# High-power active devices

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**Abstract**
Very high-power (HP) electronics represents a small part of the electronics market. In semiconductor terms, HP represents a world device market of 600 million euros out of a total 200 billion euros for all semiconductors—a mere 0.3 per cent. At the multi-megawatt spectral end, the numbers are even smaller, so that it is quite common for electronics engineers to be unaware of developments in Very High Power (VHP). In this presentation we discuss the categories of VHP active devices, the basic topologies in which they operate, and the trend towards higher voltage and current. New press-pack technologies are introduced and the salient differences between Insulated Gate Bipolar Transistors (IGBTs) and Integrated Gate Commutated Thyristors (IGCTs) are compared. Finally, recent developments in turn-off ratings for both these devices are presented.

## 1 Introduction

High-power active devices can be divided into four basic categories:

– Thyristors can be turned *on* by a gate signal but can only be turned *off* by reversal of the anode current (external commutation)

– Gate Turn-Off Thyristors (GTOs) can be turned *on* and *off* by the gate signal but require a large capacitor (snubber) across the device to limit d*v*/d*t*

– Transistors (transitional resistors) can be turned *on* and *off* by the gate (or base) signal but have high conduction losses (it is an amplifier, not a switch)

– Integrated Gate Commutated Thyristors (IGCTs) can be turned *on* and *off* by the gate signal, have low conduction loss and require no dv/dt snubber.

Of particular importance in Power Electronics (PE) today, are the Turn-off Devices (ToDs) because of their ability to actively interrupt current without external commutation. These fall into two basic categories as shown in Table 1.

**Table 1:** Turn-off devices

| **Thyristors** | | **Transistors** |
|---|---|---|
| GTO | (Gate Turn-Off thyristor) | Bipolar transistor |
| MCT | (MOS-Controlled Thyristor) | Darlington transistor |
| FCT | (Field-Controlled Thyristor) | MOSFET |
| MTO | (MOS Turn-Off thyristor) | **IGBT (Insulated Gate Bipolar Transistor)[a)]** |
| EST | (Emitter-Switched Thyristor) | |
| IGTT | (Insulated Gate Turn-off Thyristor) | |
| IGT | (Insulated Gate Thyristor) | |
| **IGCT** | **(Integrated Gate-Commutated Thyristor)[a)]** | |

[a)] The IGCT and the IGBT are shown in bold as these are practical, industrially produced ToDs used in very high power conversion and are the main subject of this presentation.

ToDs allow all the basic functions of power electronics to be realized; these include

- inverters
  voltage source (VSI)
  current source (CSI)
- choppers
  buck regulators
  boost regulators
- active rectifiers.

All these functions require complementary (fast) diodes in anti-parallel (for VSIs) or in series (for VSIs) or in a separate function (for choppers).

Figure 1 shows the grouping of high-power semiconductors in which IGBTs and IGCTs are shown in bold to highlight the fact that these are today the only devices used industrially in high-power conversion.

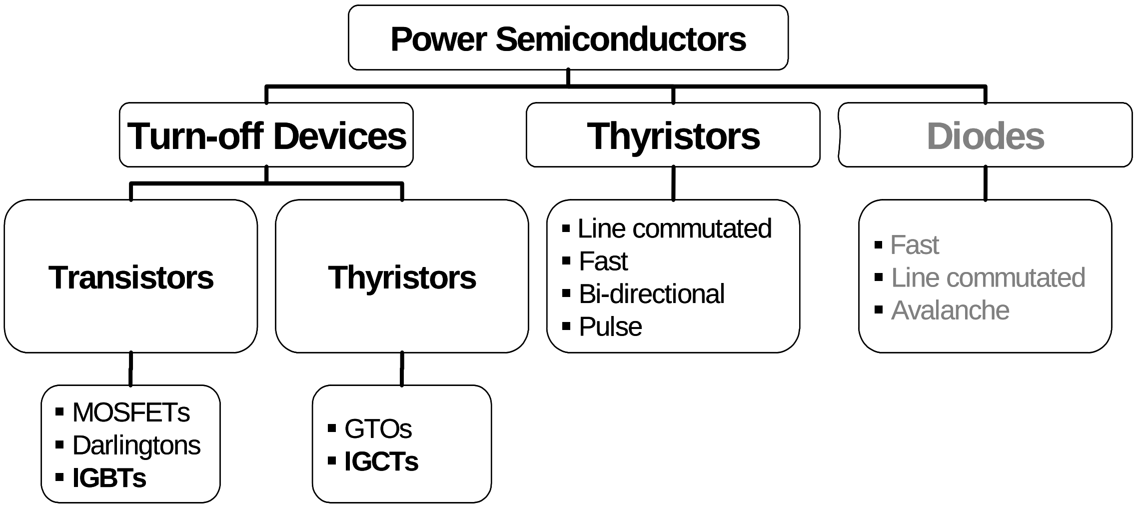



**Fig. 1:** Grouping of power semiconductors leading to today's only components for high-power conversion

Though the thyristor has long dominated power conversion because of its high-power capability, its inability to be *turned off* by simple gate-control, has led to its reduced use in power conversion. The thyristor continues to be used for DC motor drives, Static VAR compensation (power factor correction with inductors and capacitors), HVDC transmission (the interconnection of two AC networks through controlled DC bridges) and phase-controlled rectifiers. However, even in these applications, the trend is away from techniques which deform the line voltage (*harmonic distortion*) as illustrated by the 'phase control' waveform of Fig. 2(a).

Anti-parallel connected thyristors can, however, be used as static switches without distorting the line voltage as shown in Fig. 2(b). The Bi-Directionally Controlled Thyristor (BCT) [1] is a suitable device for such applications which include

- transformer tap changers,
- load transfer switches,
- line interrupters.

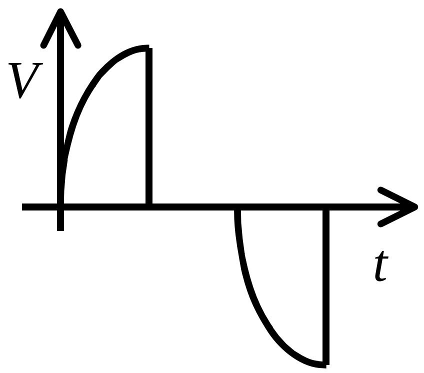



**Fig. 2(a):** Phase control of AC line voltage causes harmonic distortion

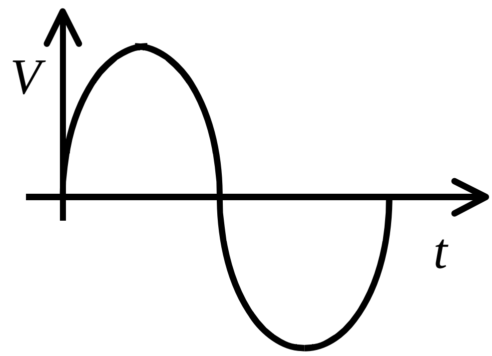



**Fig. 2(b):** Zero-voltage turn-on is used for AC switching with thyristors and causes no distortion

## 2 The growth of high-power electronics

The use of high-power turn-off devices has grown rapidly in the last 20 years. This is the result of two synergetic trends:

– the greater need for PE

– the availability of new semiconductor technologies.

The need itself has had four components:

– improved process control, e.g., for steel production

– improved power quality, e.g., for semiconductor production

– energy saving, e.g., efficient motor control

– energy trading, e.g., redirection of power flow in response to spot-market rates.

Figure 3 shows the growth of energy consumption in equivalent millions of barrels of oil per day, as well as that part of the energy consumed as electricity. The growing percentage of energy consumed as electricity is an indication for the growth of electronics through which this power increasingly flows. It shows that by 2020

– energy consumption will double

– electrification of end-consumption will quintuple.

Today, only 15% of electricity flows via electronics, and Medium Voltage (MV) conversion has only been economically possible in the last 10 years following the arrival of ToDs with high current and high voltage ratings (thousands of volts and amperes). The consequence is that power conversion at MV levels is set to grow at a faster rate than at low voltage levels.

(The low-voltage network covers the range from 110 V to 690 V. MOSFETs and low-voltage IGBTs are typically used in this area and have been for over 20 years. The MV network ranges from 3.3 kV and goes to 13.8 kV and beyond. For this network, HV semiconductors are needed with ratings from 3.3 to 6.5 and perhaps 10 kV.)

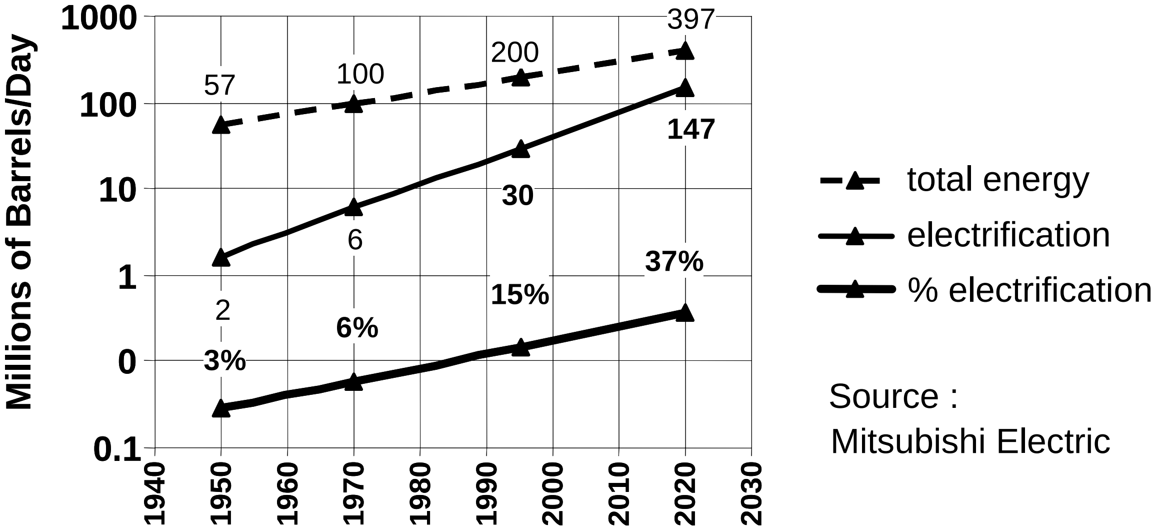



**Fig. 3:** World energy consumption drives the growing need for power electronics

## 3 Self-commutated inverters

Inverters are the basis of today's power conversions and they exist in many topologies. As explained in the introduction, only two semiconductors are candidates for modern HP conversion and one comes from the *transistor* family (the IGBT) while the other comes from the *thyristor* family (the IGCT). Two VSI topologies will be used to illustrate the fundamental differences between these two device types. In Figs. 4(a) and 4(b), an IGBT and an IGCT inverter are shown. Since the IGBT is a *transistor*, it can behave as an *amplifier* during its transition from *off* to *on*. In so doing, it can control the speed at which the current in the free-wheel diode is forced to zero (inevitably becoming negative in the process). This commutation speed is critical, as an excessive speed will cause the diodes to fail while a slow commutation will generate losses ('turn-on loss'). Figure 4(a) illustrates that no inductance is needed for this commutation thanks to the amplifier-like properties of the IGBTs. Figure 4(b), by contrast, shows that the IGCT, being a *thyristor* and behaving like a *switch*, allows no commutation control and hence requires an external inductance to avoid diode recovery failure.

The allowable rate of commutation is determined by the diode's 'ruggedness' since a fast commutation leads to a reverse recovery current ($I_{RR}$ in Fig. 5) which at high DC voltage results in high instantaneous power which could lead to diode failure. In the case of Fig. 4(a), energy is dissipated in the IGBT whereas in the case of Fig. 4(b), this energy is stored in the inductance $L$ and is subsequently dissipated in resistance $R$.

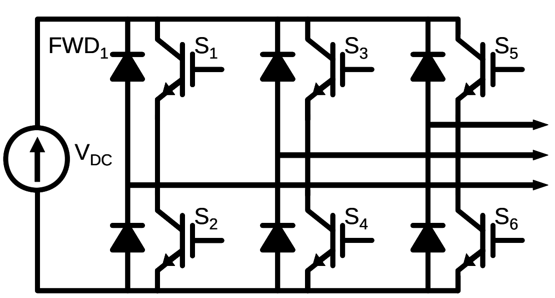



**Fig. 4(a):** IGBT inverter

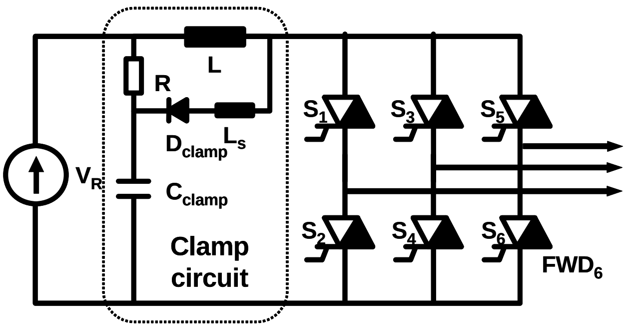
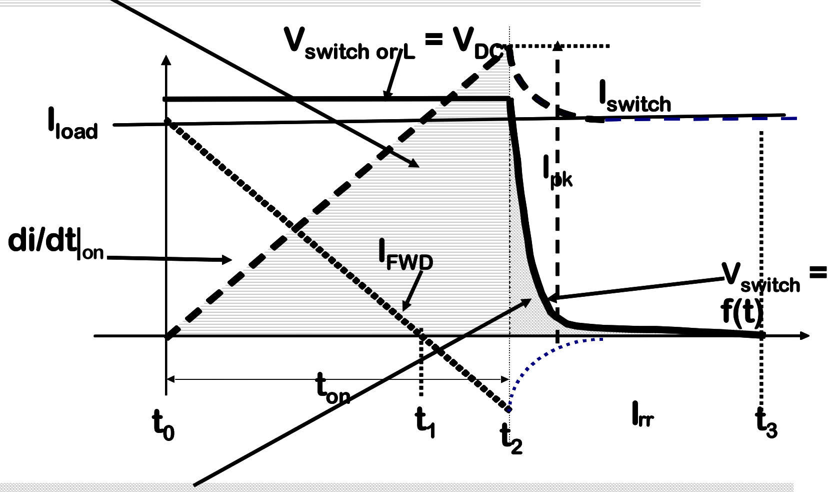



**Fig. 4(b):** IGCT inverter

This energy is shown in Fig. 5 as '$E_{\text{ON-CIRCUIT}}$' because it is a turn-on loss determined not by the active switch but by external circuit conditions (dictated by the diode characteristics). In the case of the transistor, a second loss component is generated by the slowness of the device itself and shown as $E_{\text{ON-DEVICE}}$. In practice, the total turn-on losses are the same for Figs. 4(a) and 4(b), but for 4(a) they are dissipated in the semiconductor while for 4(b) they are in the resistance *R* [2].

$$E_{on-circuit} = (t_2 - t_0) \bullet V_{dc} \bullet (I_{load} + I_{rr})/2 \ldots.(1)$$




$$E_{on-device} \approx I_{load} \bullet \int_{t_2}^{t_3} V_{switch}(t).dt \ldots\ldots\ldots\ldots(2)$$

**Fig. 5:** Turn-on waveforms for IGBTs and IGCTs showing the circuit and device-specific losses

## 4 Device features

### 4.1 Insulated Gate Bipolar Transistors (IGBTs)

IGBTs have the following salient features:

- transistor with insulated gate
- allows d*v*/d*t* and d*i*/d*t* control via gate signal (losses)
- high on-state voltage (transistor)
- high turn-on losses (no snubber)
- low gate power requirements (voltage control)
- no passives required (independent d*v*/d*t* and d*i*/d*t* control)
- produced mainly as isolated modules but also as press-packs.

IGBTs are commonly encapsulated as isolated modules allowing several modules to be placed on one heat-sink and presenting all the electrical connections in one plane for simple connection. The chips are soldered on the collector side to the isolating (ceramic) substrate and bonded by aluminium wires on the emitter side. These wires will fuse if a chip fails, ultimately causing the whole module to fail open-circuit (sometimes explosively) which makes modules unsuitable for series connection with redundant devices. For such applications, press-packs are preferred whereby the chips are pressure-contacted from both sides and no bond-wires are used. In the case of very long series strings of press-packs, involving many devices and heat-sinks, special press-packs have been developed using individual spring-contacts to ensure a correct and uniform pressure on each individual chip [3]. Both housing technologies are shown in Figs. 6(a) and 6(b). Figure 6(c) shows the sectional view of an advanced press-pack design using individually sprung chips allowing uniform chip pressure even in long stacks, while Fig. 6(d) illustrates a conventional IGBT press-pack with direct chip contacts requiring extremely accurate stack assembly.

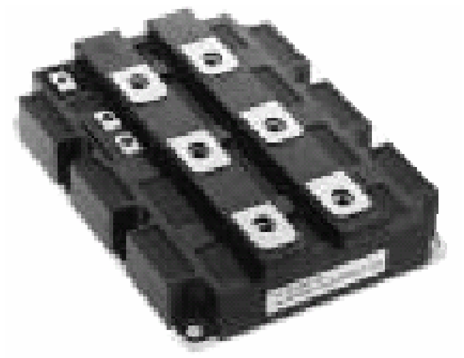


**Fig. 6(a):** Standard isolated IGBT module

**Fig. 6(b):** IGCT press-pack (ABB StakPak™)

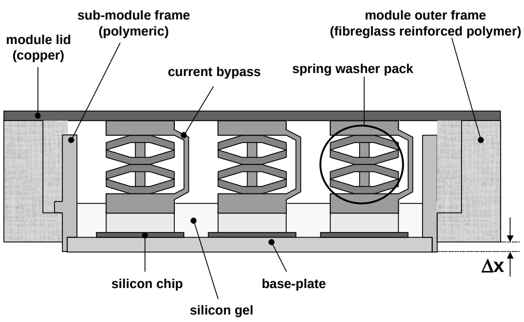



**Fig. 6(c):** Sectional view of ABB StakPak™ showing individual spring contacts

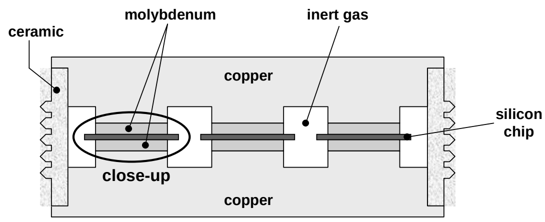



**Fig. 6(d):** Sectional view of conventional IGBT press-pack

Figure 7 shows a long IGBT press-pack stack as used in an HVDC VSI converter. Here, 20 devices and 21 heatsinks are pressed together. The picture illustrates the difficulty of achieving uniform pressure on each chip in view of the cumulative inhomogeneities resulting from mechanical tolerances.

Using conventional IGBT press-packs in long stacks would require very tight mechanical tolerances to ensure identical force on each chip in each housing:

- on assembly
- over time
- with temperature cycling
- with shock and vibration.

**Fig. 7:** An HVDC valve for a VSI. Each valve contains 20 IGBT press-packs and many valves may be series connected for a typical high-voltage DC transmission system.

### 4.2 Integrated Gate-Commutated Thyristors (IGCTs)

IGCTs have the following salient features:

– thyristor with integrated gate unit

– low on-state voltage (thyristor)

– low turn-on losses (turn-on snubber)

– no explosive failures [fault current limitation by circuit – see Fig. 4(b)]

– produced as press-packs only.

IGCTs are the newest of the high-power devices and are less well known since they are recent and used at power levels of about 300 kW and upwards to about 100 MW (with series connection) [4]. Figure 8 illustrates the principle of operation. In conduction, the device is a thyristor and the gate-unit a forward-biasing current source. At turn-off, the gate-unit becomes a reverse-biasing voltage source, which quickly commutates the entire current from the cathode to the gate thus turning the device into a pnp transistor with an open base. The resulting waveform can be seen in Fig. 9 and is similar to that of an IGBT turn-off.

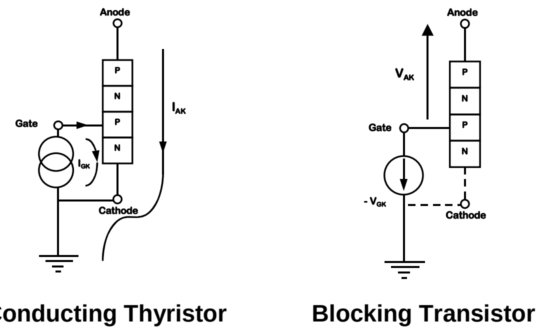



**Fig. 8:** Principle of operation of Integrated Gate-Commutated Thyristor (IGCT)

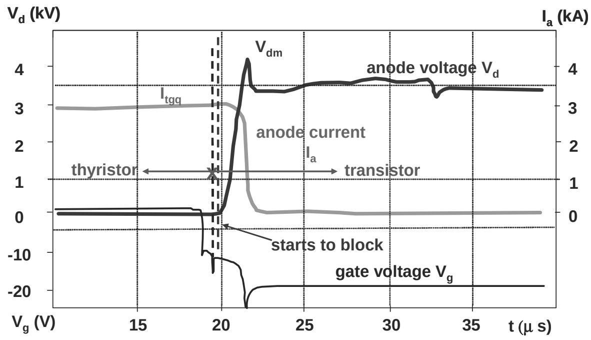



**Fig. 9:** Turn-off waveform of an IGCT

Figure 10 shows a typical 91 mm IGCT and Fig. 11 shows the internal construction of the GCT itself.

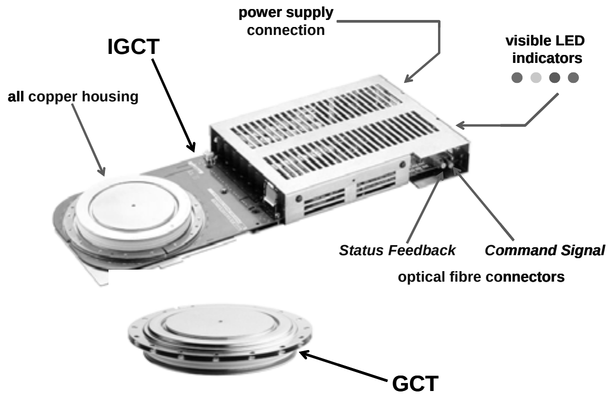



**Fig. 10:** Integrated Gate-Commutated Thyristor (IGCT) showing the semiconductor part (GCT)

**Fig. 11:** Open GCT showing a reverse-conducting wafer (diode in the middle)

As already mentioned, the IGCT has no turn-on speed control and therefore requires an external d*i*/d*t* controlling inductance. It also has no direct d*v*/d*t* control at turn-off although this can be adjusted by ‘life-time control’ (adjustment of the carrier lifetime, typically by irradiation). Figure 12 shows the effect of three different levels of lifetime control on three, otherwise identical, IGCTs and shows the different rates of voltage rise. Low d*v*/d*t* produces less ElectroMagnetic Interference (EMI) but inevitably generates higher losses [5].

As with the IGBT, the IGCT is inherently fast switching as illustrated by Fig. 13 which shows 25 kHz burst-mode operation. Its frequency limitation is determined principally by its losses (akin to the IGBT) such that the burst of Fig. 13 lasts only for 10 pulses at full rating.

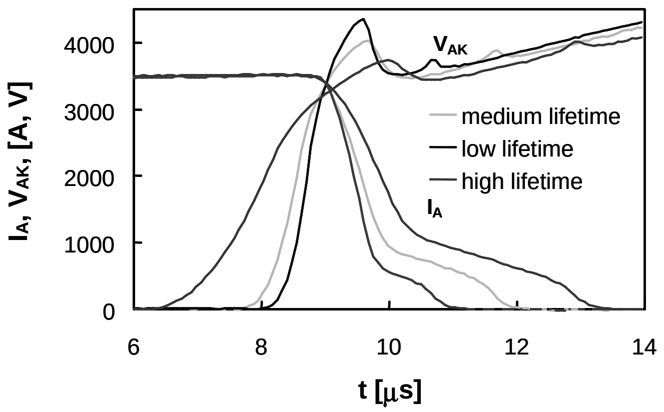



**Fig. 12:** Effect of different irradiation levels on turn-off d*v*/d*t*

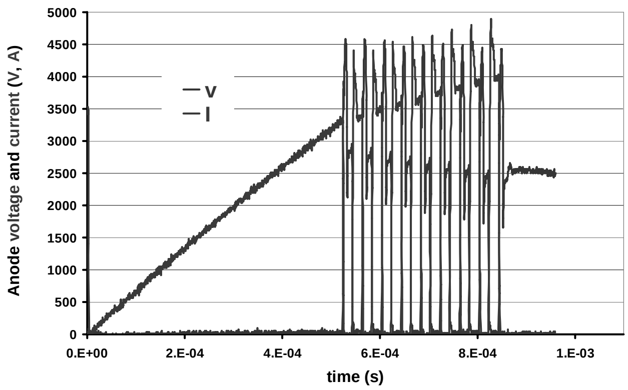



**Fig. 13:** Burst mode operation of 4.5 kV/4 kA IGCT $V_{\mathrm{DC\ START}}$ = 3.5 kV, $V_{\mathrm{DM\ PEAK}}$ = 4.5 kV, $I_{\mathrm{TGQ\ PEAK}}$ = 4 kA, $T_{\mathrm{J\ START}}$ = 25°C, $a$ = 0.5

## 5 Device trends

### 5.1 IGBTs

The main development thrust today for IGBTs is

– higher voltages (up to 6.5 kV)
– higher *Safe Operating Area* (SOA)
– softer (controlled) switching characteristics
– lower conduction losses (either with *trench* or *enhanced planar* technology)
– over-voltage self-protection (as for existing short-circuit protection).

Figures 14 and 15 show the smooth switching characteristics under nominal conditions for 3.3 kV IGBT and diode chips. These ‘soft’ switching waveforms display no abrupt changes which avoids voltage spikes and EMI even in inductive environments.

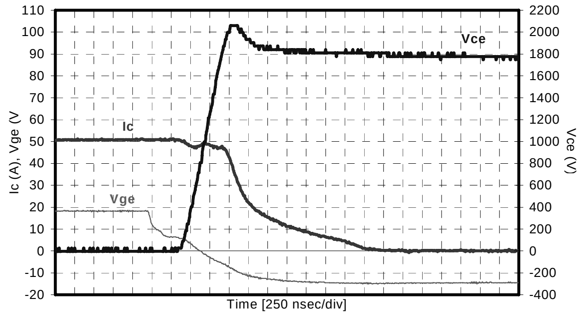



**Fig. 14:** IGBT Turn-off: $V_{CC}$ = 1800 V, $I_C$ = 50 A, $R_{GOFF}$ = 33 Ω, $L_S$ = 2.4 mH, $T_J$ = 125°C

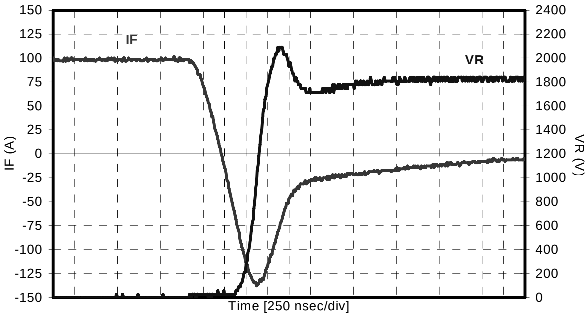



**Fig. 15:** Diode Turn-off: $V_{CC}$ = 1800 V, $I_C$ = 50 A, $R_{GOFF}$ = 33 Ω, $L_S$ = 2.4 mH, $T_J$ = 125°C

Figure 16 shows the very high SOA achieved by the latest generation of Soft Punch Through (SPT) planar IGBTs. The device (a 3.3 kV/1.2 kA module) is switched with a low gate resistance of only 1.5 Ω, a high DC link voltage of 2.6 kV and a high stray inductance of 280 nH. Furthermore, a collector current of 5kA is switched off—over four times the nominal current. Under these server conditions, the collector voltage initially rises very quickly; the electric field grows faster than the depletion layer resulting in a high electric field causing the d*v*/d*t* to slow down as the device undergoes dynamic avalanche. This normally causes failure; however, this new generation of IGBT not only sustains this condition but (with the combination of high current, voltage and inductance which ensures plenty of stored energy in the stray inductance) drives the device into a ‘quasi-static’ avalanche at 4 kV. The device has self-protected itself against an over-voltage without the use of snubbers and with neither active nor passive clamps. Thus Fig. 16 illustrates the high SOA as well as the ability of new HV IGBTs to self-protect against over-voltage (as they already do in current—see Fig. 17) [6].

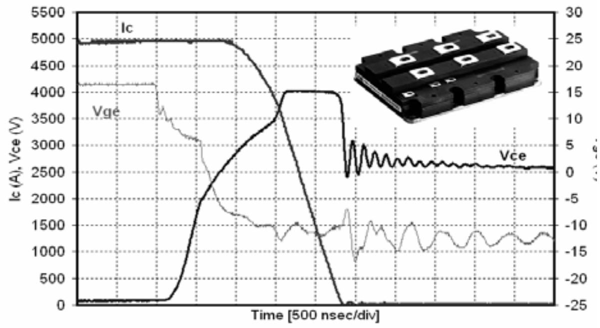



**Fig. 16:** 3.3 kV/1200 A IGBT module during turn-off (24 IGBTs) $V_{CC}$ = 2600 V, $I_C$ = 5000 A, $R_G$ = 1.5 Ω, $L_S$ = 280 nH, $T_J$ = 125°C

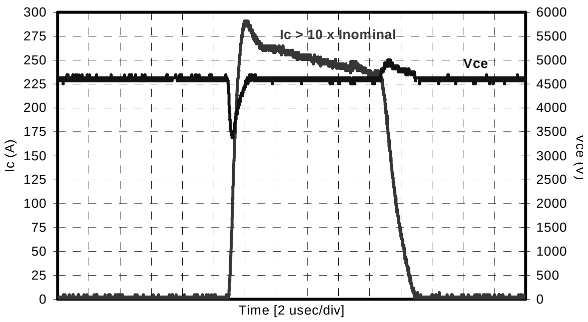



**Fig.17:** 6.5 kV/25 A IGBT SCSOA during short circuit $V_{CC}$ = 4500 V, $I_{CPEAK}$ = 290 A, $V_{GE}$ = 18 V, $L_S$ = 2.4 mH, $T_J$ = 25°C

## 5.2 IGCTs

The main development thrust today for IGCTs is

– higher SOA

– higher voltage

– higher junction temperature.

Figure 18 shows two IGCT wafers: a 91 mm asymmetric device and a 38 mm reverse-conducting device.

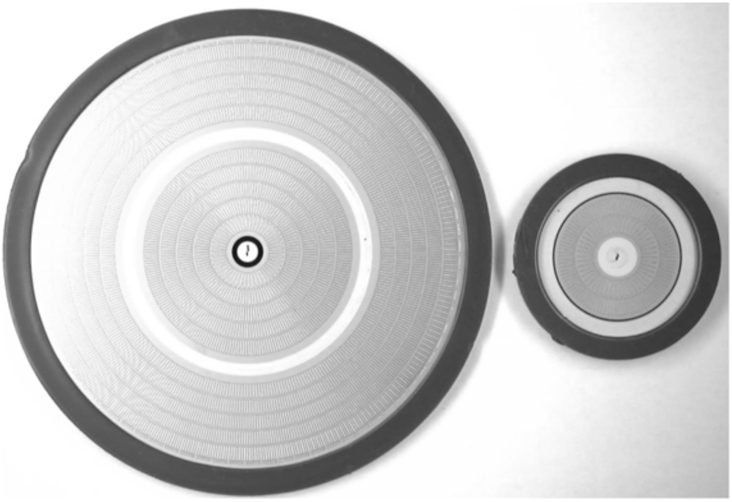


**Fig. 18:** A 91 mm asymmetric GCT wafer compared with a 38 mm reverse-conducting wafer

Today's IGCTs operate at an SOA of about 200–250 kW/cm$^2$ (the larger the wafer, the lower the average power density). The next generation will operate at 400 kW/cm$^2$ for large devices and perhaps as much as 1 MW/cm$^2$ for small ones. Figure 19 shows a developmental 4.5 kV IGCT (derived from the 4 kA device of Figs. 10 and 11 using recent SOA enhancing techniques) switching 6.5 kA instead of the usual 4 kA against 2.8 kV. Such improved devices will be in volume production within two years [7].

Figure 20 shows an experimental 10 kV IGCT operating at 250 kW/cm$^2$. SOA enhancing techniques can also be applied to this device but its future will depend more on diode developments at this voltage level [8].

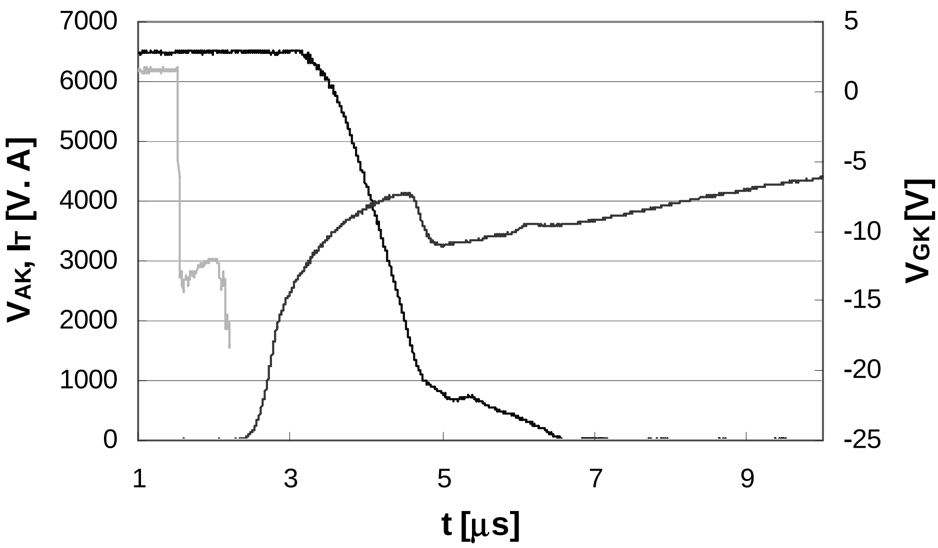



**Fig. 19:** *Developmental* 91 mm/4.5 kV IGCT with improved GU and silicon design, allowing 50% SOA improvement

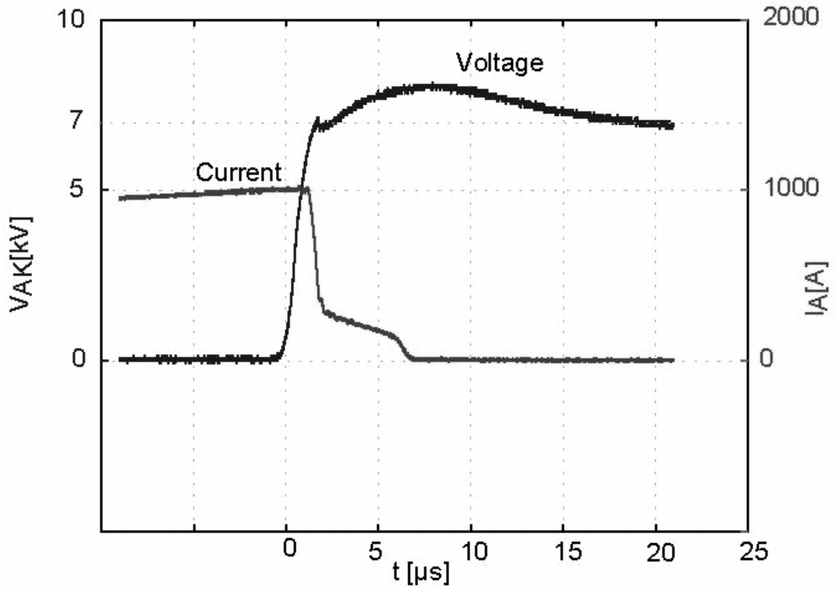



**Fig. 20:** *Experimental* 68 mm/10 kV IGCT switching 1 kA against 7 $kV_{DC}$ and achieving 250 $kW/cm^2$

It has been shown that the IGCT is amenable to a potential improvement by adding an additional gate contact to the anode side as illustrated in Fig. 21. It can then be operated as an Integrated-Gate Dual Transistor (IGDT) with potential advantages described below [9].

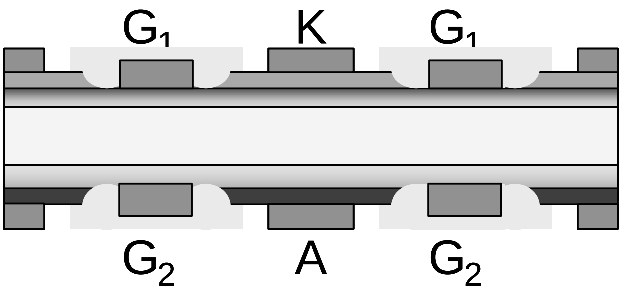



**Fig. 21(a):** Structure of the IGDT

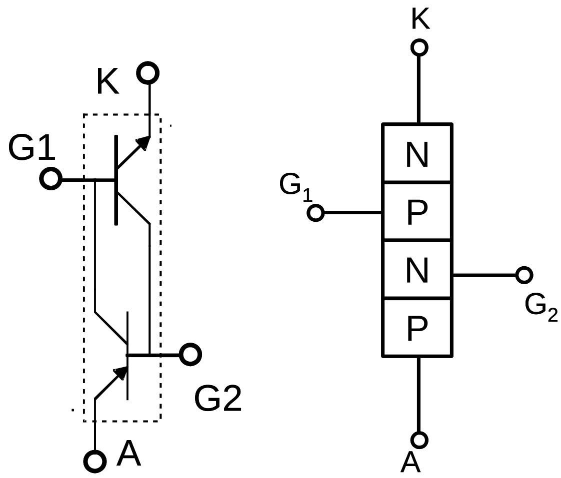



**Fig. 21(b):** Principle of the IGDT

Figure 22 shows the turn-off of an experimental 91 mm/4.5 kV IGDT turning off 3.3 kA against 2.8 kV. This device has not been irradiated to reduce its tail current (losses) and yet it can be seen to have no tail-current (in contrast to the waveform of Fig. 19 for instance). This is because the ‘anode gate – $G_2$’ allows charge extraction from the thick p-base thus eliminating the turn-off losses without irradiation which results in lower conduction losses. Further potential advantages lie in the control of leakage current and tail current as illustrated by Figs. 22 and 23 which opens up the *theoretical* possibility of active voltage sharing (static and dynamic) without snubbers.

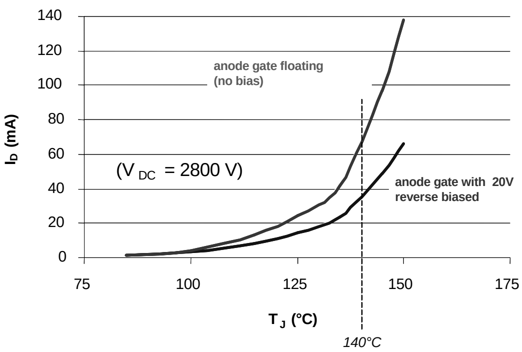



**Fig. 22(a):** IGDT leakage current *reduction* by anode gate control

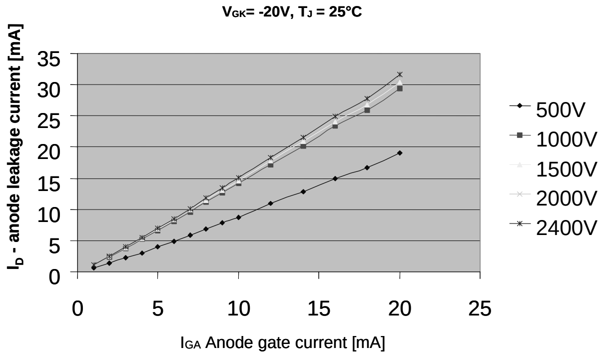



**Fig. 22(b):** IGDT leakage current *increase* by anode gate control

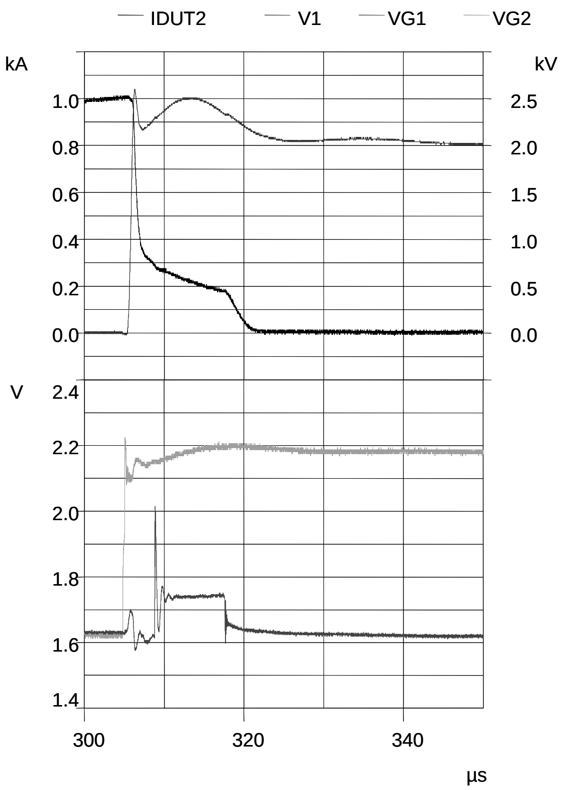



**Fig. 23(a):** IGDT tail current *increase* by anode gate control

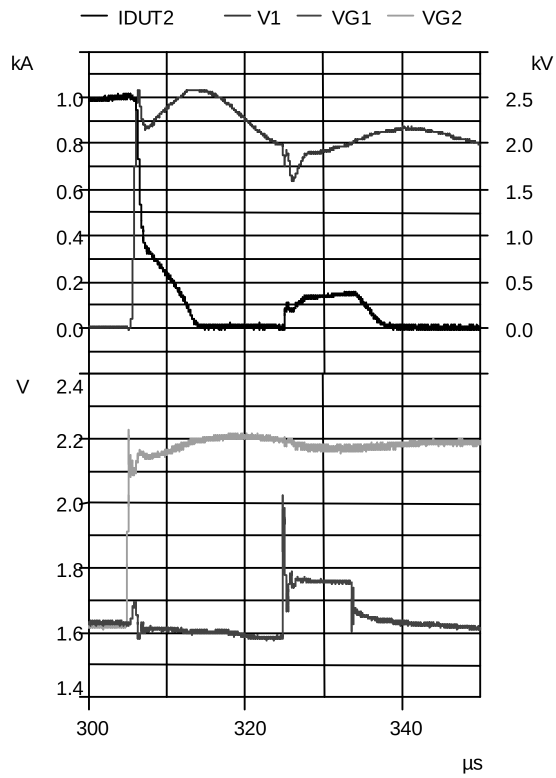



**Fig. 23(b):** IGDT tail current *delayed increase* by anode gate control

Finally, an (as yet) untested feature lies in the possibility of firing both gates simultaneously at turn-on, leading to a high-voltage device capable of extremely high d*i*/d*t* and peak current for pulsed-power applications such as thyratron replacement.

## 6 Conclusions

For high-power conversion, only two devices are available today:

– IGBTs

– IGCTs.

Safe Operating Area is increasing from 250 $kW/cm^2$ to 1 $MW/cm^2$. New high SOA IGCTs will be in production soon.

IGBTs are now capable of voltage self-protection as they were, traditionally, capable of current self-protection (i.e., fault current limitation). These devices are already in production.

The 10 kV IGCT has been demonstrated as has the IGDT, but both devices await business opportunities and development resources.

## References

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