentioned above has a carrier lifetime of around 0.5 µs, with even higher values observed for some samples.

Although important advances have been made, further research and development are necessary before silicon carbide devices can be produced on a commercial scale. For example, the problems associated with the passivation of surfaces and the quality of the MOS interfaces, both of which are critical factors for power MOSFETs, have to be understood and solved.

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Two assembly lines ordered by VW do Brazil

VW do Brazil has awarded a contract to ABB Flexible Automation GmbH of Germany for the delivery of engine assembly and final-assembly lines for Volkswagen's facility in San Carlos in the province of São Paulo. Beginning in mid-1996, the San Carlos plant will have an annual production capacity of approximately 400,000 engines. ABB Flexible Automation is undertaking this project in collaboration with the local ABB company in São Paulo.

A similar assembly line for the same type of engine was supplied by ABB and taken into operation in the previous year in VW's Chemnitz, Germany, works, where it has exhibited a high level of flexibility and availability.

Order for the 170-MW Houay Ho hydropower plant in Laos

The Korean *Daewoo Corporation* has placed an order with a Swiss consortium comprising ABB Power Generation and Sulzer for prime movers and electrical equipment for the 170-MW Houay Ho hydropower plant in Laos. The total value of the order is US$ 18 million, of which ABB's share is approximately US$ 11 million.

ABB Power Generation will supply the entire electrical equipment for the plant, including two generators, the control and monitoring system, and switchgear.

On completion, the Houay Ho plant will supply electrical energy to grids in Laos and Thailand.

Major power transmission project in Saudi Arabia

ABB and the British company Reyrolle have received an order from *SCECO Central* of Saudi Arabia to construct one of the largest substations ever to be built in the Middle East. The 380/132-kV substation, which is to be sited east of Riyadh, will form a vital node for the interconnection of power generation plants in the country's central region.

ABB will supply the substation's 132-kV gas-insulated switchgear, the static compensator for regulating the grid voltage levels, and the auxiliary services equipment. ABB will also be responsible for all the engineering work and will supply the complete power line interconnection.

ABB's share of the overall project, which has a total value of some US$ 300 million, is valued at about US$ 175 million.

Work on the substation, which is scheduled for connection to the utility's power grid by March 1997, will commence immediately. Completion is expected by 1999.

165-MW gas turbine for a smelter in Bahrain

Aluminium Bahrain (ALBA) has awarded ABB Kraftwerke AG of Mannheim, Germany, a contract to add a 165-MW gas turbine of type GT13E2 to the 800-MW combined cycle power plant, ALBA 3, that ABB had built earlier for the company's aluminium smelter. The new machine is scheduled to go on line in May 1997.

ABB Kraftwerke AG led the consortium that built the ALBA 3 plant, which was handed over in June 1993 and for which ABB supplied six type GT13D gas turbines, two steam turbines and other key equipment.

ABB power plant control unit receives EU environmental certificate

Mannheim-based ABB Kraftwerksleittechnik GmbH was awarded the European Union's Eco-certificate in November 1995, making it the first ABB Group company worldwide to meet the requirements of the corporate environmental performance audit as laid down by the EU Eco-Audit Directive 1836/93.

The EU Eco-Audit Directive is designed to involve commercial organizations in a voluntary assessment of their environmental performance. Prior to being awarded the certificate, the power plant control unit had introduced an environmental management system and set rigorous environmental targets. The Eco-Audit certifies that the company is run according to sound environmental principles and verifies that protection of the environment is an integral part of its corporate policy. The certification is officially registered with the regional industrial chamber of commerce (IHK) in Mannheim.