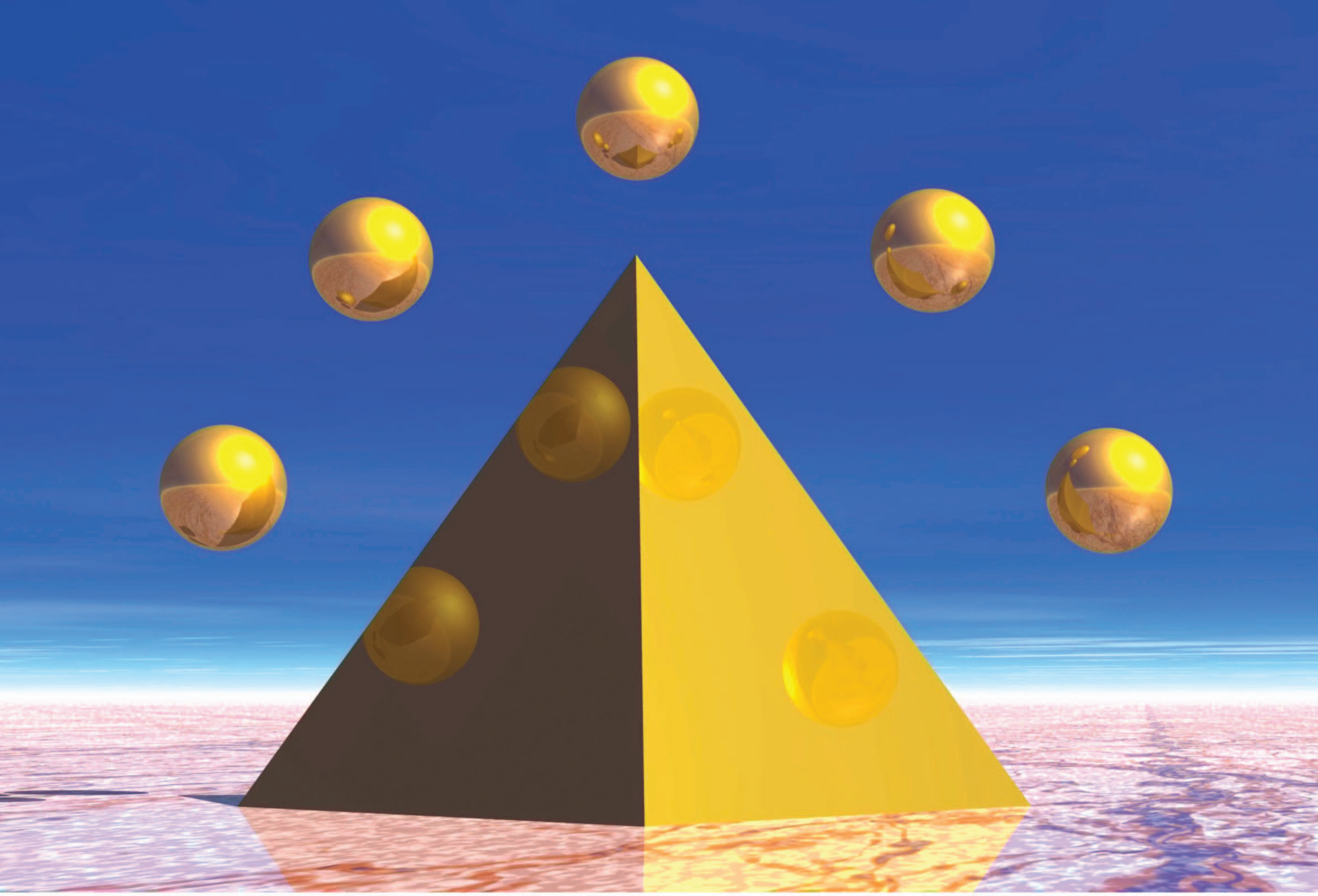

Silicon Carbide Power Transistors

A New Era in Power Electronics Is Initiated

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During recent years, silicon carbide (SiC) power electronics has gone from being a promising future technology to being a potent alternative to state-of-the-art silicon (Si) technology in high-efficiency, high-frequency, and high-temperature applications. The reasons for this are that SiC power electronics may have higher voltage ratings, lower voltage drops, higher maximum temperatures, and higher thermal conductivities. It is now a fact that several manufacturers are capable of developing and processing high-quality transistors at cost that permit introduction of new products in application areas where the benefits of the SiC technology can provide significant system advantages. The additional cost for the SiC transistors in comparison

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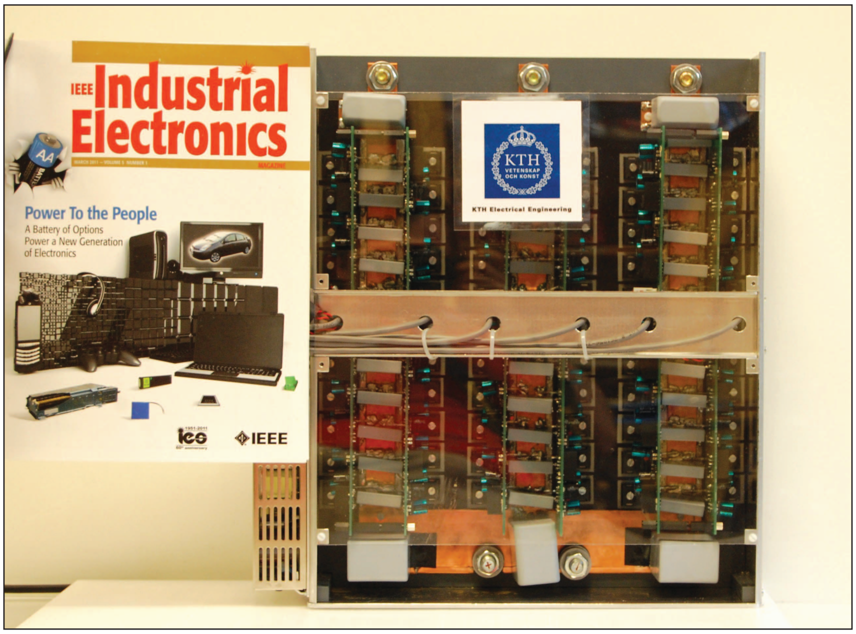

FIGURE 1 – A 40-kVA SiC inverter (300 × 370 × 100 mm^3) shown together with a copy of *IEEE Industrial Electronics Magazine*.

with corresponding Si alternatives are significantly smaller today than the reduction in cost or increase in value seen from a systems perspective in many applications. In all these cases, the SiC transistors are unipolar devices, such as the junction field-effect transistor (JFET), the metal-oxide-silicon field-effect transistor (MOSFET), and the bipolar junction transistor (BJT). The latter may seem to be a bipolar device, but from experiments, 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 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% (Figure 1). Truly, a new era in power electronics has begun.

Overview of the Available SiC Devices

The dramatic quality improvement of the SiC material [1] 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 [1], [2]. Nevertheless, the SiC device market is still in an early stage, and today, the only available SiC switches are the JFET [2], [3], BJT [4], and MOSFET [5], [6]. Commercially available SiC devices are still not in mass production. Thus, the market price of these components is 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 of 1,200 V and current ratings of few tens of amperes are available. Regardless of the type of SiC device, the driver for 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 [2]. To start with, an overview of the currently available SiC devices is given followed by the driver aspects for each device.

SiC 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 [7]. It was during these years that a few research groups had started mentioning the advantageous characteristics of the SiC material compared with Si [8], [9]. 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 [8], [9]. 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 [2], 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), as shown in

Figure 2. 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. This SiC JFET is a normally on device, and a negative gate-source voltage 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 [2], [10] 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 [11]. 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 [12], [13]. A cross-section schematic of its structure is shown in Figure 3. 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 conduction state. The pinch-off voltage for the DMVJFET equals approximately −6 V, 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.

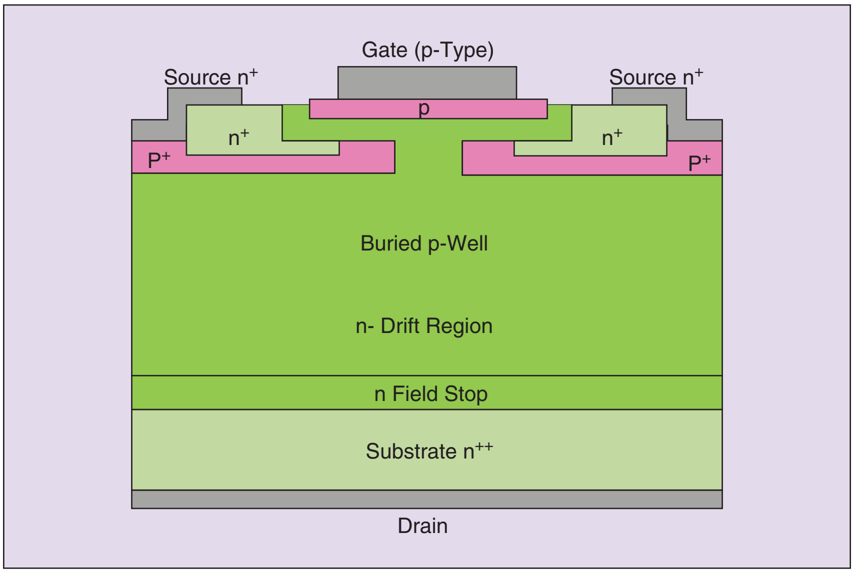

FIGURE 2 – Cross section of the normally on SiC LCJFET.

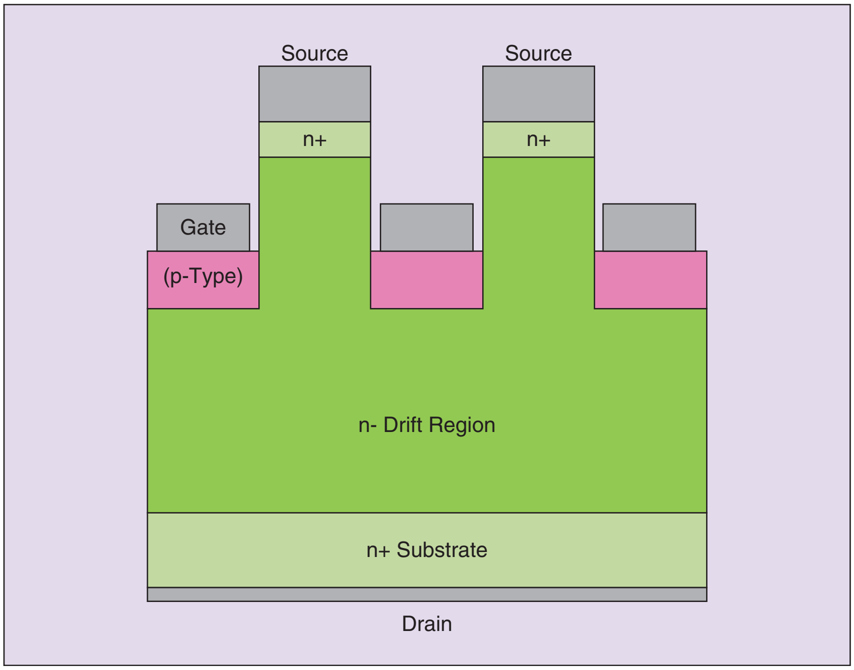

FIGURE 3 – Cross section of the SiC VTJFET.

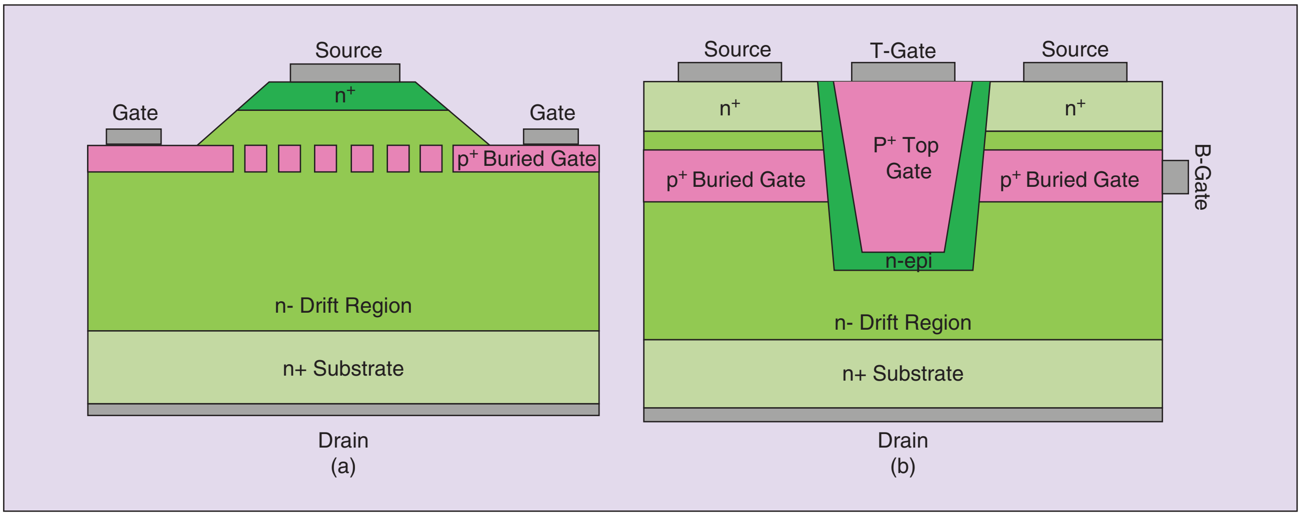

FIGURE 4 – (a) Cross section of BGJFET and (b) SiC DGTJFET.

Two additional SiC JFET designs have been presented [Figure 4(a) and (b)] [14]. The buried grid JFET (BGJFET), shown in Figure 4(a), 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. Figure 4(b) 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 [14]. 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 mΩ at room temperature can be found. As for the normally on JFETs, the normally off counterparts (EMVTJFETs) are available at current ratings up to 30 A and have on-state resistances of 100 and 63 mΩ.

SiC 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/cm^2) [4] 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 [15]. The fabrication of the SiC BJTs with improved surface passivation leads to current ratings of 50 A at 100 °C and current 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 the future.

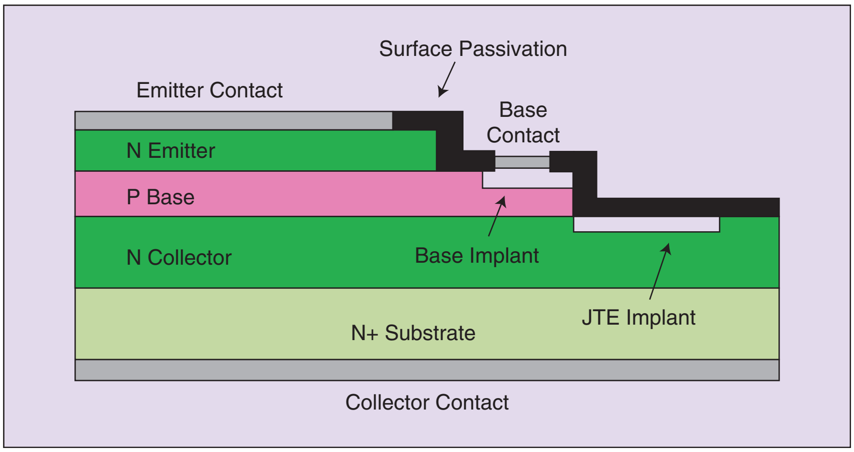

FIGURE 5 – Cross section of the SiC BJT.

SiC 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 long time periods and at elevated temperatures, 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 [1], [5]. At present, 1.2-kV SiC MOSFETs with current ratings of 10–20 A and on-state resistances of 80 and 160 mΩ 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 [43]. 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.

SiC 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 [2], [16]. 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 [38].

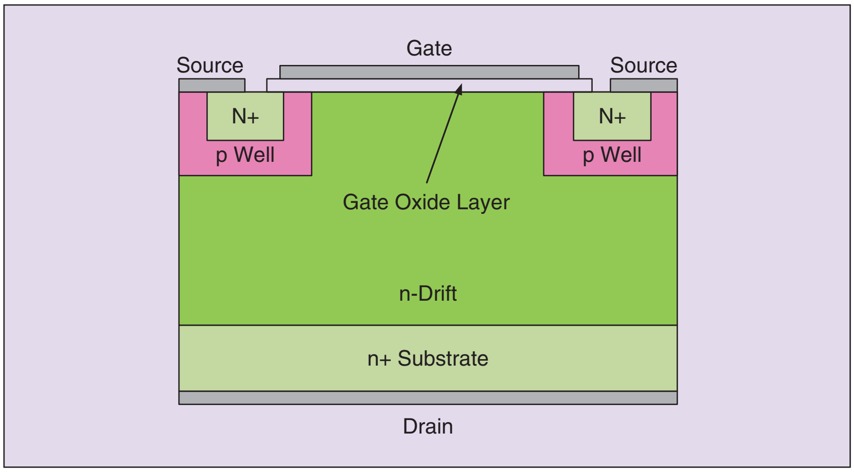

FIGURE 6 – Cross section of the SiC MOSFET.

Gate and Base Drivers for SiC Devices

To use the advantageous performance of SiC devices compared with the Si counterparts, special driver designs are required. Such gate and base 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.

Normally On SiC JFET Gate Driver

The normally on SiC JFET is a voltage-controlled device. Thus, a negative gate-source voltage, which should be lower than the pinch-off voltage, is required to keep this device in the off state. The most widely used gate driver for the SiC JFET was proposed a few years ago [17] (Figure 7). The main part of the driver is a parallel-connected network consisting of a diode D, a capacitor C, and high-value resistor R_p, while a gate resistor R_g is connected in series with the gate.

During the on state of the SiC JFET, the output of the buffer, V_g, equals 0 V, and the device is conducting the current. When the JFET is turned off, the buffer voltage, V_g, is switched from 0 V to $-V_s$. At this time, a current peak is supplied to the gate-source junction of the JFET through

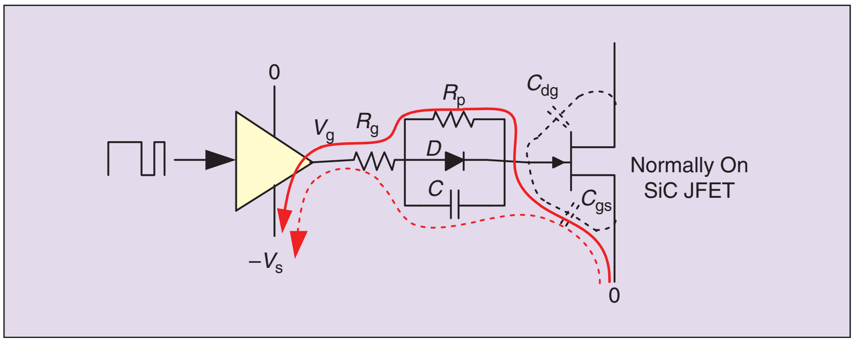

FIGURE 7 – Gate driver of the normally on SiC JFET.

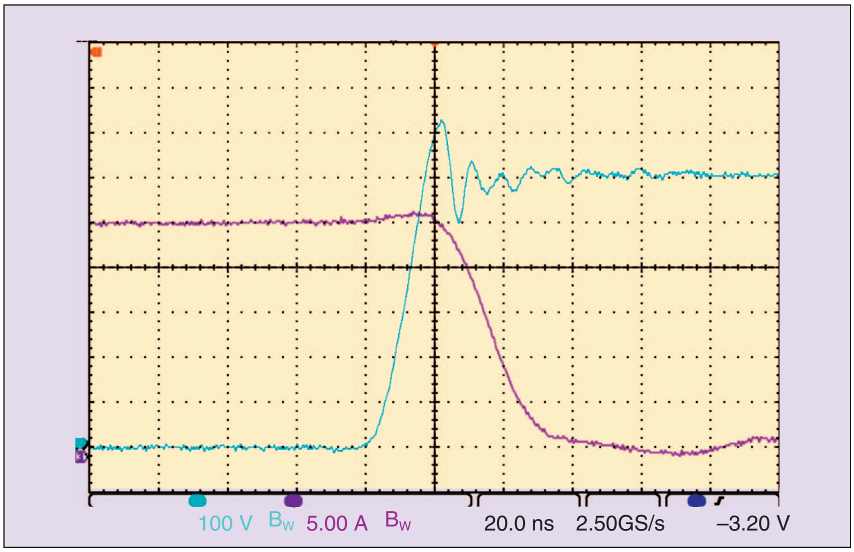

FIGURE 8 – Turn-off process of the normally on SiC JFET (V_{DS}: drain–source voltage—100 V/div and I_D: drain current—5 A/div, time base 20 ns/div).

the gate resistor R_g, and the capacitor C, as shown with the dashed line in Figure 7. Hence, the parasitic capacitance of the gate-source junction, C_{gs}, is charged, and the voltage drop across the capacitor C equals the voltage difference between $-V_s$ and the breakdown voltage of the gate. During the steady-state operation in the off-state, a low current is only required to keep the JFET off. This current is supplied through the resistor R_p, as shown with the solid line in Figure 7. It is worth mentioning that the value of R_p should be chosen carefully to avoid breakdown of the gate-source junction. Regardless of the choice of R_p, it is possible to adjust the switching performance to any desired speed by selecting an adequate value of the gate resistor R_g. The switching performance of this gate driver, when it is used with a SiC LCJFET, is shown in Figure 8.

Despite the overwhelming advantages of the normally on SiC JFET, the main problem with this device is that a possibly destructive shoot through is obtained in case the power supply for the gate driver is lost. It is, therefore, more than essential to design smart gate drivers to overcome such problems.

Normally Off SiC JFET Gate Driver

Even though the normally off SiC EMVTJFET seems to be a voltage-controlled device, a substantial gate current is required during the conduction state to obtain a reasonable on-state resistance [18]. In addition to this, high-current peaks should be provided to the gate so that the recharge of the gate-source capacitance of the device is faster. A two-stage gate driver with resistors has been proposed for a 1,200-V/30-A normally off JFET (Figure 9). This driver consists of two stages: the dynamic one with a standard driver and a resistor R_{B2}, which provides high voltage, and thus high-current peaks, during a short time period to turn the JFET on and off rapidly. The second stage is the static one with a dc/dc step-down converter, a BJT, and a resistor R_{B1}. The auxiliary BJT is turned on when the dynamic stage is completed. The static stage is able to supply a gate current of approximately 200 mA during the on state of the JFET. An important advantage of this driver is the absence of the speed-up capacitor, which might cause duty-ratio limitations because of the associated charging and discharging times. Finally, another gate driver for normally off SiC JFETs has been presented in [19] to use the fast switching performance of this device.

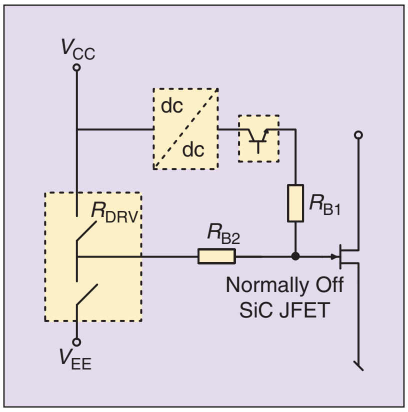

FIGURE 9 – Two-stage gate-drive unit for normally off SiC JFETs.

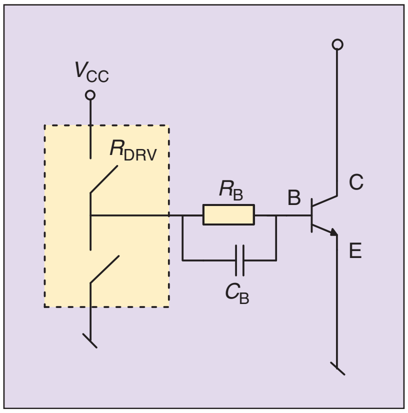

FIGURE 10 – Base-drive unit with speed-up capacitor for a SiC BJT.

SiC BJT Base Driver

As already mentioned, 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, C_B, in parallel to the resistor [4] (Figure 10). Hence, the switching performance might be improved, but this improvement depends on the supply voltage, V_{cc}. 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 [20]. A turn-on process using this driver is shown in Figure 11. 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.

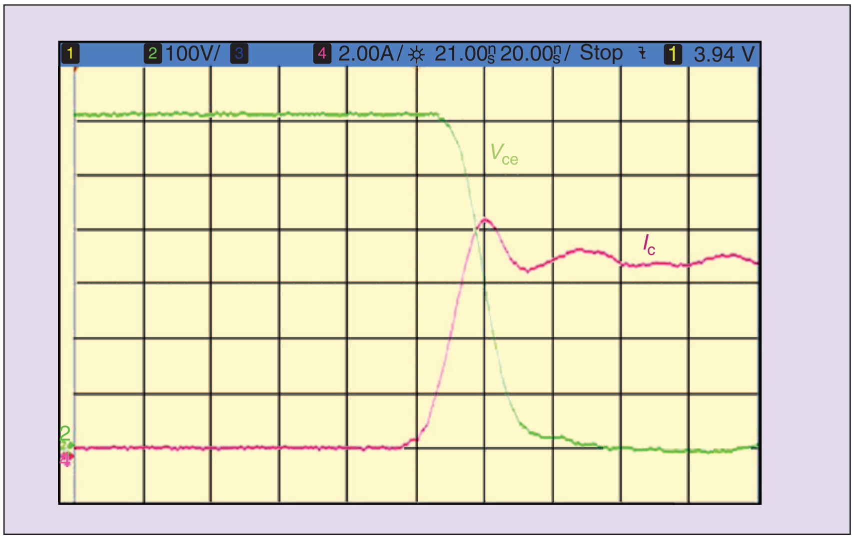

FIGURE 11 – Turn-on process of the 6-A SiC BJT with dual-source base driver (V_{ce}: collector–emitter voltage—100 V/div and I_c: collector current—2 A/div, time base 20 ns/div).

Parallel Connection of SiC Devices

In several power electronics applications, higher current ratings are required than those of the available SiC transistors. It is, therefore, necessary to build either multichip 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 nonuniform 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 [21]. 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 speeds. 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 [22]. 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 [23] shown in Figure 1. 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 (Figure 12) and the outstandingly high efficiency (more than 99.5%) constitute the two driving factors to invest in such a converter.

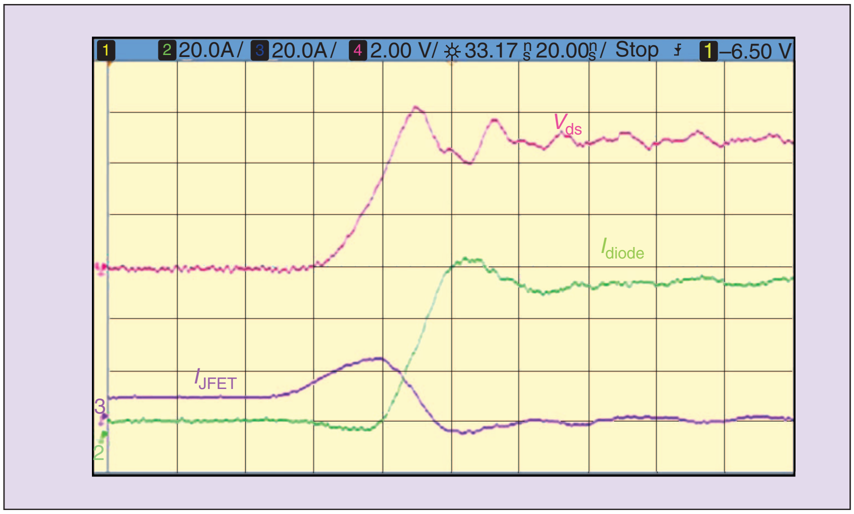

FIGURE 12 – Turn-off process of 10 parallel SiC JFETs (V_{ds}: drain–source voltage—200 V/div and I_{JFET}: drain current—20 A/div of one single JFET) with antiparallel SiC Schottky diode (I_{diode}: diode current—20 A/div, time base 20 ns/div).

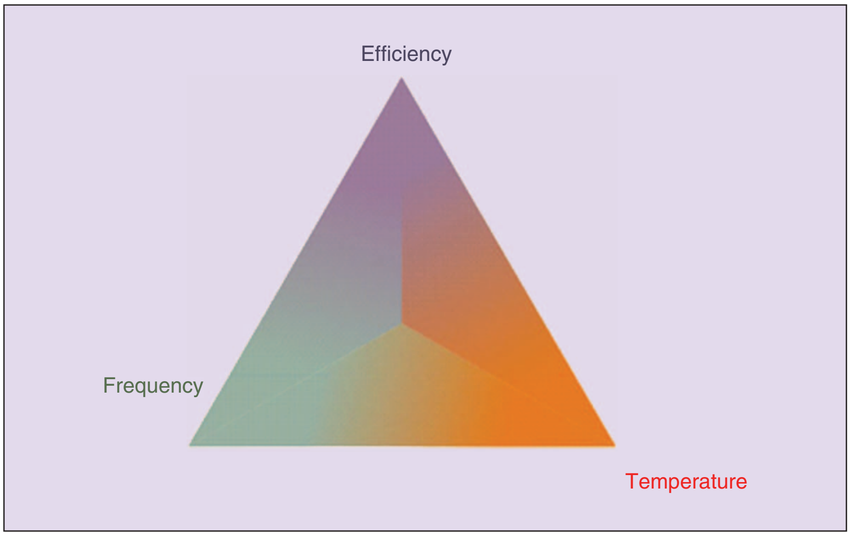

FIGURE 13 – Three main directions in the design of power electronics converters with SiC devices.

Possibilities

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 (Figure 13).

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 [24]. From a system perspective, the design advantages are reduction of size and weight of passive elements (e.g., inductors, capacitors) [25]. 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 [26].

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 [23]. 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 °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 °C, the thermal resistance of the heat sink 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 [27]. The SiC devices were operating at 250 °C while the case temperature was below 200 °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 [28], [29] but the development of SiC control electronics is also promising [30].

Overview of 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 what 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 groups around the world.

Photovoltaics

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.

AC Drives

As the state-of-the-art Si devices almost fulfill the requirements for inverter-fed ac drives [32] 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 [24]–[26] or when a high switching frequency is necessary to feed a high-speed motor.

Hybrid Electric Vehicles

The gains when employing SiC transistors in inverters for hybrid electric vehicles are extremely high [33]–[36]. 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 withstand high temperature operations, which is a great challenge.

High-Power Applications

The high blocking voltage capability of the SiC devices makes them attractive in the area of high-power converters for grid applications [37] such as HVdc. According to [14], 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 in [38]. 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 [39]. 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 in [40]. These devices are compared with the 4×5 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 [24], where six 1.2-kV transistors connected in a supercascode 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 [41]. 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 [42]. 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 [43].

Conclusions

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.

Biographies

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