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POWER SEMICONDUCTORS – STATE OF THE ART AND FUTURE TRENDS

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Abstract
The importance of effective energy conversion control, including power generation from renewable and environment-friendly energy sources, has increased due to rising energy demand. Power electronic systems for controlling and converting electrical energy have become the workhorse of modern society in many applications, both in industry and in the home. Power electronics plays a very important role in traction and can be considered as workhorse of robotics and automated manufacturing systems.
Power semiconductor devices are the key electronic components used in power electronic systems. Advances in power semiconductor technology have improved the efficiency, size, weight and cost of power electronic systems.
At present, IGCTs, IGBTs, and MOSFETs represent modern switching devices. Power integrated circuits (PIC) have been developed for the use of power converters for portable, automotive and aerospace applications. New materials (SiC and GaN) have been introduced for advanced applications.
This paper reviews the state of these devices and elaborates on their potentials in terms of higher voltages, higher power density, and better switching performance.

Keywords: power semiconductor devices, power MOSFETs, Thyristor, IGCT, IGBT, wide band gap devices

1. Introduction

Power electronic systems for controlling and converting electrical energy have become the workhorse of modern society in many applications. Put quite simply, power is everywhere. For example, power electronic systems play a dominant role in making more efficient use of electric power in many appliances, both in industry and in the home. The use of power converters for variable speed drives results in energy savings and recovers the additional converter cost within a short period of time. Power electronics plays a very important role in traction by enabling the use of electric cars and trains and can be considered as workhorse of robotics and automated manufacturing systems. The importance of effective energy conversion control, including power generation from renewable and environment-friendly energy sources, has increased due to rising energy demand.

Power semiconductor devices are the key electronic components used in power electronic systems. Many power semiconductor devices have been developed and produced since the invention of the thyristor in 1956, which marked the beginning of the modern era of power electronics, which can be called the solid state power electronics revolution.
The introduction of neutron transmutation doping (NTD) of silicon in the 1970s enabled the development of high voltage large-area diodes and thyristors, and the invention of the IGBT in 1985, the first device of real commercial value which combines the advantages of bipolar and MOS features. Within 25 years, the IGBT has systematically pushed the application of bipolar devices towards the highest voltage classes and current ratings.
Power semiconductors play a leading role in the progress of power electronics, since they are essential for satisfying the constantly growing demands on performance, cost and reliability. Advances in power semiconductor technology have improved the efficiency, size, weight and cost of power electronic systems. Cost reduction has provided an important motivation for developing better switching devices in power converters.
Power integrated circuits (PIC) have been developed as a result of recent advances in circuit integration technology, and this has led to a significant improvement in reliability and to reductions in size, weight and cost. This has extended the use of power converters for portable, automotive and aerospace applications.

There are still many challenges connected with optimising the construction of power semiconductor devices and integrated systems for emerging new applications. Innovation in the area of power semiconductors requires a concerted multi-disciplinary effort linking physicists, engineers, technologists, circuit designers and end-users. The most important directions in present-day research and development are:

- improved switches - higher blocking voltage, higher on-state current density, higher switching frequency, easy to drive
- power integration - integration of logic and power circuits in a single chip with increasing applications in the area of power management, automotive, telecommunication, power supply, etc.
- improvements in reliability – solutions in device construction and technology, thermal management and

- packaging, better knowledge of how to use power semiconductors safely.

Efforts at improving power semiconductor devices from the current state-of-the-art is, ultimately, fuelled by increasing cost pressure, as high reliability is nowadays taken for granted. Cost reduction can essentially be achieved by:

- Lower component cost, i.e., higher output current for a given device area;
- Lower component count. In the high voltage arena, in essence this means larger devices, and/or higher voltages per device;
- Reduced cost and size of the entire power electronic system, i.e., of the cooling system, the filter unit, the mechanical structure, and all auxiliary parts.

Silicon as a well-established starting material that has already met these requirements for more than 50 years. However, for some applications wide band-gap materials like SiC and GaN offer the potential to overcome both the temperature limitations and the power management limitations of Si.

2. Semiconductor switching devices

The ideal switch should have: very high blocking voltage in off-state, very low on-state resistance, very short (zero) turn-on and turn-off times, very low turn-on and turn-off power dissipation. The switch should have only one gate, easy control and it should be in the off-state without a controlling signal.

In real power semiconductor device structures, described in details in e.g. in [1],[2], the high blocking voltage is connected with the existence of a thick space charge region (depletion layer) at the PN junction that spreads with increasing voltage into a low doped area of the structure. A PN junction breakdown occurs if the electric field in the depletion layer reaches its critical value E_{crit}. From simple theory, the breakdown voltage V_{BR} depends on donor concentration N_D in a low doped area, as

$$V_{BR} = \frac{\varepsilon_0 \varepsilon_r E_{crit}^2}{2eN_D} \, . \qquad (1)$$

The breakdown voltage may also be expressed as

$$V_{BR} = \xi w_D E_{crit} \, , \qquad (2)$$

where w_D is the thickness of the high resistivity (low doped) region and $0.5 < \xi < 1$ ($\xi = 0.5$ for the non punch through case, $\xi = 1$ for an ideal PIN structure). Therefore, the thickness of the structure increases with increasing blocking voltage, as shown in Fig.1. Perfect junction surface termination is necessary in order

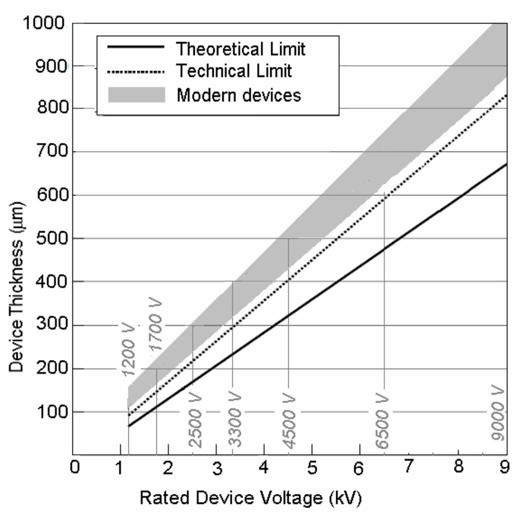


Fig.1. Comparison between the minimum device thickness and breakdown voltage

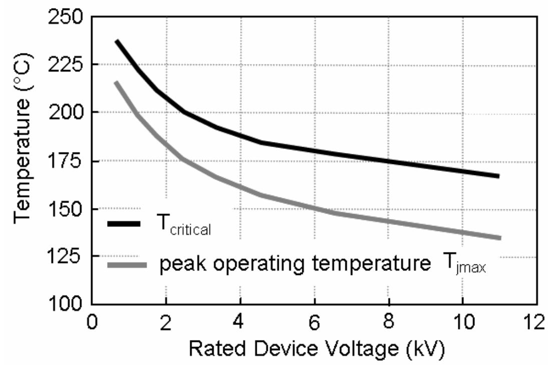


Fig.2. Critical thermal runaway temperature and the estimated maximum safe operating temperature T_{jmax} of silicon devices [3]

to obtain a high breakdown voltage.

A common design objective of power semiconductor switches is to optimize the combination of conduction losses and switching losses (in the form of heat), because the maximum operating temperature T_{jmax} is limited to prevent thermal breakdown. The maximum power losses are limited by

$$P_{AV\,\max} \le \frac{T_{j\,\max} - T_a}{R_{thja}} \qquad (3)$$

$T_{j\,max}$ is the maximum junction temperature, T_a is the temperature of the ambient, and R_{thja} refers to the thermal resistance between the semiconductor junction and the ambient. Thus, the maximum current in a particular application is influenced not only by the characteristics of the device but also by the thermal resistance of the encapsulation and the thermal resistance of the heat sink.

The maximum operating temperature T_{jmax} decreases with the device blocking voltage [3][4], as shown in Fig.2.

The power losses of a hard switching device operating at frequency f can be expressed by

$$P_{AV} = \psi I_{on} V_{on} + f(W_{on} + W_{off}) \, , \qquad (4)$$

where I_{on} is on-state current, V_{on} is on-state voltage, W_{on} are on-state losses, W_{off} are off-state loses and ψ represents the duty cycle.

Eqs. (3) and (4) provide limits for device application, as demonstrated in Fig.3. Some important features of the most important types of switching devices are discussed bellow.

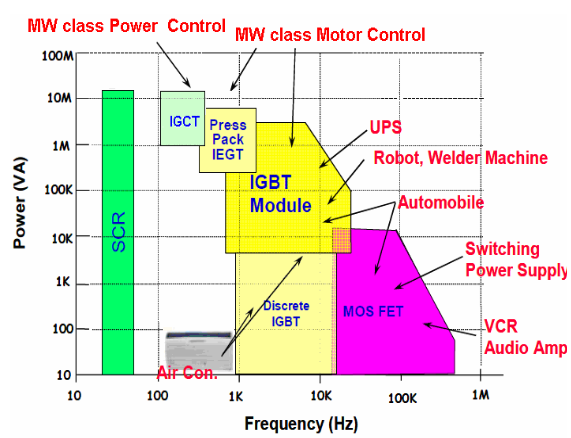


Fig.3. Application fields of power devices [5]

2.1. Thyristors

The modern era of power electronics which can be called the solid state power electronics revolution began with the invention of the thyristor in 1956. At that time, the thyristor was the only device in the voltage class of hundreds of volts that had been properly mastered technologically. The thyristor structure needs a broad base of low doped material to meet the requirement for high blocking capability, as is shown in Fig. 1. During the conductive (on-state) phase, the interior of diode and thyristor structures is flooded with a large number of positive and negative charge carriers (holes and electrons) during the conductive (on-state) phase, giving the device a strongly enhanced conductivity with respect to the substrate, as demonstrated in Fig.4. Thyristors therefore have relatively very low voltage drop in the on-state. During device turn-off, the electro-hole plasma must be removed in order to recover the blocking capacity. This is accomplished by the recovery voltage, whereby an electrical field builds up. As a result, current still flows as the voltage increases, i.e., high losses W_{off} arise in the form of heat. Consequently, as follows from (4), thyristors can be used in applications operating at lower frequencies.

The introduction of neutron transmutation doping (NTD) of silicon in the 1970s enabled the development of high voltage large-area diodes and thyristors. The area of the devices is limited by the diameter of the silicon single crystals prepared by the float zone method. The progress in the float-zone technology is shown in Fig.5. Devices up to 150 mm in diameter can now be produced [6]. Thyristors are therefore appropriate for controlling high currents in the range of some hundreds of amperes to several kilo amperes. Advances in material and process technology had nowadays led to the fabrication of thyristors with blocking voltage up to 10 kV [7] [8] and experimental structures with blocking voltage 13 kV have been already prepared [9]. High voltage thyristors can be utilized advantageously for applications in which several thyristors are connected in series, because this enables a significant reduction in the number of components necessary for the construction of high power converters.

Nowadays, thanks to these devices, variable speed drives in the megawatt range for industrial applications and for transportation are the state-of-the-art, and it would be hard to imagine the power transmission and the grid stabilization sectors, where applications extend well into the gigawatt range, without solutions based on power thyristors. For line commutated high

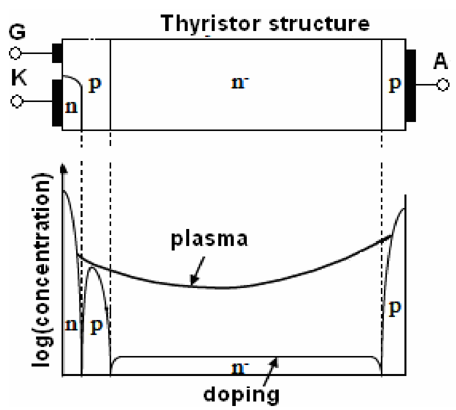


Fig.4. The thyristor structure and the plasma distribution in the conductive state

voltage direct current (HVDC) systems, the direct light triggered thyristors (LTT) have been available since 1997 for the 8 kV range including the protection functions [10].

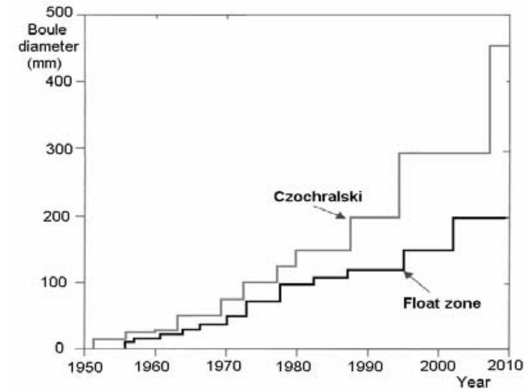


Fig.5. The increase of the maximum available diameter of silicon single-crystal boles

For variable speed drives, GTOs have been replaced by the Integrated Gate Commutated Thyristors (IGCT) that due to very hard turn-off signal do not need a snubber. IGCT is a well-established device for high power applications such as medium voltage drives, inverters, power quality applications and traction. IGCTs consist of a large number of in-parallel operated thyristor cells driven by a single gate unit. These devices are very sensitive to structural inhomogeneities and need a high level of carrier lifetime control [11] [12]. Advanced IGCT technologies feature a very large SOA and high surge robustness. IGCTs with blocking voltage up to 10 kV and rating currents up to several kA may lead to progress in the development of drives with a lower number of in- series connected devices. A disadvantage of devices with very high blocking voltage is the lower maximum operating temperature (see Fig. 2) [12] and the longer turn-off time.

Press-pack encapsulation provides the required thermal cycling ruggedness, low parasitic inductance, low thermal resistance and flexible design (easy series connection in stacks).

2.2. Power MOSFETs

Since their introduction in 1974, several quite different types of MOS transistor have been developed that are able to switch relatively high currents and voltages, and can therefore be used in power electronic circuits. Power MOS brings the following benefits to power electronic applications:

- high input impedance
- high power gain
- voltage control
- thermal stability.

At present, power MOS field-effect transistors (power MOSFETs) are the most commonly used devices in power electronics applications up to tens kW range. Since there is no excess carrier injection in the on-state, the turn-off losses W_{off} are low, and devices can be operated at relatively high frequencies. The turn-on and turn-off times depend on the input gate capacitance, mainly on the gate drain capacitance C_{GD}, which may be very high due to the Miller effect [1],[2].

In addition to the basic on-resistance and gate charge, other parameters are also becoming more relevant as the switching frequencies and output currents are going up.

These include the body diode reverse recovery, the internal gate resistance and the output charge of the MOSFET (Q_{OSS}). Low voltage MOSFET products are now being optimized to minimize the diode reverse recovery (FREDFETs) as well as the output capacitance. One such development has been the integration of a MOSFET and a Schottky diode.

When there is a monolithically integrated Schottky along with a MOSFET, there is a significant reduction in the reverse recovery and forward diode drop for the product.

A MOSFET device is composed of numerous unit cells in parallel, which should have similar cell characteristics. For the discrete power MOSFET, two basic device cell configurations are mostly used. The VDMOS structure and the Trench FET (UMOS) structures are shown in Fig.6.

Trench FET devices have gained immense attention in recent years due to the significant reduction in on-resistance and die cost. For low voltage (40 V -100 V), high-frequency switching applications, the channel resistance is the most dominant factor.

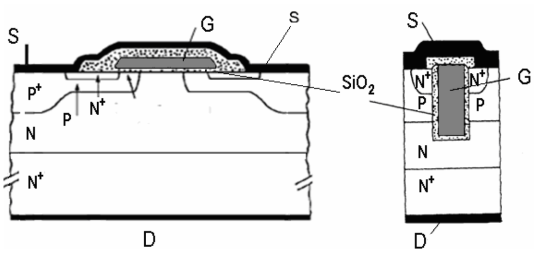


Fig.6. Basic MOSFET cell configurations: VDMOS (right) and Trench FET (left)

Reduced cell pitch and higher cell density was the first main focus area for trench gate device, and has led to the development of cell density higher than 10^8 cells per cm^2. This has resulted in a reduction of more than 50% in the specific on-resistance and a corresponding reduction in die cost.

The challenge in scaling Trench FET is that its structure suffers from an inherent high gate-drain or Miller capacitance C_{GD}. Therefore, an increase in Trench FET cell densities is accompanied by an increase in C_{GD}, which degrades the switching performance of the device [13]. The higher gate charge associated with higher cell density has been overcome by incorporating a thick oxide at the bottom of the trench (Trench Bottom Oxide or TBO) [14].

Unfortunately, the specific on-state resistance ($R_{ON}.S$) of power MOSFET increases drastically as its breakdown voltage $V_{DS(BR)}$ increases. Due to the limitation of the maximum electric field, a high breakdown voltage requires the drift region to be lightly doped and thick, which in turn causes $R_{ON}.S$ to be very high. For conventional vertical power MOSFET this is given by the relationship

$$R_{ON}S \propto V_{DS(BR)}^{2.6} \qquad (5)$$

In both VD MOS and Trench-MOS structures, the on-state resistance increases with the maximum blocking voltage and applications with both VDMOS and Trench FETs are limited up to 300 V.

This problem has been solved by reconstructing the high voltage junction form using the super-junction design [15].

High voltage power MOSFET technology based on the Super Junction concept has attracted a great deal of attention over the past ten years [16]. SJFET has evolved from a conventional DMOS under the name CoolMOS. In a SJFET, the body of a DMOS is extended to a vertical strip in the epitaxial layer, as shown in Fig.7, and in this way the high-voltage blocking capability is obtained in both horizontal and vertical directions. This enables the same blocking voltage to be obtained with lower resistivity of the drift region.

In this way, power MOSFETs may operate in the blocking voltage range up to 1000 V with acceptable on-state losses. The super junction concept can be gainfully applied to lower breakdown voltages.

Due to the limited chip area, high power MOSFETs are often realised as several in-parallel connected chips in a single module package. Even minimum differences in the threshold voltage and transconductance may cause an increase in switching losses and may decrease the maximum operating frequency.

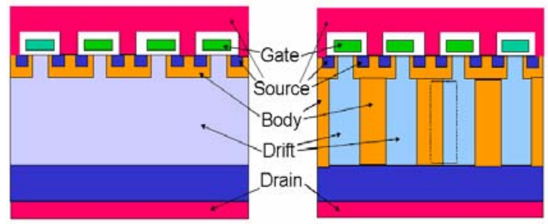


Fig.7. A comparison of VDMOS and SJMOS structures

The packaging is also very important, because even modest loop inductance will dramatically slow the switching edge rates while adding significant voltage stresses to the MOSFET as the leakage inductance dissipates the stored energy. The net effect is typically an increased switching loss and reduced efficiency. Module structures

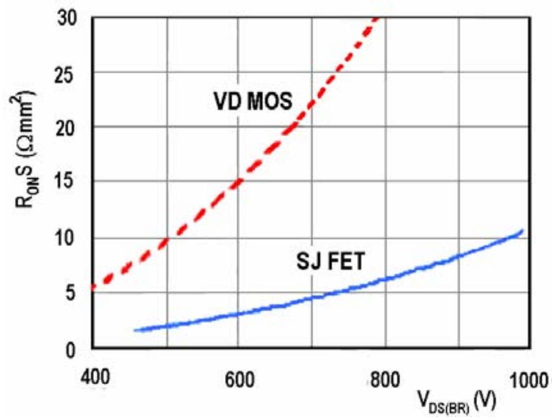


Fig.8. Comparison of the voltage dependency of the area specific R_{DSon}: SJ FET (Cool-MOS™) versus conventional power DMOS .

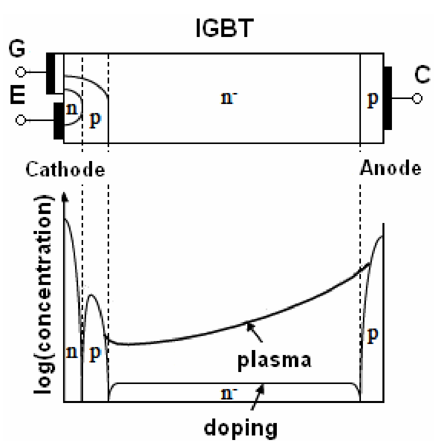
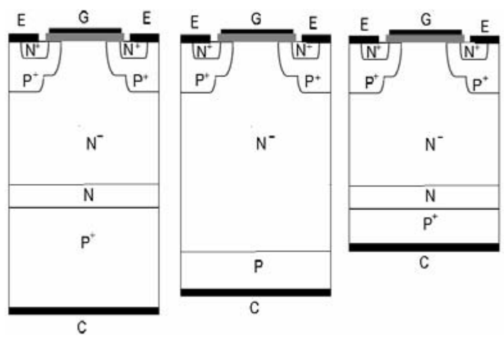


Fig.9. The IGBT structure and the plasma distribution in the conductive state

with internal inductances of less than 1 nH have been realised for high frequency operations [32].

2.3. IGBTs

The Insulated Gate Bipolar Transistor (IGBT) combines the advantages of a MOS gate structure with the superior low conduction losses of bipolar transistors. As demonstrated in Fig. 9, the hole injection from the P^+ collector region strongly enhanced the conductivity with respect to the substrate. However, the enhancement is lower than in the case of the thyristor structure, where there is injection from both cathode and anode emitters. The on-state voltage drop of IGBT is therefore higher than that of a thyristor structure of the same base thickness. The main conduction path through an IGBT can be modelled as a diode in series with an MOS transistor. Efforts to improve the cell density and forward voltage drop of IGBT have led to the emergence of the trench-gate structure as shown in Fig. 6, which offers an on-state voltage drop comparable to a diode, but shows inferior turn-off performance [17],[18].



a) PT IGBT b) NPT IGBT c) SPT IGBT

Fig.10. Different vertical IGBT designs

The excess carrier charge stored in the base of IGBT is much lower than in the thyristor structure. Consequently, te turn-off time and the turn-off losses W_{off} are significantly lower in comparison with thyristors allowing higher frequency operation. The switching speed is limited by the stored charge in the drift region and the minority carrier lifetime determines the turn-off time. The use of lifetime reduction techniques to decrease the turn-off time increases the forward voltage drop in non-punch-through (NPT) IGBTs. The punch-through (PT) structure supports the same forward blocking voltage with smaller thickness of the N-base region of the PNP transistor. This results in an improved trade-off between the forward voltage drop and the turn-off time, and makes them preferable for use up to 1200 V. As the voltage ratings are extended, the large thickness of the drift region makes the epitaxial growth expensive and the NPT IGBT structure is used [19]. Nowadays, the main stream is the IGBT technology utilizing the Soft-Punch-Through (SPT) or Field-Stop (FS) anode buffer structures. They are processed at relatively thin wafers providing low total losses and wide square SOA [20],[21]. Various vertical IGBT designs are shown in Fig.10.

IGBTs have replaced BJTs for medium voltage/power applications and are replacing thyristors in many high power applications.

In typical inverter applications, IGBTs are connected with antiparallel freewheeling diodes, as shown in Fig.11. The connection is usually realised as a module consisting of IGBTs and anti-parallel free-wheeling diodes (FWD). Parameters of FWD seriously influence the IGBT losses and should be optimised. The reverse conducting IGBT (RCIGBT) has been developed to decrease number of devices [22].

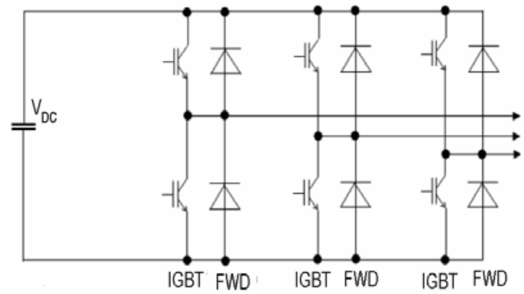
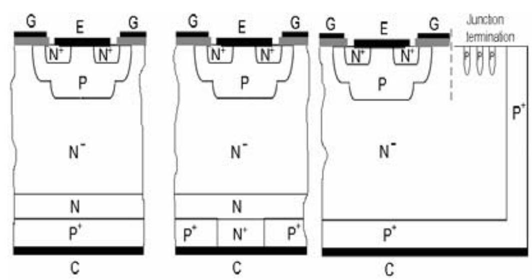


Fig.11. A typical inverter with IGBTs

In recent years, an AC-AC direct conversion circuit, or a matrix converter has been studied for commercial purposes. The conventional bi-directional switch consists of two IGBTs and two diodes [23] as shown in Fig. 13(a). Series diodes are needed to support the reverse bias, because there is only a very low reverse blocking capability if conventional IGBTs are used, leading to an additional on-state voltage drop. However, reverse-blocking IGBTs (RBIGBTs) can reduce the total number of the devices in the circuit, and can reduce the total loss of the converter, since the RBIGBTs can form the bi-directional switch without diodes [24], as shown in Fig. 13(b). A bidirectional switch which implements two antiparallel IGBTs in a single chip is under development [25].



IGBT RC IGBT RB IGBT

Fig. 12. IGBT design

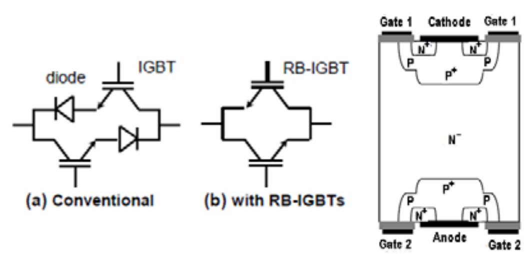


Fig. 13. IGBT bi-directional switches

Present-day technology enables maximum chip size of about 400 mm^2. For high power IGBTs, several in parallel connected IGBT chips and antiparallel connected diodes are mounted in a single module. Standard modules with Al_2O_3 ceramics, in versions with and without a baseplate, and high-power modules with AlN ceramics and an AlSiC baseplate are used to keep minimum thermal resistance, and also minimum parasitic inductances and capacitances. Weak points in module reliability are the substrate solder joint (if there is one), the chip solder and the bond wires [33]. New technologies such as low temperature joining [34] [35] were developed to improve the reliability of the module,. For applications where several devices in series connection are used, press packed IGBT [36] encapsulation has been also developed.

3. Diodes

Diodes are an essential component in power electronics applications. Diodes are produced in a very broad range of reverse voltage and forward currents. Silicon single wafer diodes are able to block more than 9 kV [7] [9] over a wide temperature range and are able to conduct more than 4000A in 6-inch wafer technology.

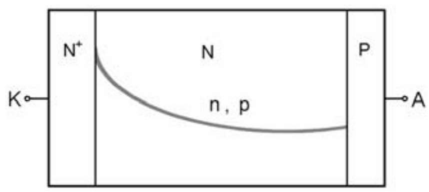


Fig.14. Optimised carrier distribution in a forward biased soft-diode structure

In applications, diodes are used for uncontrolled rectifying. In high power fast switching applications (e.g. in inverter applications), there is a need for fast power diodes with a short reverse recovery time (small reverse recovery charge) together with low operating power dissipation and high breakdown voltage. High speed, high voltage diodes (employed e.g. as freewheeling diodes for IGBTs) have to be developed for fast and hard decommutating. Major design objectives also include "soft recovery" switching behaviour.

Considerations for the design of fast soft reverse recovery diodes were reported in [26] [27]. For a good trade-off between reverse recovery charge and forward power losses, the charge carrier distribution must not have a significant minimum (as shown in Fig.4) and should increase from anode to cathode, as indicated in Fig.14. This can e achieved either by creating a suitable carrier lifetime axial gradient (various techniques are described in [28],[29],[30]), or by decreasing the efficiency of the anode emitter [31].

Another important requirement is a short forward recovery time at high di_F/dt created due to IGBT operation. If the forward current rises before the conductivity modulation of the middle region is fully effective, the overshoot of forward voltage that occurs at turn-on is connected with high power dissipation, which may also make the device fail.

None of these dynamic problems occur in Schottky diodes, where is no conductivity modulation due to minority carrier injection into the high resistivity region, which is necessary for reaching a high breakdown voltage. The time constants associated with the turn-on and turn-off processes are limited only by the time required to charge and discharge the capacitance of the space charge region at the metal-semiconductor contact. Unfortunately, with increasing breakdown voltage, the forward characteristics deteriorate and silicon Schottky diodes are limited with breakdown voltage of about 100 V [1], [2]. The Junction Barrier Schottky (JBS) structure, formed by the parallel integration of a Schottky diode and a P^+-N-N^+ junction diode [1], is often used to overcome problems with low resistance to current overloading,. For high voltage application, Schottky (or JBS) diode are fabricated from wide band gap semiconductors.

4. Wide band-gap devices

Silicon devices are generally limited to operation at junction temperatures in the range of 200ºC. Wide band-gap semiconductors, such as SiC, GaN and diamond [37] offer the potential to overcome both the temperature and power management limitations of Si. Basic material parameters are shown in Table 1.

Table 1. Basic material parameters of Wide Band- Gap semiconductors

Material	W_g (eV)	μ_n (cm²/V.s)	μ_p (cm²/V.s)	E_{crit} (MV/cm)	λ (W/cm.K)	ε_r
Si	1.12	1 450	450	0.23	1.5	11.7
4H - SiC	3.26	950	115	2.2	3.8	10
GaN	3.39	1000	350	3.3	1.3	8.9
Diamond	5.6	2200	1800	5.6	20	5.7

As follows form (1) and (2), that a critical electric field which is one order higher (in comparison with silicon) enables the same breakdown voltage to be reached with conductivity of the basic material that is two orders higher. This enables lower on-state voltage and higher breakdown voltage of devices to be achieved. Unfortunately, there are some technological limits. Diamond process technology is in its very early stage and there is no diamond power device in the market. SiC and GaN process technologies are more mature and are therefore more attractive from the device manufacturer's perspective, especially for high power and high temperature electronics.

The improvements with SiC are impressive. Four- inch wafers are now available, and six-inch wafer have been announced. High quality wafers no longer show micropipes [38]. However, there are other defects e.g. screw dislocations and basal plane dislocations that have to be overcome.

Concerning SiC rectifiers, Schottky diodes and now JBS diodes are commercially available with nominal current up to 25 A and voltage up to 1.7 kV [39]. They match perfectly as freewheeling diodes with Si IGBTs and SJ FETs (1200 V, 600 A IGBT modules with SiC Schottky diodes are already commercially available [40]. The configuration of IGBT together with an SiC diode as freewheeling diodes combines the superior conduction performance of IGBT chips with the ultra low reverse recovery losses of SiC Schottky diodes. With concepts of this type, the Schottky-diode voltage range can be extended to 3-4 kV [41].

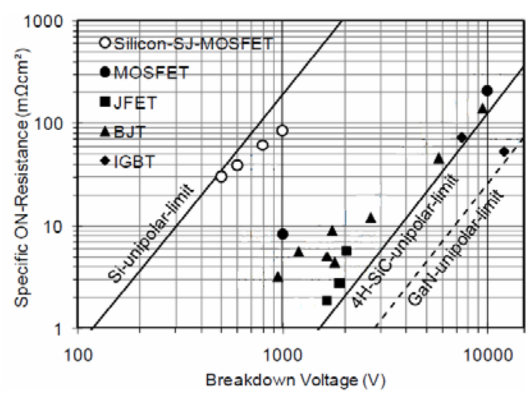


Fig. 15. Specific on-resistance of 4H-SiC devices vs. blocking capability [37]

PiN diodes will only be relevant for reverse voltage over 3kV. 50 A, 10 kV SiC PIN diodes have already been fabricated [42]. Before commercialisation, however, they still need to overcome their reliability problem (forward voltage drift due to stacking faults in SiC substrates).

Regarding SiC switches, functional samples of SiC MOSFETs (<5kV) or the SiC IGBT (>5kV), SiC BJT and SiC GTO have already been fabricated [43]. Though their parameters are promising, they also suffer from reliability problems similar to PiN junction rectifiers. The dependences of specific on-resistance of 4H-SiC devices on blocking capability

are shown in Fig.15.

The cascade pair consisting of a high-voltage, normally-on SiC JFET and a low-voltage Si MOSFET, is the only SiC switch that is already being applied. The switch is realised in the form of a module in the connection shown in Fig. 16. At present, Modules up to 100 A operating at frequencies over 20 kHz are referred to in [44].

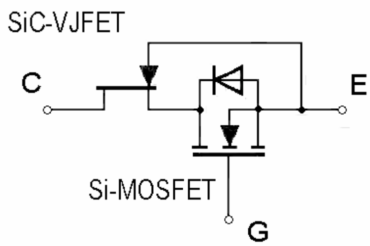


Fig.16. Cascode topology arranging the high voltage blocking SiC-VJFET in series with a 50 V MOSFET

GaN technology is competitive with SiC in the field of preparing high voltage power Schottky diodes. GaN is usually grown on sapphire, which is about an order of magnitude cheaper than SiC and gives GaN devices a significant cost advantage. Recently, even the growth of GaN on standard silicon wafers has been reported [45]. GaN devices [46] and especially low-cost semi-vertical Schottky diodes for 600 – 1200 V can overtake or displace SiC devices.
With both SiC devices and GaN devices, high temperature capabilities cannot be fully used because there are still existing packaging limits, and on a short to mid term scale no revolutionary progress is expected [37].

5. Conclusion

This paper has presented and discussed the basic physical limits and the present state-of-the-art of the most important types of power semiconductor devices. For the near future, high-power electronics will continue to utilize the Si devices, especially silicon switching devices. IGBTs and IGCTs will compete on an equal level for high-voltage high-power applications. In medium voltage applications (1 – 3 kV) IGBTs remain the most important switching devices, especially in combination with SiC or GaN Schottky or JBS diodes. For voltages below 1000 V, superjunction MOSFETs will provide high frequency fast switching in competition with IGBTs. The voltage range below 300 V will be the domain of power MOSFETs (mostly trench MOSFETs). The SiC and GaN Schottky and JBS diodes have become very important for increasing the quality of IGBT modules. The SiC and GaN switches have to wait for a breakthrough in higher power applications till improvements in quality of basic materials can be reached. The development trends of power device technologies will continue to provide power electronic systems with exceptional performance, increased comfort, energy savings and growing accent on the sustainable use of natural resources.

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