Contents

INSULATED GATE BIPOLAR TRANSISTORS (IGBTs)

By our Editorial Staff

Insulated Gate Bipolar Transistors are being used more and more widely. Modern drive system engineering would not be the same without these devices.

IGBTs are ideally suited to applications where high voltages coupled with high currents must be switched. They are found in voltage converters, heavy-duty control circuits and audio power amplifiers. The first project that used IGBTs was published in this magazine in December 1994 (1-to-3 phase converter).

Noteworthy properties of IGBTs are the ease of voltage control and the low losses at high voltages. These characteristics make one think of power MOSFETs. However, the effective on-resistance of IGBTs is significantly lower than that of MOSFETs. The relevant symbols and equivalent circuits of n-doped and p-doped IGBTs are shown in Fig. 1. Note, however, that the symbols are (not yet) world-standardized, so that others may be encountered.

When the gate-emitter potential exceeds the threshold, $V_{GE(th)}$, a collector current flows. The current amplification, I_C/I_G, of an IGBT, is very high: 10^9, which is possible because the gate current only needs to charge the effective input capacitance (ignoring the tiny leakage currents through the gate oxide). Perhaps more appropriate is the transconductance, $\Delta I_C/\Delta V_{GE}$ (see Fig. 2). The definitions of saturation and linear range are the same as for standard bipolar transistors.

Construction of IGBT

An IGBT consists of a heavily boron-doped substrate (p+), which is fused on to the collector, on which a phosphorus-doped n-eptiaxial layer is deposited. The gate and emitter are epitaxial layers formed by a high-resolution n-channel DMOS process. Since the transistor therefore obtains an n-p-n-p structure, like a silicon-controlled rectifier (SCR), a p+ diffusion layer is inserted into the centre of the device. This layer reduces the current amplification of the upper n-p-n transistor and prevents any latch-up effects of the SCR. Without it, the IGBT would cut off at high currents owing to the breakdown of the gate control.

A separate p-base region permits independent control of the threshold voltage at the gate during the onset of conduction.

The maximum permitted reverse voltage is determined by the thickness and resistance of the n-epitaxial layer, which is optimized for a minimum forward voltage.

Switching characteristics

IGBTs (and power MOSFETs) have a gate-emitter threshold potential, $V_{GE(th)}$, and a capacitive reactance. To make these devices conduct, that is, before a collector current can flow, it is necessary for the input capacitance to be charged to a voltage that exceeds $V_{GE(th)}$. To switch off an IGBT, a resistor, R_{GE}, between gate and emitter is required, via which the input capacitance can be discharged. The minimum value of R_{GE} is specified in the data sheet of the relevant IGBT.

An IGBT has a peak controllable collector current that is dependent on the gate-emitter dv/dt transient. The higher this ratio, the lower the controllable collector current.

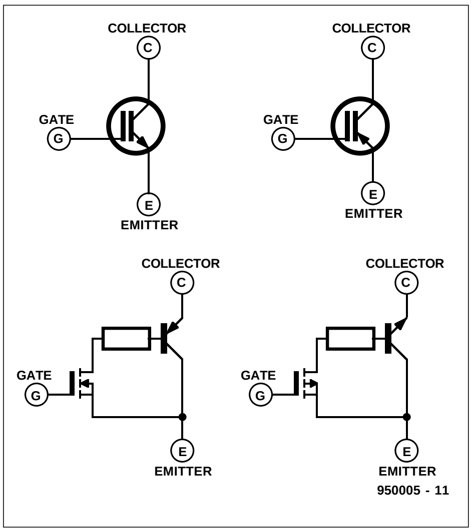

Fig. 1. Graphical symbol and equivalent circuit of n-IGBTs and p-IGBTs.

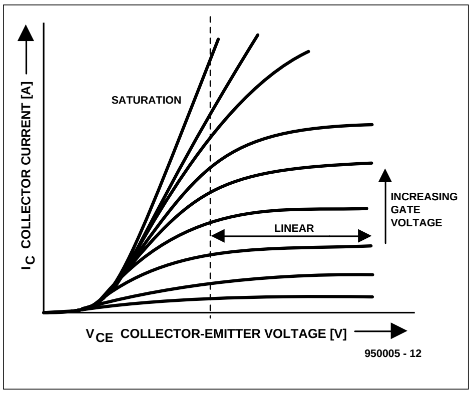

Fig. 2. Output characteristics of an IGBT.

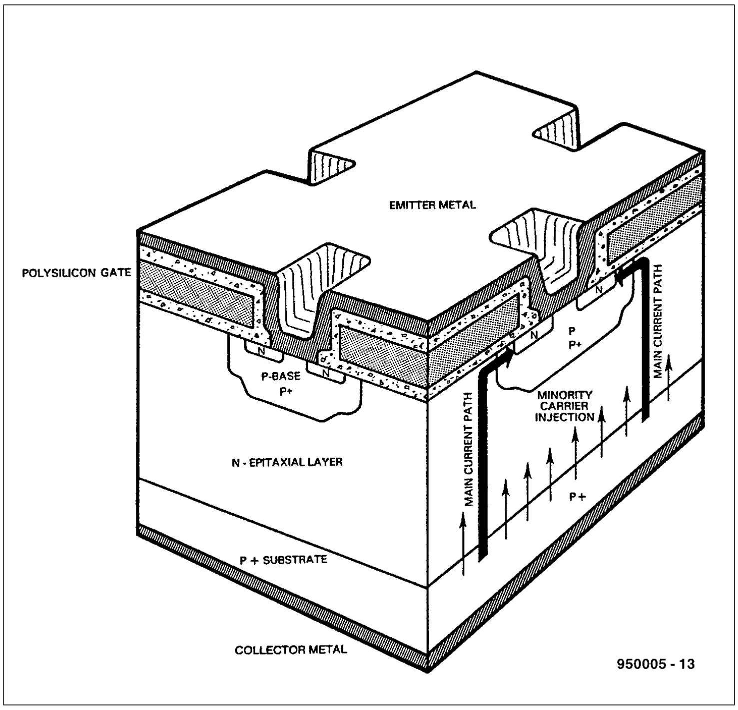

Fig. 3. Construction of an Insulated Gate Bipolar Transistor.

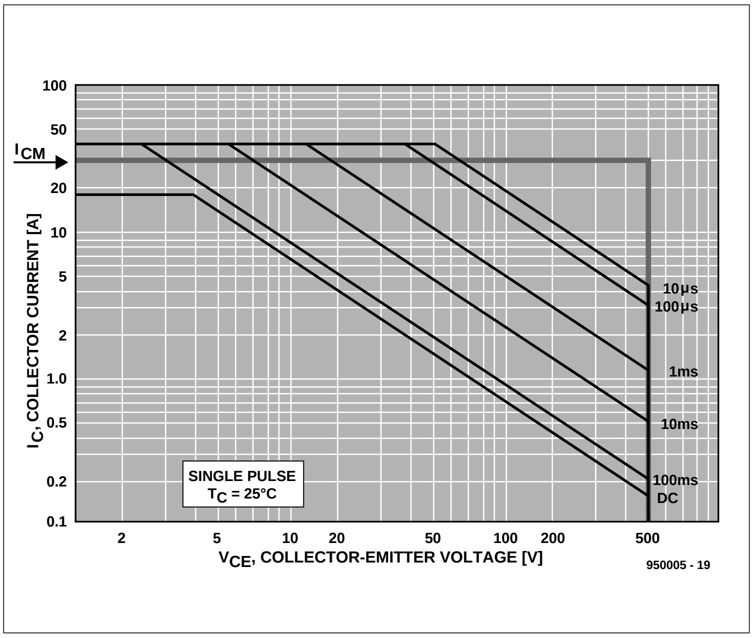

Fig. 4. Safe Operating Area (SOA) during normal operation and when the IGBT gets switched off. (peak values of I_C and V_{CE} shown).

Because of its construction, the switch on and switch off times of an IGBT are influenced by the gate-emitter impedance.

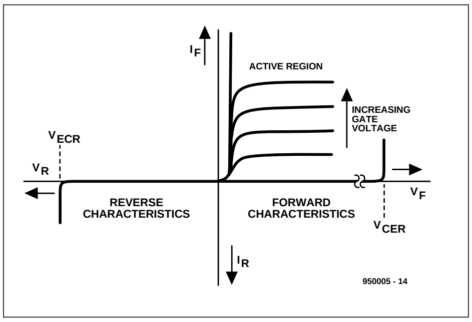

Fig. 5. Parametersof the collector characteristics.

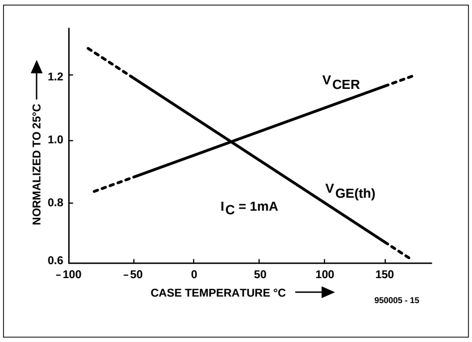

Fig. 6. Temperature dependence of V_{CE} and $V_{GE(th)}$.

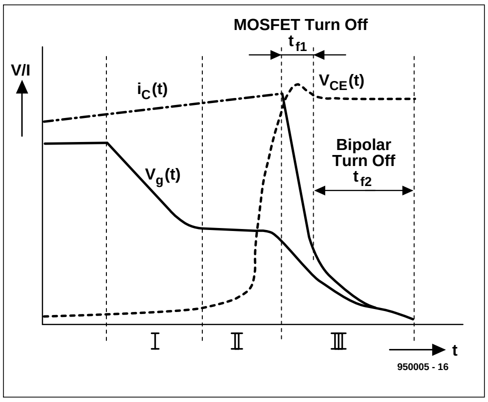

Fig. 7. Various phases in the switching off of an IGBT.

This impedance is much lower as that of a power MOSFET handling comparable voltages and currents. An IGBT is switched on by a positive potential on the gate and emitter terminals. When V_{GE} is greater than $V_{GE(th)}$, (which in switching applications is always the case), a collector current flows.

The switch-off behaviour of an IGBT is a mixture of that of a standard bipolar transistor and that of a power MOSFET. The switch-off time is determined by three different stages: I, II, and II, in Fig. 7. During the first phase, the gate-emitter voltage drops until the onset of the Miller effect (gate-collector capacitance) and V_{CE} rises. The second phase is typified by a constant gate potential (Miller effect). During this phase, the rising collector-emitter voltage causes a diminishing gate capacitance and a reversal of the gate polarity. Thereupon, the emitter voltage rises to a peak value, which is determined by the drive circuit. The final phase consists itself of stages: (a) the (very short) switch-off time, t_{f1}, of the MOSFET, and (b) the rather longer switch-off time, t_{f2}, of the bipolar transistor. The latter time does not commence until the MOS channel is off and the base of the p-n-p transistor is open.

Owing to the various phases of the switch-off time, it is difficult to put a value on the losses on the basis of the 10–90% switch-off time given in the data sheet. Instead, the equivalent switch-off time, $t_{F(eq)}$ is taken which assumes a linear decay of the collector current; however, the following expression gives the actual decay time:

$$t_f = 2/I\int_{t_o}^{\infty} i(t)\mathrm{d}t$$

If inductive loads are switched, the switch-off losses are given by

$$^1/_2 \cdot V_{CE} \cdot I_C \cdot f \cdot t_{f(eq)}.$$

Since the switch-off period of the bipolar transistor part of the IGBT is really constant, the duration of the switch-off period of the MOSFET part can be influenced by the correct choice of R_{GE}. The higher the value of this, the longer the switch-off period. In case of an inductive load, the period may be protracted to such an extent that operation without a snubber network becomes possible.

There are slow and fast IGBTs. For applications of slow types (d.c. and a.f.), the minimum switch-off current is of prime importance, whereas with fast types the switch-off characteristics should be as linear as possible (Fig. 9). For high-frequency applications, fast IBGTs with small R_{GE} should be used; this ensures that switching losses are kept to a minimum.

The typical Safe Operating Area (SOA) of an IBGT is shown in Fig. 4. The device can handle peak currents exceeding the maximum collector direct current; this current is limited only by the thermal threshold and the thickness of the connecting leads.

Sources: ‘IGBT Driver’; Toshiba, March 1993.
SGS Thomson: Technical Note 1/5.

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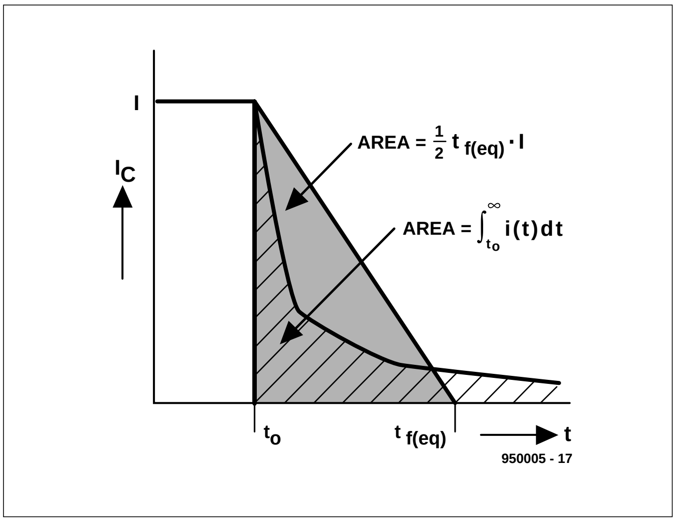

Fig. 8. Power losses at switch-off can be assessed from the equivalent decay times.

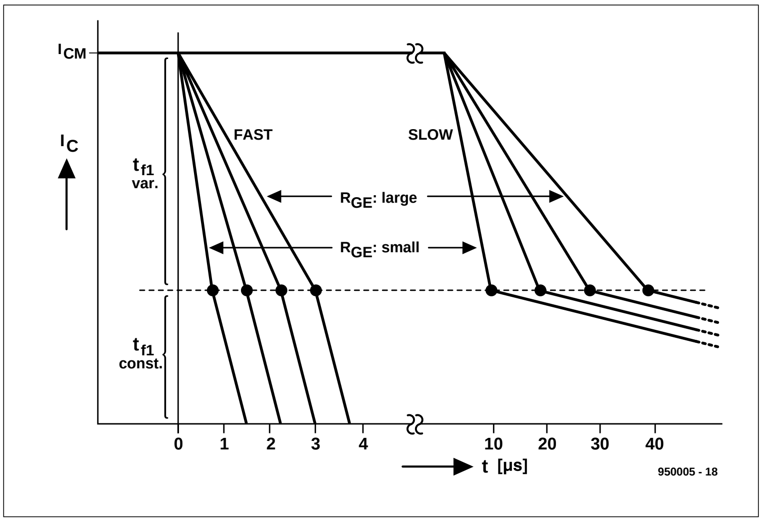

Fig. 9. Switching off of fast and slow IGBTs with various values of gate-emitter resistance.