Power semiconductors

Part one: Basics and applications

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Over the last 10–15 years, in the wake of rapid progress in semiconductor technology, silicon power switches have developed into highly efficient, reliable, and application-friendly devices. These devices have firmly established themselves in high-voltage and high-current applications, handling power outputs ranging from one megawatt to several gigawatts. Power semiconductor devices have started a quiet revolution, in the course of which, electromechanical solutions are gradually being improved by the addition of power electronics, or even completely replaced by power-electronic systems.

This article, which is intended for a relatively knowledgeable readership, is the first of a two-part contribution, in which ABB Review takes a tour of high-power semiconductors. In this first part, different classes of devices are presented, in particular the IGBT and IGCT. Specific advantages and disadvantages of these devices are compared, as are some important aspects concerning their application. In the second part, to be published in ABB Review 1/2007, thermal issues and aspects of housing design are discussed. Moreover, an attempt will be made to predict future developments, and what importance "wide bandgap" materials, such as SiC (silicon carbide), GaN (gallium nitride), and diamond, will gain in the high power arena.

It was the introduction of neutron transmutation technology in the 1970ies that made the manufacture of power semiconductor devices with blocking voltages of greater than circa 1000 V possible. Only this technique permits silicon to be produced with the required doping homogeneity.
At that time, the thyristor was the only device in this voltage class that had been properly mastered technologically. However, the number of applications was restricted, as this device did not permit forced current interruption at an arbitrary point in time. In the 1980ies and 1990ies, the thyristor was joined by devices with turn-off capability, namely the GTO (Gate Turn-Off Thyristor), and later the IGBT (Insulated Gate Bipolar Transistor) and the IGCT (Integrated Gate Commutated Thyristor). These devices increased the spectrum of efficiently operable task definitions significantly. Nowadays, thanks to these devices, variable speed drives in the megawatt range are 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 semiconductor components.

In the last 10 years, the IGBT and the IGCT (which replaced the GTO) have been developed further with regard to losses, voltage withstand capability, current carrying capacity (SOA = Safe Operating Area), and ease of use. Therefore, the old paradigm that IGBTs are for "small" power outputs and IGCT for larger ones, which was still generally accepted in the mid 1990ies, no longer applies. IGBTs are now used successfully in applications with an output of over 300 MW [1]. The conclusion that the IGCT will lose its raison d'être as a result of the advance of the IGBT is incorrect, however, as is witnessed by the strong growth of applications, mainly in the medium-voltage range. The decision as to which component is most suitable for a desired application depends on a number of technical factors, which will be illuminated somewhat in this article. However, the know-how and experience of the user in making the selection should not be underestimated in this context. Since the performance and the reliability of semiconductor devices is strongly dependent on the service conditions and the physical design of the system (electric, thermal, mechanical), users will, whenever possible, make use of platforms where they have the most extensive experience.

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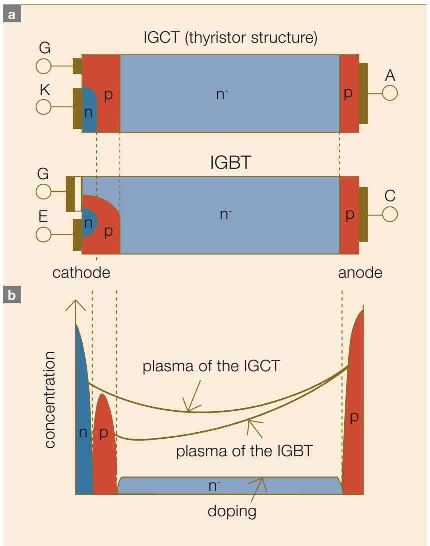
Design objectives of the IGBT and the IGCT

Introduction

The doping of the silicon body of power semiconductors, ie, the conductivity of the substrate, must be reduced continually as the targeted breakdown voltage increases. As a result, components that rely during on-state on their substrate conductivity (so-called unipolar or majority carrier components, eg, the power MOSFET and the Schottky diode), exhibit at blocking capabilities exceeding 200–1000 V an on-state voltage drop that is too high for economic operation (the limit depends on the type of component and application). Consequently, silicon power semiconductors above 600 V are usually designed as conductivity-modulating (plasma) devices. The interior of such a device is flooded with a large number of positive and negative charge carriers (holes and electrons) during the conductive phase, lending the device a strongly enhanced conductivity with respect to the substrate. Such components are frequently termed "bipolar components" in the power semiconductor industry, although the use of this expression is not strictly correct from the technical point-of-

1 Component structures and doping zones of the IGCT and the IGBT a and qualitative comparison of the plasma distributions in the conductive state b



Semiconductors have become ubuiquitous in a wide range of applications, including power transmission a traction applications b and industrial drives c

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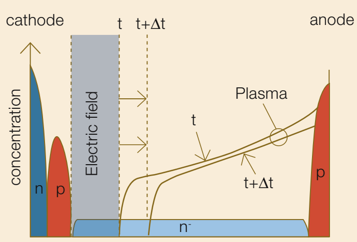
view (this will be discussed further in part two of this article, to be published in the next edition of ABB Review).

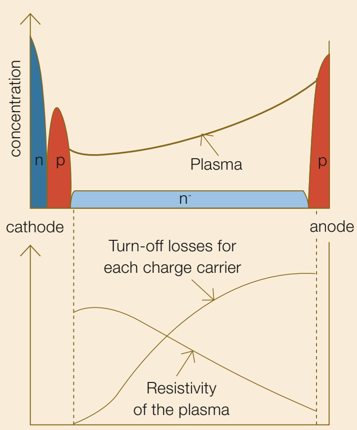
During device turn-off, in order to recover blocking capacity, the plasma must be removed. This is accomplished by the recovery voltage, whereby an electrical field builds up, driving the negatively charged electrons to the anode and the positively charged holes to the cathode. As a result, current still flows as the voltage increases, ie, losses arise in the form of heat.

2 Inside an IGBT/IGCT during turn-off



An electric field is built up at the pn-junction on the cathode side and sweeps out the plasma. The nearer the charge carriers are to the cathode, the lower the voltage at which they are removed.

3 Geometric dependency of the plasma conductivity and turn-off losses inside the IGBT.



By comparison with 1, it becomes evident that the IGCT has a better plasma distribution.

Optimization of forward-power losses and turn-off losses by adjustment of the plasma distribution

The common design objective of high-voltage power semiconductor switches (whose best-known types are the IGBT and the IGCT) is the optimization of the combination of conduction losses and turn-off losses. In practical terms, this means that the semiconductor should have the lowest possible voltage drop in the on-phase (ie, a dense plasma should build up) without high turn-off losses arising when the excess charge is removed.

> The minimum thickness of a power semiconductor is predetermined by the desired blocking capacity and the breakdown field strength of the silicon.

1 shows the typical plasma distribution of IGBT and IGCT components. The main difference between them is that the IGCT builds up a dense plasma near the cathode, while the excess charge density in the IGBT drops relatively sharply from the anode to the cathode. The reasons for this are explained later in this section.

The importance of this charge carrier distribution is illustrated by considering the turn-off process: during switching off, the component regains its blocking capability through the build-up of an electric field from the pn-junction on the cathode side into the n^- zone 2. The recovery voltage sweeps out the plasma from the cathode to the anode. The charge carriers near the cathode are removed at a low voltage, and therefore, generate low turn-off losses, whereas the carriers near the anode flow out of the device at a high voltage, causing high losses.

This consideration makes clear why the plasma distribution of the thyristor is also generally regarded as a desirable ideal for the IGBT: the voltage drop in the conducting mode is determined mainly by the region of the lowest plasma density, which explains why an IGBT has higher conduction losses than a comparable thyristor. Therefore, if the plasma of the IGBT at the cathode can be increased successfully, the on-state losses can be reduced without considerably higher turn-off losses arising 3.

The primary cause for the low plasma density at the cathode of the IGBT is a weak “carrier storage effect”: the holes originally injected by the anode can enter the p-zone on the cathode side relatively easily, and from there, leave the component via the (required) contacting of the emitter to the p-zone without hindrance (see 1). In contrast to this, due to the non-existent contact to the p-zone, the thyristor has a pronounced carrier storage effect. The potential barrier of the pn-junction at the cathode contact prevents holes from entering the n-zone.

Two different concepts for the improvement of the plasma distribution in the IGBT have been proposed: one very effective option consists in the application of the trench principle [2], in which the holes are prevented from “finding” the p-zone by a skillfully designed geometric cathode structure. As an alternative, a weak potential barrier can be generated by means of a doping layer in front of the p-zone to keep the holes away from this zone [3]. A detailed explanation of these methods can be found in literature, eg [4].

Modern IGBTs, which are designed in accordance with one of these basic approaches, have correlations between conduction losses and breaking losses, which come very close to those of IGCTs. Although future improvements are possible, the latest designs (eg, the SPT+ from ABB [8]) have already been optimized so well that no great steps can be expected.

Lower losses through a reduction in the thickness

A reduction in the thickness of the components is the most effective parameter for reducing total losses. The reasons for this are simple: the resistance of the device in the conducting state decreases as a result of the lower thickness, and at the same time, there is less plasma in the device during the conductive phase, thus resulting in lower losses during turn-off.

The minimum thickness of a power semiconductor is predetermined by the desired blocking capacity and the breakdown field strength of the silicon. 4 shows two different aggressively designed devices with the same blocking capability.

It is apparent that the maximum blocking capacity for a given element thickness is obtained by means of a field strength distribution being as close as possible to the breakdown limit over the entire thickness.

The gradient of the field strength dE/dx 1 can be adjusted by the doping concentration in the silicon.

In practice, there are limits to the aggressive design of the field strength distribution, and therefore, to the minimum thickness of the devices:
1. If the doping concentration in the semiconductor is set at a very low level, the electric field extends over the entire thickness of the component, even at low voltage. The entire plasma can therefore be removed at a low voltage during turn-off. Although this is theoretically desirable (since turn-off losses decrease as a result), it also causes the current to break off abruptly on reaching a certain voltage (the point at which the device is cleared of plasma). This effect is referred to as snap-off. The high *di/dt* generates overvoltages in stray inductances and can initiate undesirable oscillations in combination with capacitances. 5 shows examples of a desirable ("soft") and a bad ("hard") turn-off waveform.

The stray inductance makes a greater difference in power semiconductors for high currents than in small discrete components. Firstly, the leakage inductance is higher on account of the physically larger assemblies, and secondly, the semiconductor experiences a much higher stress through a given stray inductance. To illustrate this, a hypothetical discrete 50 A IGBT chip is compared with a 1000 A module, the latter being assembled from 20 discrete 50 A chips. The stray inductance in the circuit with the discrete chip is assumed to be at 20 nH, and that of the module, 100 nH. The calculation of the stored inductive energy ($E_{ind} = LI^2/2$) shows that, at rated current, each chip of the module experiences an inductive load 100 times greater than the discrete chip (2.5 mJ, compared to 25 μJ). This shows that components for high power outputs have to be dimensioned for a much softer switching behavior than chips for small assemblies on printed circuit boards. In practical terms, engineers must make the components thicker than would be theoretically necessary. This naturally implies extra losses, as is shown in the example in 5.

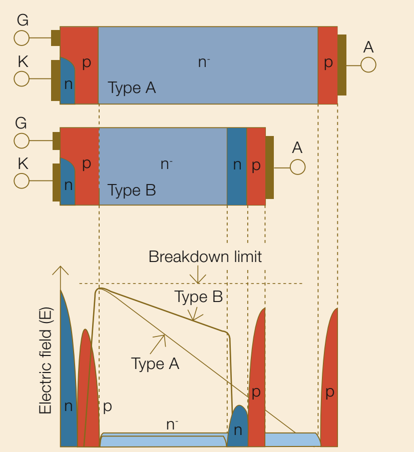
The semiconductor should have the lowest possible voltage drop in the on-phase without high turn-off losses arising when the excess charge is removed.

In addition to the design-in of a certain extra thickness, the snap-off can be reduced by a skilful arrangement of dopings on the anode side of the component. Manufacturers use different names for concepts that are similar (at least in their action), eg, SPT (Soft Punch Through) [5] or FS (Field Stop) [6].

It should also be pointed out that it is more important than ever for users to restrict the stray inductances in their systems as much as possible, on account of the more offensive design of modern components.

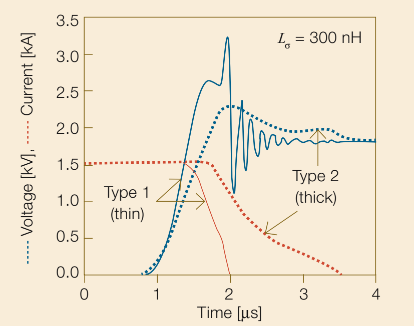
2. The second limitation is attributable to cosmic radiation. If a high-energy nuclear particle from space, eg, a proton, strikes a silicon nucleus, the released energy generates a very high quantity of electrons and holes. If the device is in blocking mode at high voltage, these carriers are multiplied in avalanche-like mode due to the high field strength in the component. This causes a highly localized breakdown of the component, which may result in the destruction of the device. Manufacturers have, therefore, developed dimensioning rules, according to which components must be designed with respect to thickness and field strength distribution to ensure that the probability of destruction by cosmic radiation is restricted to an acceptable degree. This is specified at approximately 1–3 FIT (Failures in time) per cm² of component surface area. This corresponds to 1–3 failures per billion operating hours and cm². Proof of the failure rate of new components is

4 Different vertical designs of a power semiconductor, through the example of a thyristor-structure.



The voltage across the device is proportional to the area under the electric field. The mid-section (n⁻) is usually referred to as the drift zone in unipolar components and the n⁻ base in bipolar components.

5 Effect of snap-off during turn-off of a large 3.3 kV/1500 A IGBT module under the influence of a high stray inductance.



The "Type 1" IGBT is significantly thinner than the "Type 2" (340, resp. 380 μm, see also 6).

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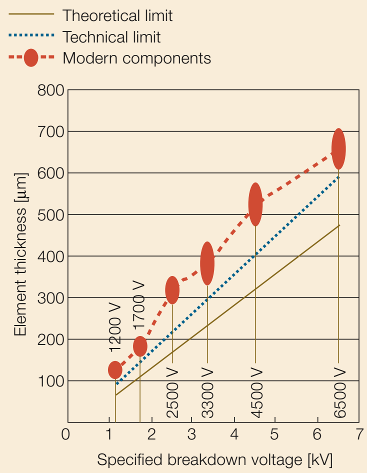
nowadays usually obtained by proton or neutron bombardment in accelerators, which simulates the effect of natural cosmic radiation with sufficient accuracy.

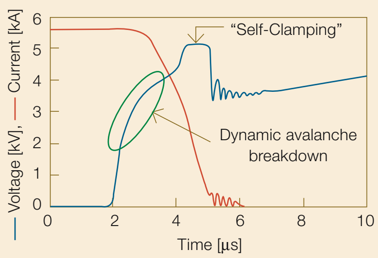
High-voltage components of the latest generation are already close to the practical limits with regard to thickness. 6 illustrates the position of the latest components in relation to the calculated theoretical limits. Although a further reduction in thickness below the current level would be theoretically possible, it would be at the expense of a more severe snap-off or significantly higher turn-off losses. At present, it is questionable whether users will accept such devices.

6 Comparison between the calculated theoretical minimum thickness of the component



Assuming no extra thickness, and breakdown occurring at room temperature – approximate technical minimum thicknesses (practically achievable values, without consideration of electrical bahavior), and the thicknesses of modern components (the red areas represent the different values of individual manufacturers).

7 Turn-off of an IGCT with an active area of 40 cm² under SOA conditions, without a protection (snubber) circuit.



The switching power density is more than 500 kW/cm². Avalanche breakdown first reduces the steepness of the voltage ramp, and then limits the overvoltage.

An IGBT can be controlled by the gate voltage during turn-on/turn-off, whereas the switching transients in the IGCT are governed only by the internal dynamics of the component.

Increase in turn-off capability (Safe Operating Area, SOA)

The useful output current of a power semiconductor is restricted both by the capability of the housing technology to dissipate power losses, and by the maximum current that can be safely controlled during turn-off. Part two of this article will deal with the housing technology in detail, whereas SOA aspects are covered here.

It was generally assumed in the 1990ies that the occurrence of a dynamic avalanche breakdown was an unsafe operating condition. Such a breakdown occurs if the power density (which is calculated as the current that can be turned off multiplied by the DC link voltage) reaches approximately 150 kW/cm².

From theoretical considerations, the conclusion that dynamic avalanche breakdown is unsafe cannot be maintained. On the contrary: the effect is self-limiting [4] and can, therefore, be considered harmless. Consequently, it makes sense for manufacturers to raise the destruction limit of the components to the highest possible level. Power densities of more than 1 mW/cm² have already been successfully demonstrated in all modern components (IGCT, IGBT and diodes). An example, showing that large components can safely control very high power outputs, is shown in 7.

Today, due to thermal limitations, it is hardly possible to operate components at more than approximately 100 kW/cm² RMS power. Therefore, the question is legitimate whether an SOA margin much beyond this limit is of practical importance. The answer is affirmative for the following reasons:

- In large-area power semiconductor devices, it cannot be assumed that the current flows uniformly through the semiconductor. Irregularities in the cooling, different coupling inductances and slightly varying semiconductor properties can lead to substantial temperature differences and inhomogenous electrical loads, the latter particularly during turn-on and off [7]. Substantial power margins can save components from failing under such conditions. Several large equipment manufacturers were able prove a causal connection between the power margins and the field reliability, even when the components were nominally operated within the specification limits.
- A high tolerance for dynamic avalanche breakdown prevents overvoltages beyond the specified nominal voltages (see 7).
- A high SOA power margin can be used to cope with rarely occurring overload conditions (eg, fault conditions). The high dissipated energies during such events can most often be tolerated, since a turn-off usually occurs only once.

Increase in the maximum junction temperature

The extension of the temperature limits is closely connected with the properties of the housing technology and is, therefore, discussed in more detail in part two of this article.

The IGCT and IGBT in comaparison

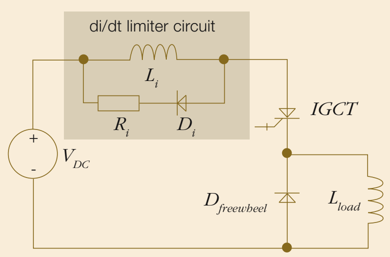
The lower driver power of the IGBT is frequently cited as a key advantage of this device as compared to the IGCT. The difference in driver power is attributable to the fact that the IGBT is controlled by a MOS input, whereas the IGCT is a current-controlled device. In practice, however, the differing power requirement is crucial only in a small number of applications, since the IGCT's driver power is low enough that it can usually be provided at an acceptable effort.

On the other hand, the most important application-related difference between an IGCT and an IGBT lies in the fact that the IGBT can be controlled by the gate voltage during turn-on/turn-off, whereas the switching transients in the IGCT are governed only by the internal dynamics of the component. This difference, which may not seem significant at first glance, has far-reaching consequences for the circuit topology and for applications where parallel and/or series connection is required.

Differences in circuit topology

On account of the IGCT's internal thyristor structure, the device can build up current very quickly during turn-on, ie, it produces a steep *di/dt*, which generates an unacceptably high stress in auxiliary diodes. Because of this, the *di/dt* in IGCT circuits must always be restrained by a limiter circuit. In voltage source inverters, this usually consists of a small inductance in series with the switch 8. Although this increases the complexity of the circuit, it has several beneficial characteristics:

8 IGCT phase test circuit



The current gradient permitted by the inductor L_i during turn-on reaches a maximum di/dt_{max} equal to UDC/L_i. The elements D_i and R_i form a freewheeling circuit for L_i, thus limiting the overvoltage during the turn-off of the IGCT.

1. In voltage source inverters without external *di/dt* limitation (typical IGBT circuits are examples of this), the *di/dt* must be limited by controlling the switching device itself. This causes substantial turn-on losses. In inverters with high voltage ratings, the combination of turn-on losses of the switch and recovery losses of the diode make up 40 to 60 percent of the total inverter losses, depending on the switching frequency. Significantly lower turn-on losses occur in a silicon switch upon the use of a passive *di/dt* limiter, relieving the device of thermal load and, by consequence, enabling in principle, a higher output power for the inverter. However, it should be noted that the losses occur nevertheless, since they are merely transferred to the freewheeling circuit of the *di/dt* limiter (they occur in the resistance R_i and the diode D_i of 8). The interpretation that an inverter with a *di/dt* limiter circuit always generates lower total losses than a conventional IGBT inverter is therefore incorrect.

> In large-area power semiconductor devices, it cannot be assumed that the current flows uniformly through the semiconductor.

2. The second benefit is that, as a result of passive *di/dt* limitation, the current can increase only relatively slowly when a fault occurs (eg, a short-circuit in the inverter bridge or in the load). Hence, there are two effective strategies available for coping with such events: (a) If the fault is detected in time, it is possible to initiate a normal turn-off. (b) The energy stored in the DC link can be discharged by firing all switches, dispersing it evenly in all semiconductors (the inductance L_i can be dimensioned to mainatin the short-circuit current in the safe area).

Parallel and series connection

As the switching transients of an IGCT cannot be externally influenced, the gate control circuit must drive the whole device absolutely simultaneously to guarantee a homogeneous and therefore safe turn-off process. The tolerable time difference is less than 100 ns, which means that IGCTs can only be operated in parallel or series with a relatively large effort. In both cases, passive or active snubber circuits must compensate for even the smallest differences in switching times between IGCTs (caused by control timing errors and local conditions, eg, temperature). If this cannot be achieved, individual IGCT devices can be overloaded. The cost and complexity of such snubber circuits is, in most cases, too high when compared to the IGBT alternative.
To conclude, IGCTs are best used in applications in which each switching function is carried out by a single device.

In the second part of this article on high-power semiconductors, which will be published in ABB Review 1/2007, aspects of the housing design are discussed. The article will also look at the potential of "wide-band-gap" materials.

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