INFLUENCE OF GATE AND BASE DRIVE ON POWER SWITCH BEHAVIOUR

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ABSTRACT

This paper looks at the influence of the drive circuit on the switching behaviour of electronic devices belonging to different families. In particular Bipolar Junction Transistors (BJT) are considered as a representative of current driven devices, and Power MOSFETs and IGBTs as representatives of voltage driven devices.

1. BJT

In order to switch a BJT quickly and with low switching losses, minority carriers must be injected into and extracted from the base of the transistor very rapidly.

1.1 Turn-On Switching

In terms of input signal, the transistor base-emitter junction can be schematically represented by a variable resistance r_{bb} and a voltage source. When the base-emitter junction is cut-off the r_{bb} value is relatively high. When carrier injection begins, r_{bb} is modulated and its value decreases in a time which is of the order of the carrier lifetime (a few tenths of a nanosecond). If the transistor is driven from a current source, the rate of rise of the base current is imposed by the driver stage and the initial high value of r_{bb} does not influence the rate of rise of the collector current (see fig. 1).

Figure 1: Rate of rise of positive base current when the driver circuit acts as:
       a) a voltage source
   b) a courrent source
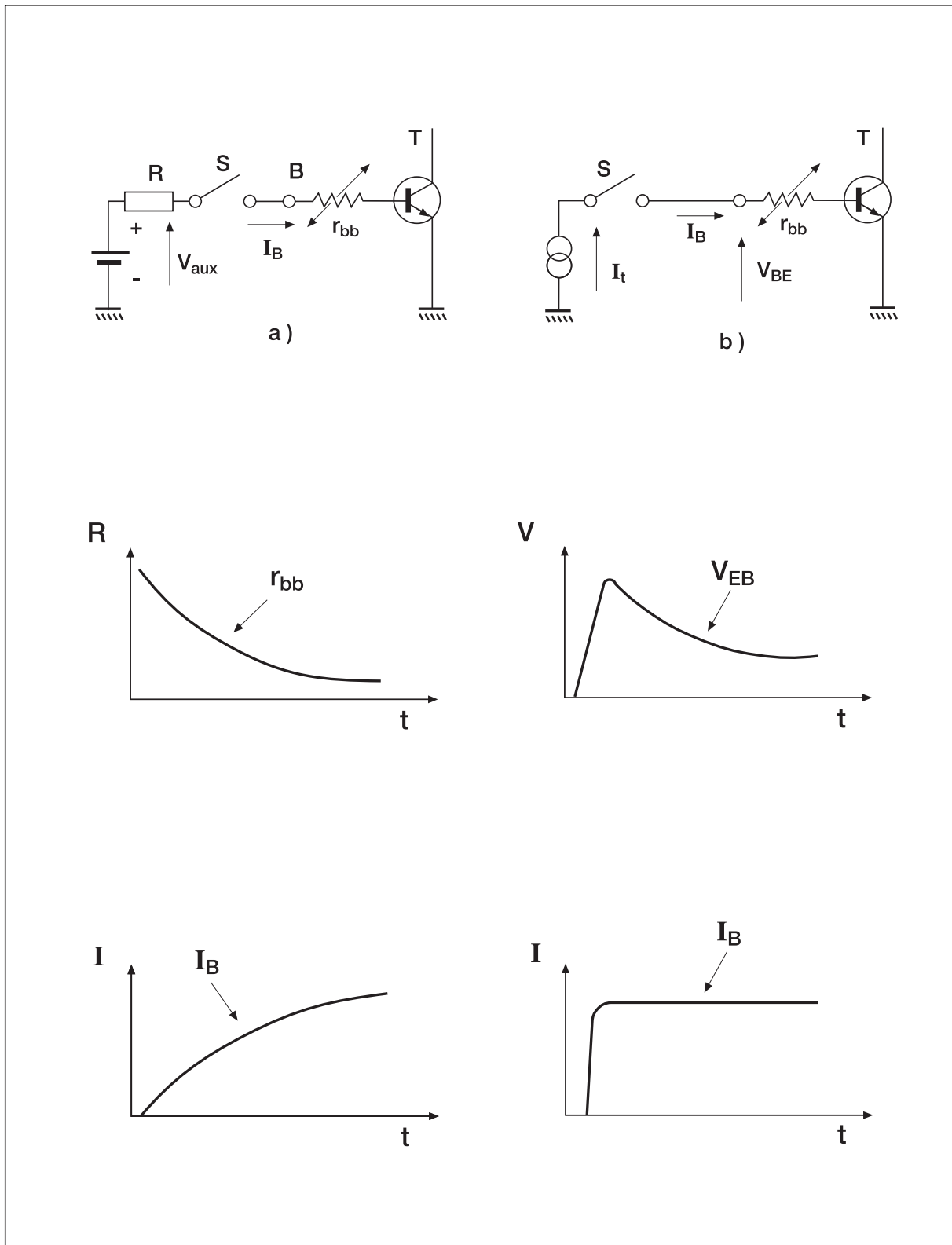
1.2 On-state

Once the transistor is turned on, the driver stage has to provide a positive base current in such a way as to prevent the device entering an over-saturated state. This state corresponds to very low $V_{CE(sat)}$ (low conduction losses), but the collector region is fully saturated by the minority carriers injected from the base. Consequently the advantage of the low voltage drop is offset by a longer turn-off switching time.

Over-saturation can be avoided if the drive is able to supply a base current proportional to the collector current in such a way as to keep the ratio of I_C/I_B constant; however this requires a complex driver. The use of an anti-saturation network can avoid the collector-emitter voltage falling below than 0.6-0.7 Volts, and hence can keep the transistor operating point outside the deeply saturated region; see fig. 2.

Figure 2: Transistor in the on - state
a) stored charge Q is very large if the V_{ce} is very small
b) an anti - saturation circuit avoids the V_{ce} being lower than 0.6 - 0.7 Volts
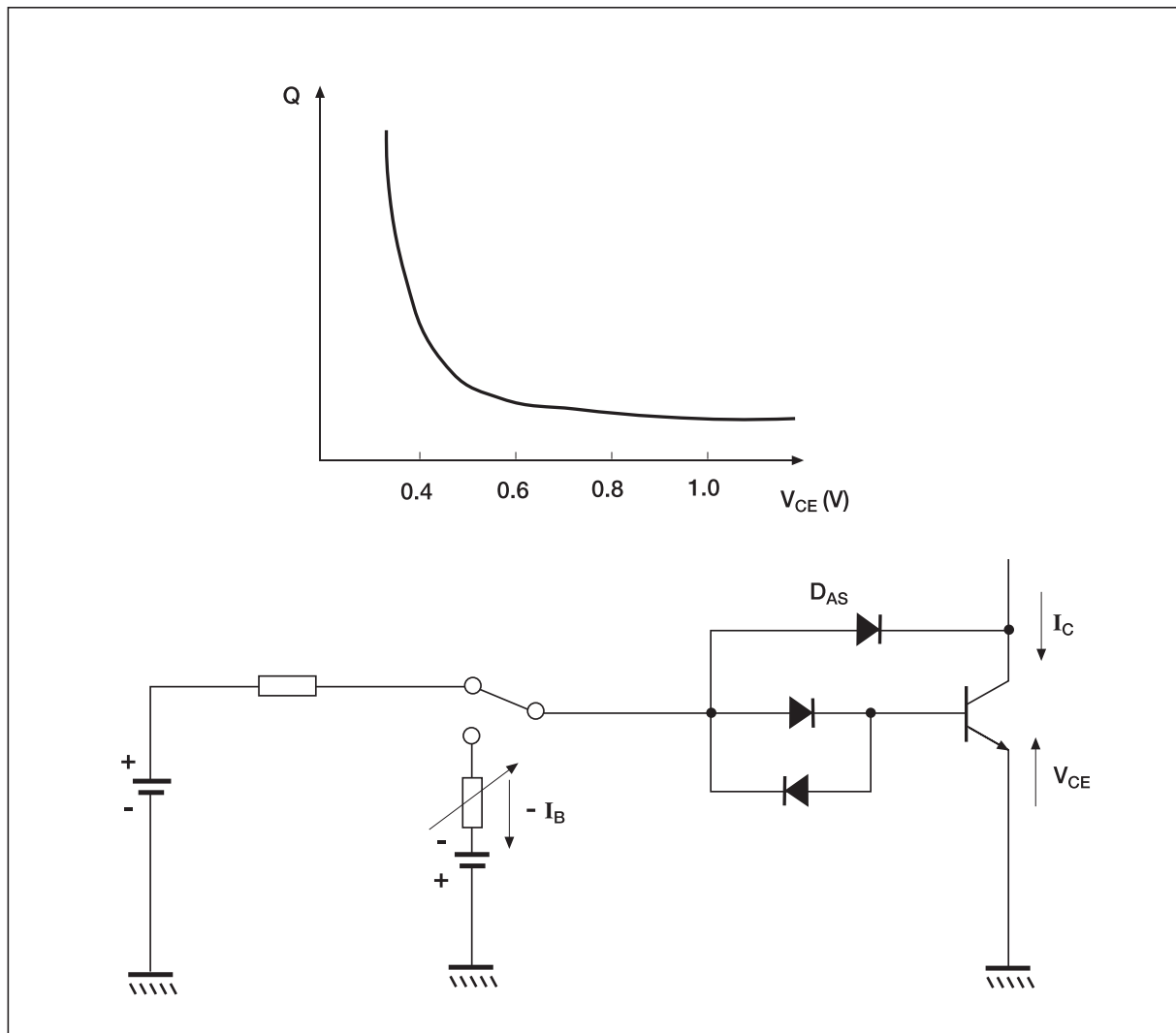
1.3 Turn-Off Switching

The transistor behaviour during this phase essentially depends upon the following parameters:

a. the negative base current or extraction current I_{b-} (see fig. 3)
b. the saturation state of the transistor during the previous conduction phase.

Figure 3: Schematic behaviour of the base current at turn - off
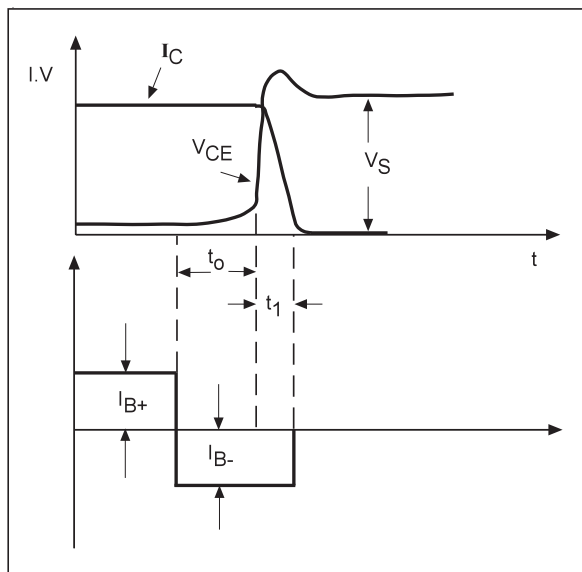
The quantity of charge the driver stage has to remove in an over-saturated transistor is higher than in the case of a quasi-saturated transistor. The larger the magnitude of the negative base current I_{b-} and the lower the degree of saturation of the transistor, the shorter the storage and fall times.
Typical values of storage time and fall time are given on the datasheet of the transistor for specified conditions. However, if the transistor conduction time lasts only a few microseconds, the saturation state cannot be reached. In this condition the turn-off delay time is smaller than the values on the datasheet. Today, most transistor manufacturers specify the storage time as a function of the conduction time t_p (see fig. 4).

Figure 4: Storage time VS. conduction time for BUF410 transistor
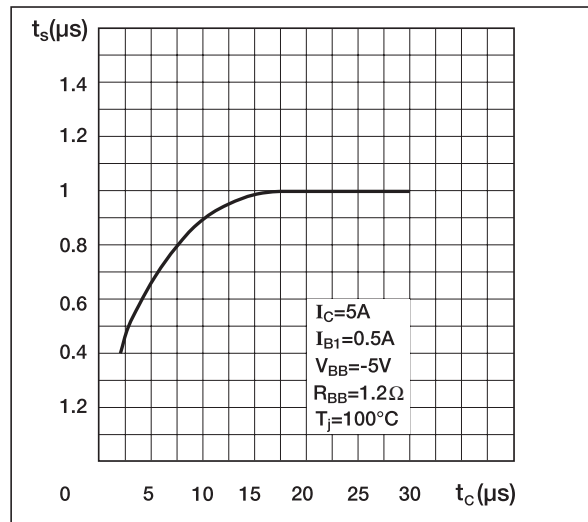
Reduction of the storage time may require an extremely high value of extraction current. However a high value of I_{b-} can lead to a change in the safe operating area (SOA) due to the current focussing effect. Fig. 5 shows how an increase of the negative base current leads to an increase of the SOA at low current and a reduction of the SOA at high current.

Figure 5: Effect of the negative base current magnitude on the transistor safe operating area
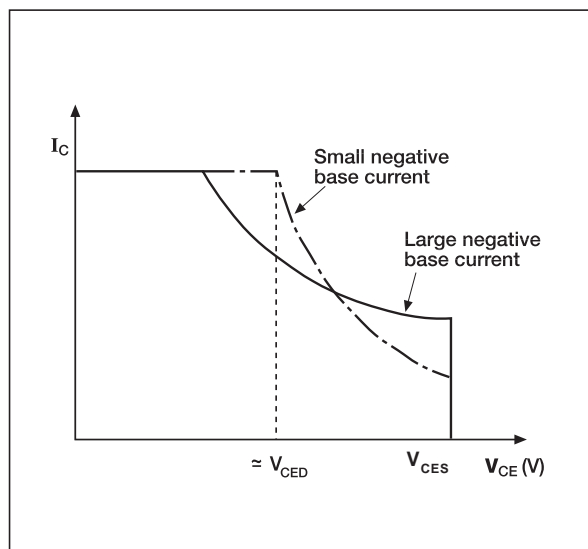
The design of modern bipolar transistors is oriented towards structures with reduced current focussing effect and reduced switching times. Hollow emitter and cellular ETD technologies has been developed for this purpose.

1.3.1 Negative Polarisation at Turn-Off

A negative base-emitter voltage (in the order of the transistor base-emitter breakdown voltage BV_{EB}) can be applied in order to reduce the effect of the parasitic base resistor r_{bb} at turn off. This resistor behaves inversely to the turn on phase and limits the extraction current when the base-emitter junction approaches cut-off (see fig. 6).

Figure 6: Limitation of the negative base current due to the base resistance r_{bb}


$$-I_B = \frac{V_{B\,off} - V_{BE}}{Z + r_{bb}}$$
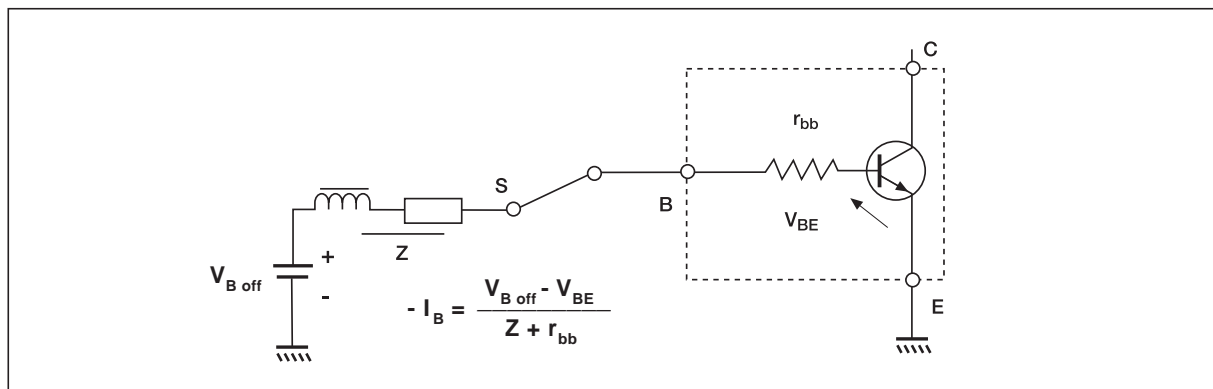
For example a high voltage ETD transistor such as the BUF410 can be turned off with a base-emitter resistance in the order of 0.3 Ohms. In this condition oscillogram 1 shows a fall time $t_f < 100ns$. ($I_c = 8A, T_j = 100°C$).

If an negative base-emitter voltage of 2.5 Volts is applied, the fall time is reduced to less than 50ns, see oscillogram 2.

Oscillograms 1/2: BUF410 turn - off
　　　　　　　　　1) without negative bias
　　　　　　　　　2) with negative bias
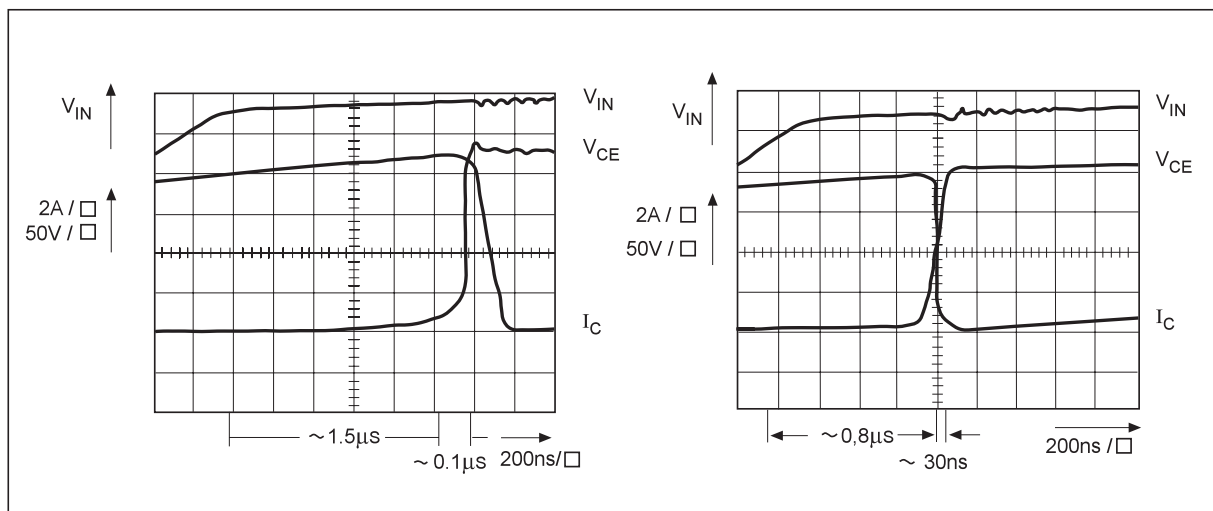
2. MOSFET/IGBT

Voltage driven devices have gained great popularity because of the high impedance of their input; a MOSFET gate that requires a minimum of only 8 Volts and microjoules of energy to switch on and off. These characteristics mean that the drive circuit is very simple compared to that of the BJT.

2.1 Turn-On Switching

The most important parameter the drive has to control during the turn-on switching is the dI/dt of the drain/collector current. This parameter is important because turn-on losses depend on the dI/dt value. In fact in most applications with inductive loads the turn-on switching occurs when the freewheeling diode is conducting. The recovery of the freewheeling diode permits the device and not the load to define its dI/dt. An increase of the dI/dt of the drain/collector current corresponds to a reduction of turn-on losses, but at the same time RFI will increase (see fig. 7).

Figure 7: Turn-on switching with a conducting freewheeling diode
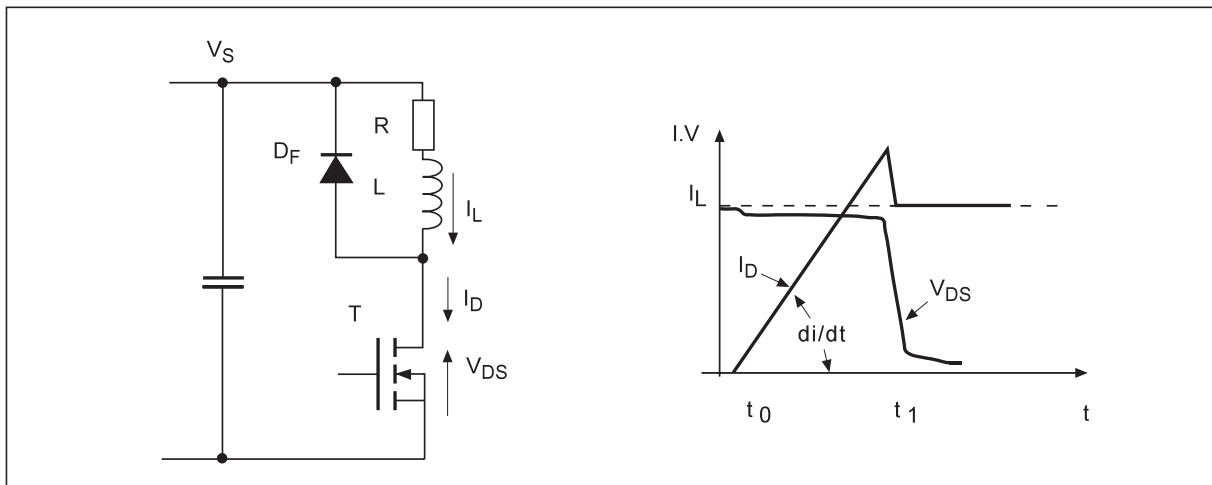
The dI/dt can be controlled by controlling the rate of increase of the gate voltage.

The circuit can be implemented simply by a gate resistor $R_{G(on)}$ as shown in fig. 8.

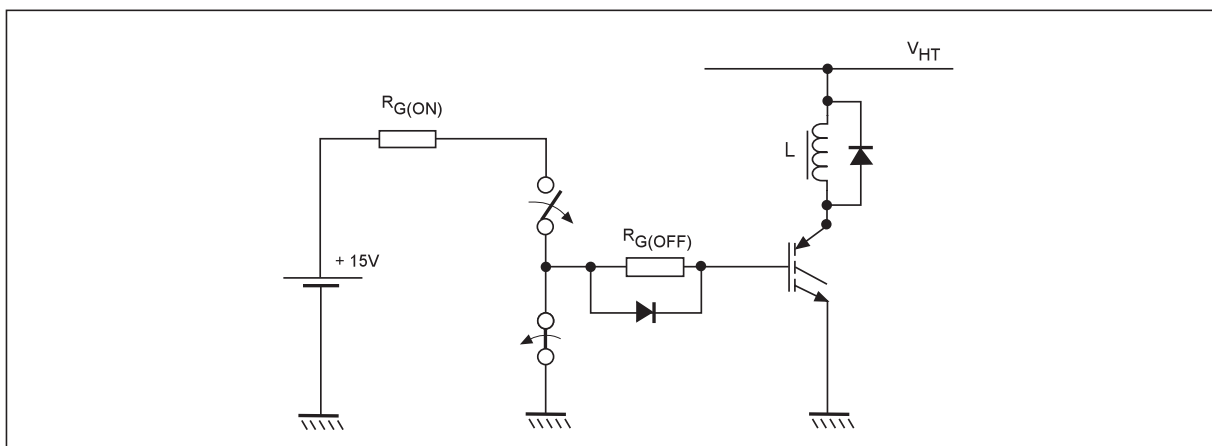**Figure 8:** Principle of drive stage controlling dI/dt at turn - off

Fig. 9 shows the curves of dI/dt as a function of the gate resistor $R_{G(on)}$ for a 500 Volt, 20 Amp IGBT.

Figure 9: dI/dt at turn - on V_s $R_{G(on)}$ for the 500V - 20A IGBT (STGH20N50)
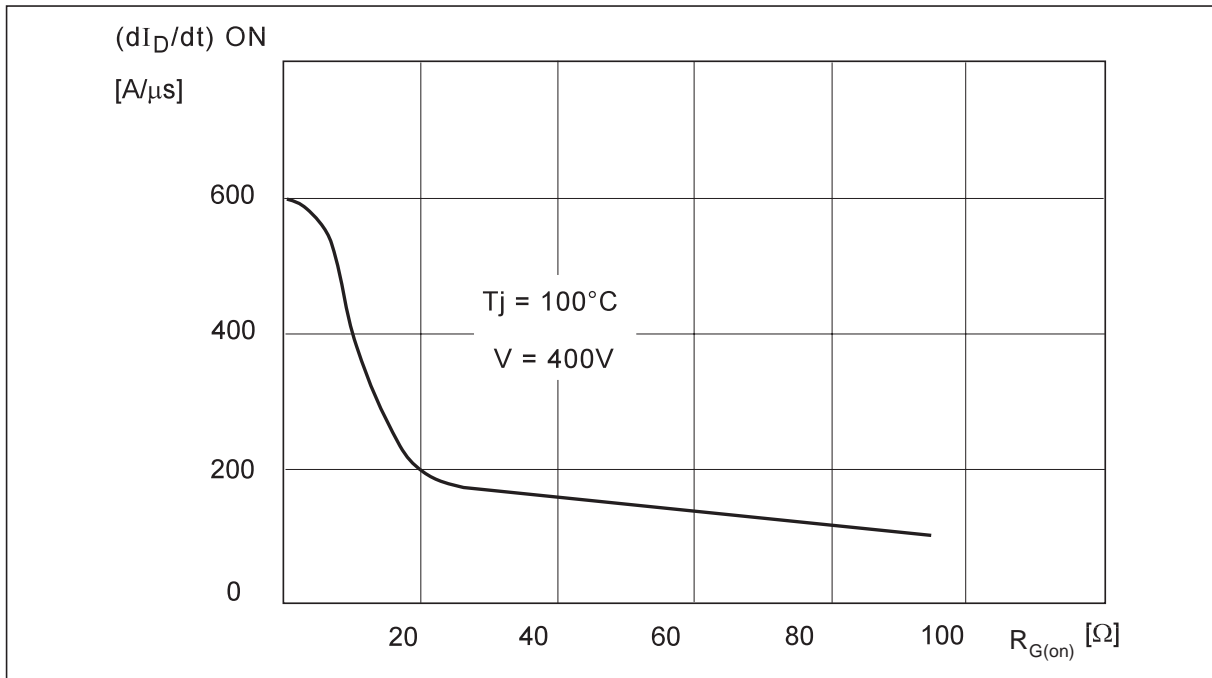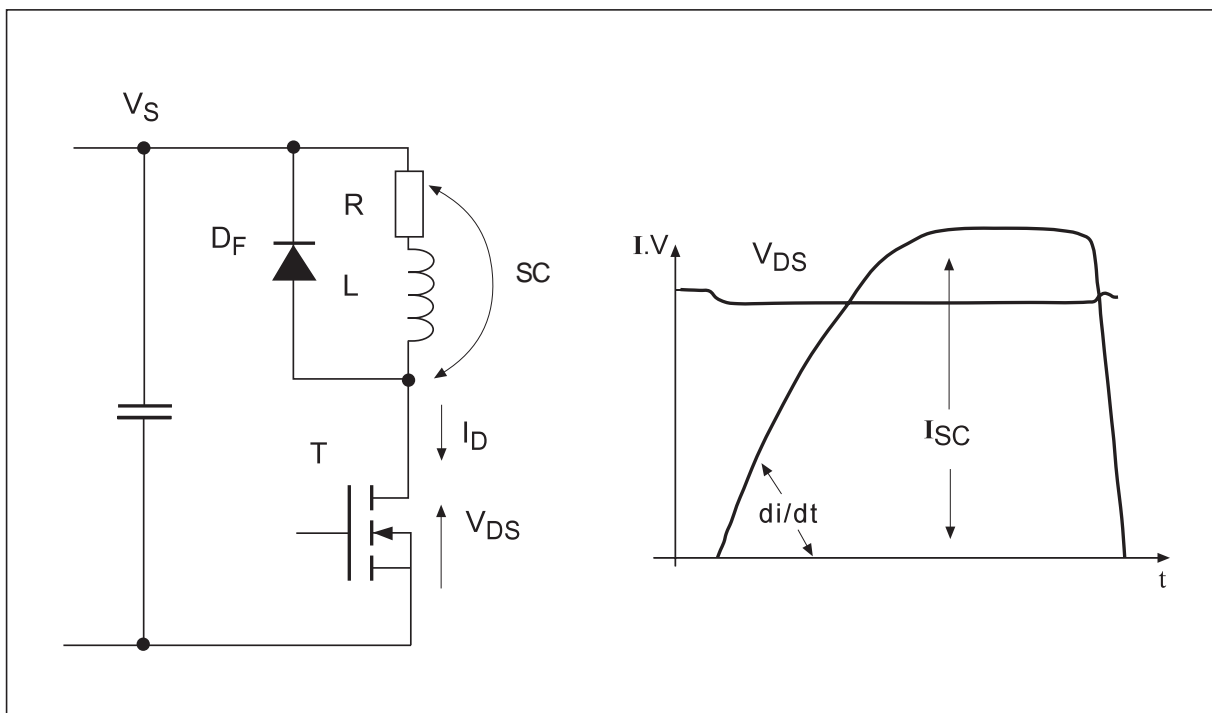

Figure 10: Switching - on to a short circuit
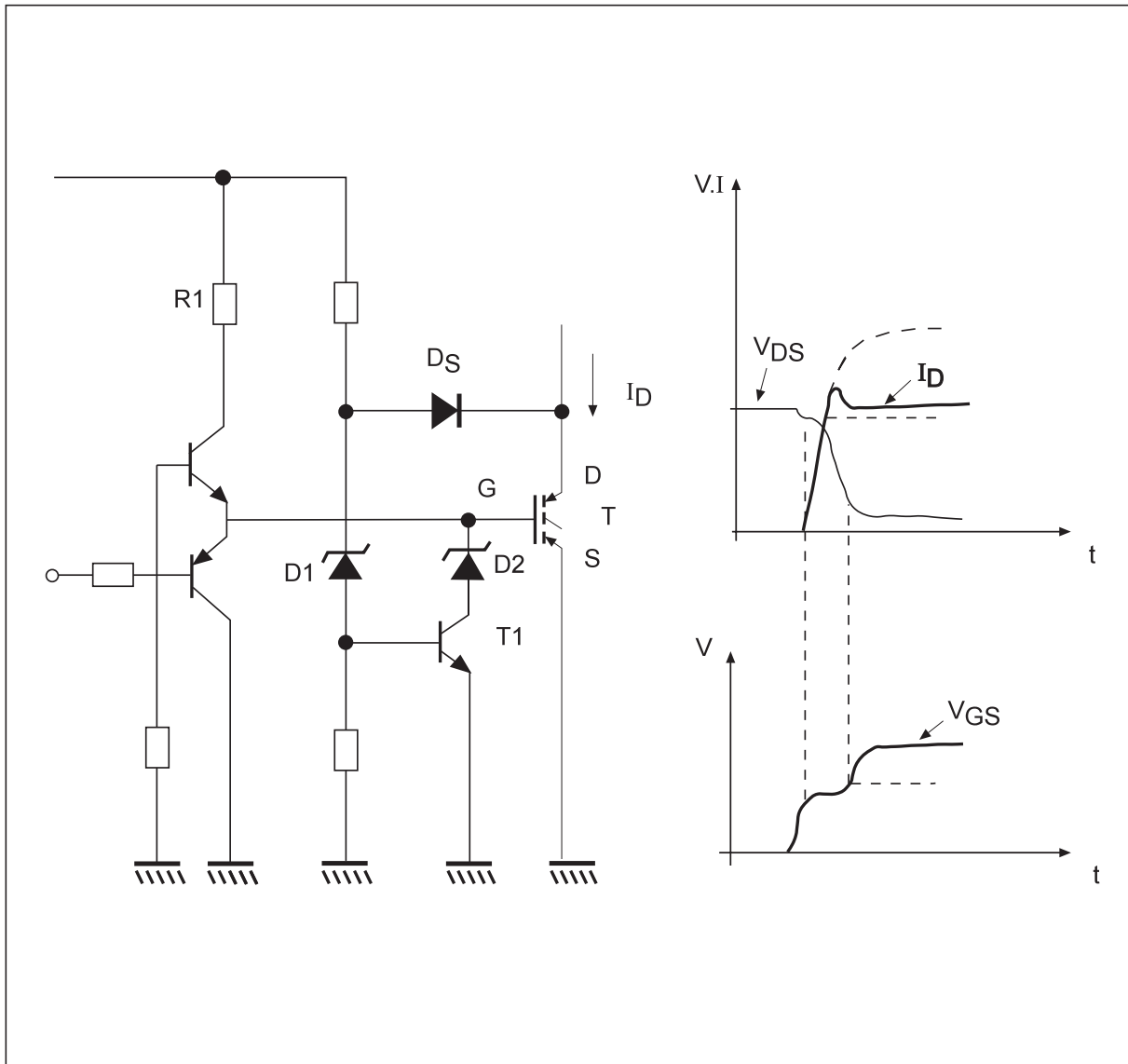
2.1.1 Turn-On Switching during Short Circuit Conditions

In load short circuit conditions, all the supply voltage is applied across the device and the short circuit current I_{sc} is fixed by the gate-source/emitter voltage (see fig. 11).

Figure 11: Principle of drive stage controlling dl/dt and short circuit current amplitude

The energy the device dissipates in this condition can be very high and destruction of the device can occur in a few microseconds if no protection is activated. All protection circuits have a feedback loop to inform the drive of the abnormal condition; however it can take too long for the drive to turn off the devices. A reduction of the gate-source/emitter voltage leads to a reduction in the short circuit current I_{sc} which in turn leads to a lower power dissipation and hence to a longer time before destruction. The simple circuit of fig. 12 will carry out this function.

Oscillograms 3 - 5: Turn - off behaviour as a function of $R_{G(off)}$ for 1000V - 30 A IGBT
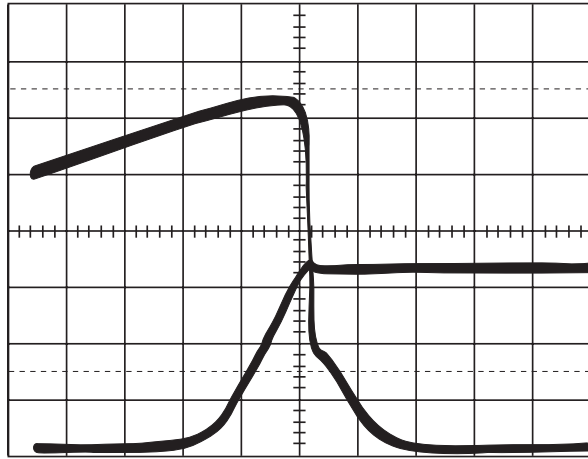
Oscillogram 3: $R_{G(off)} = 100\Omega$

V_D

I_D
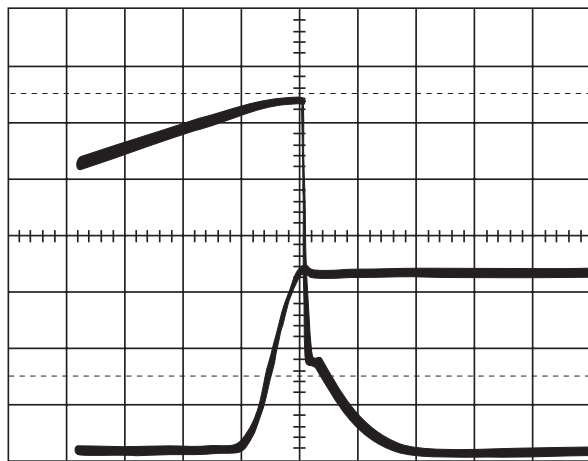
Oscillogram 4: $R_{G(off)} = 47\Omega$

V_D

I_D
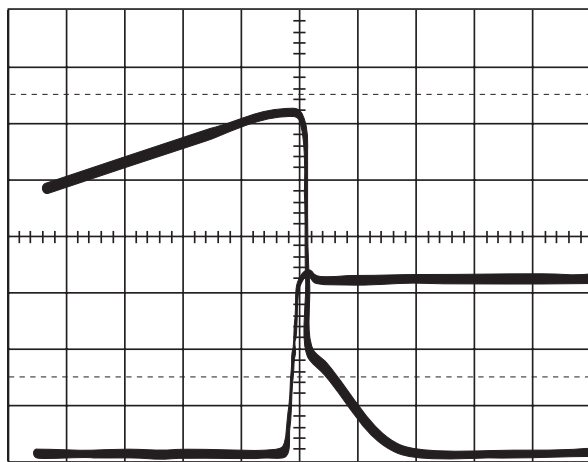
Oscillogram 5: $R_{G(off)} = 10\Omega$

V_D

I_D

2.2 On State

Gate drive does not influence the on state and consequently has no effect on the conduction losses.

2.3 Turn-Off Switching

If the drive circuit is able to control the rate of change of the gate-source/emitter voltage at turn off, then the dV/dt of the collector voltage can also be controlled. Once again the control can be performed by a gate resistor $R_{G(off)}$ as shown in fig. 12. The higher the intrinsic value of dV/dt the lower the turn off losses, as can be observed by the sequence of oscillograms 3 through 5 for a 1000 Volt IGBT turn off. The gate resistance is varied between 100 Ohms and 10 Ohms. In particular, an IGBT device shows the current tail phenomenon. The sequence of oscillogram shows how the gate drive cannot attenuate the tail effect and associated losses. This is because once the MOSFET section of the IGBT has turned off, the bipolar part remains open base and the base extraction current mechanism cannot work, as shown in fig. 13.

Figure 13: Equivalent circuit of IGBT
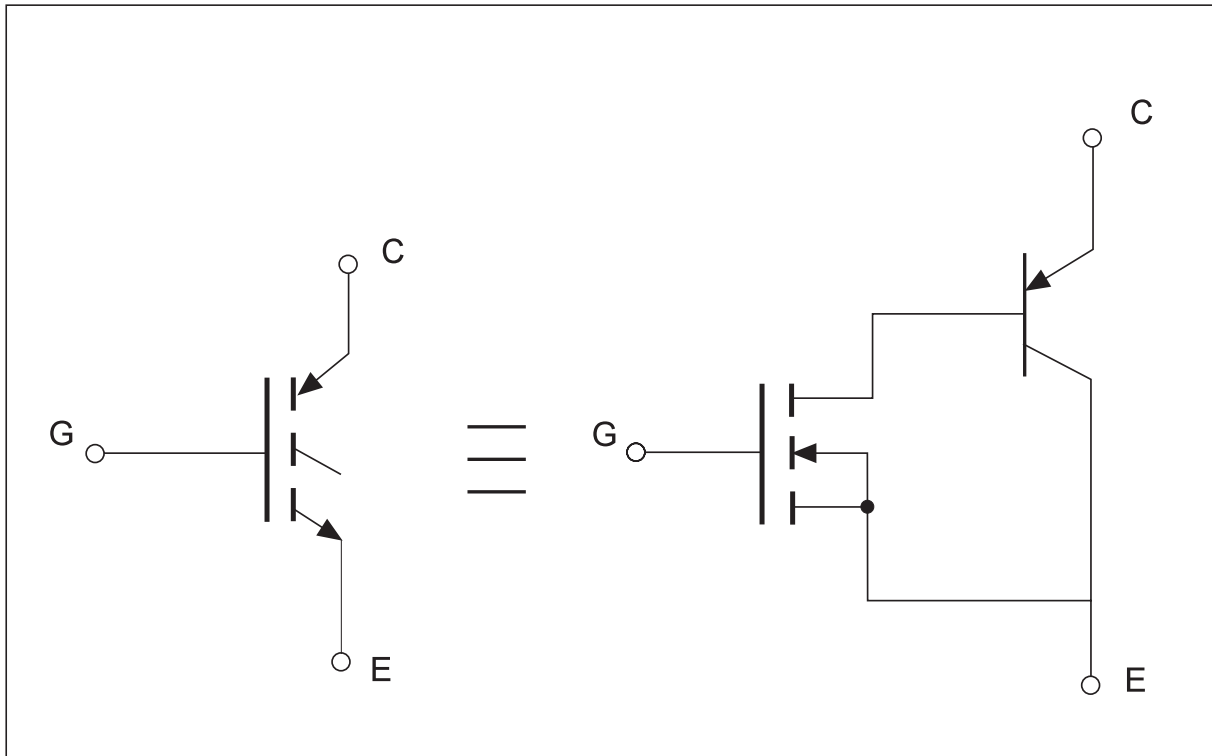
2.4 Off State

During the off state the MOSFET/IGBT can be subjected to dV/dt caused by others devices (static or passive dV/dt). For example in a half-bridge structure, the switching on of the upper switch causes a dV/dt on the lower switch.

The presence of a parasitic capacitance C_{GD}/C_{GC} between drain/collector and gate exposed to the external dV/dt causes a current which flows through the drive output resistance. Depending on the value of the drive output resistance, the switch can be turned on, increasing global losses (see fig. 14).

Figure 14: IGBT reconduction can happen at off - state due to the static dV/dt
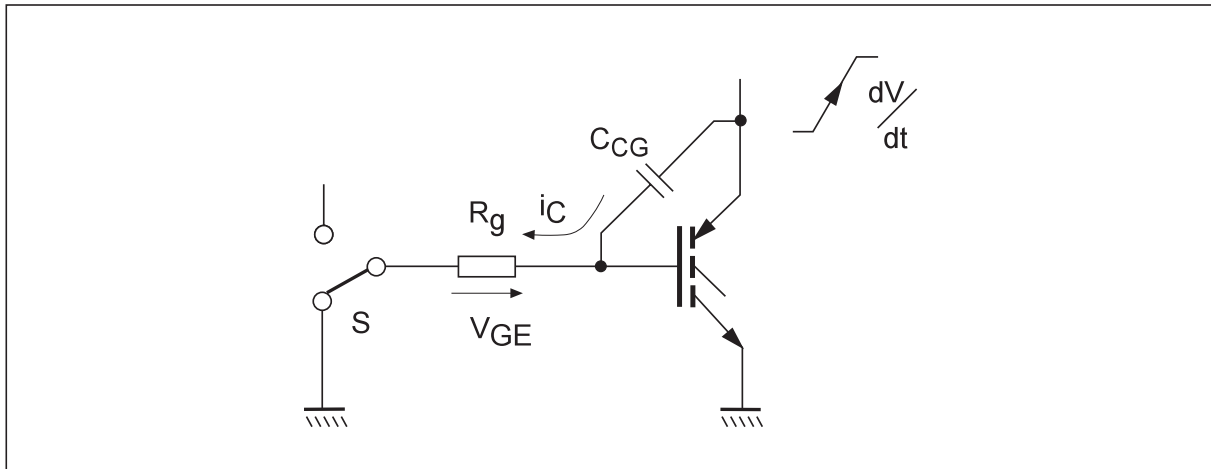
In order to avoid switch reconduction, during the off state the driver stage must have:

a) a very low output impedance
b) an eventual negative bias.

The negative bias is necessary in all cases where the parasitic inductance L_p of the device package can reach high values. For packages such as the TO-220, TO-218 and ISOTOP, point (a) is enough to ensure that there is no risk of reconduction. Larger packages require a negative bias.

CONCLUSION

A well-designed drive stage can improve the performance of power switches and reduce global losses.

- The storage time and switching losses in a BJT circuit can be reduced and SOA extended by using a base drive circuit which behaves as a current source at turn on, avoids transistor over-saturation in the on state, and which supplies a suitable value of extraction current at turn off.

- It is possible to modify the switching times of a power MOSFET or an IGBT in order to reduce switching losses and the generation of RFI by using a three state gate drive circuit, i.e. with a different output impedance at turn on, turn off and off state.