APPLICATION ARTICLE

CHARACTERISTICS OF POWER SEMICONDUCTORS

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ABSTRACT

This paper aims to give a brief overview of the essential characteristics of power semiconductors, and to provide a guide in their selection for particular applications.

It considers the characteristics of various power components when operating like a switch - either blocking current or voltage, or conducting with a small voltage drop.

Their behaviour is examined in terms of:

(i) Typical current and voltage ratings (switchable power) permanent current - short overcurrent;

(ii) The switching behaviour: switching speed and switching losses;

(iii) Drive requirements.

Advantages and disadvantages are summarised, and the relative cost of each solution indicated.

Currently, the main types of power semiconductors are the Power Diode, the power Bipolar Junction Transistor (BJT), the Thyristor (Triacs and SCRs), the Gate Turn-off Thyristor (GTO), the Power MOSFET, and the Insulated Gate Bipolar Transistor (IGBT).

2 THE POWER DIODE see figure 1.

2.1 Current

The physical parameter which limits current is the maximum junction temperature; the temperature at which destruction of the device occurs. Hence the maximum current in a diode depends essentially on the cooling; in practical terms on the thermal resistance (for DC operation), and on the thermal impedance (for short duration surge currents).

2.2 Voltage

The device is destroyed if the electric field across the N region of the diode becomes strong enough to cause breakdown - hence the voltage ratings of the transistor (forward, V_F and reverse, V_{DRM}) depend upon the thickness of this region.

2.3 Switching

Power PN diodes have a "memory" effect due to the storage of minority carriers. If the voltage across a diode which has been conducting in the forward direction is suddenly

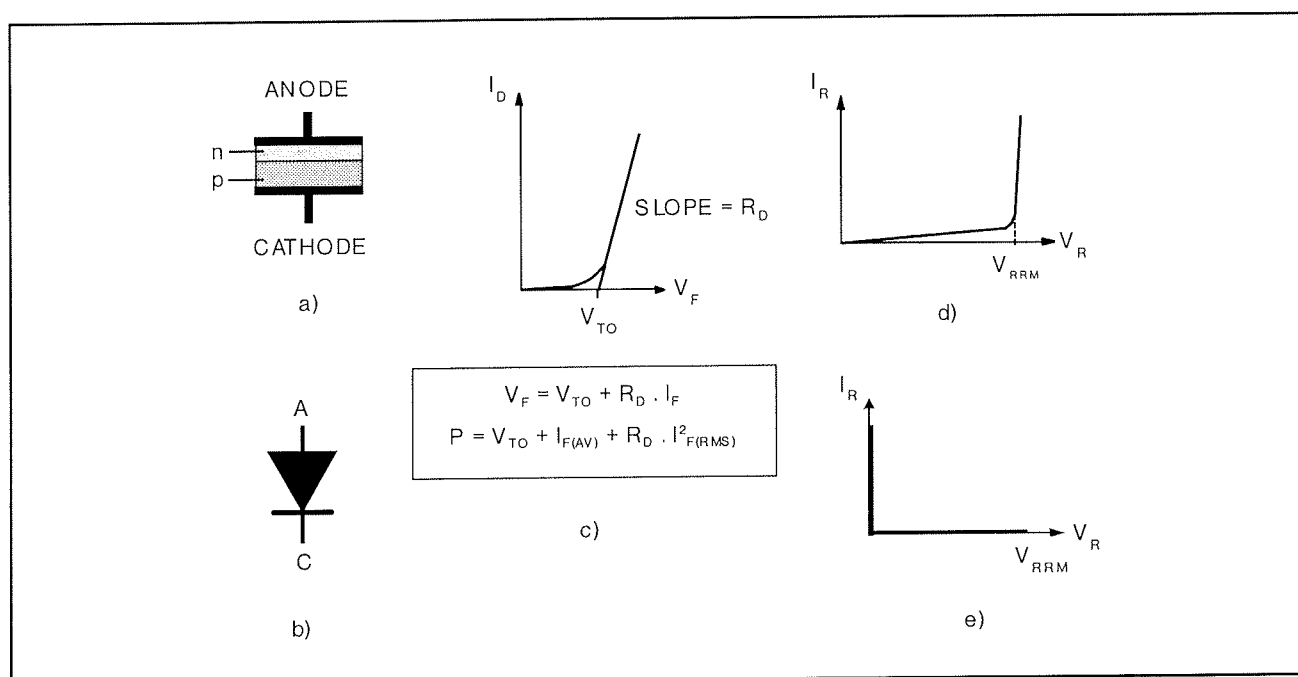Figure 1.   Power Diode: a) Simplified structure
                             b) Circuit symbol
                             c) Current limits
                             d) Voltage limits
                             e) Safe Operating Area

reversed, the p and n regions of the diode are still full of minority carriers, which can cause the diode to behave like a short circuit for a short period of time until the minority carrier density falls. The reverse current due to this effect can cause problems: current spikes, noise, overvoltages, and supplementary switching losses.

Figure 2 shows the turn-off behaviour. The main parameter is the reverse current, I_{RM}, and in some case the recovery charge Qr. The reverse current increases with dI_R/dt (slope of decreasing current before turn-off) and with junction temperature.

A fast PN diode is a diode made with a reduced minority-carrier lifetime, which leads to a reduction in the diffusion length (ie the average distance travelled by a minority carrier before recombination).

If the diffusion length is shorter than the thickness of the silicon N region, the diode's on-resistance increases drastically. However the maximum voltages that the diode can withstand depend upon the thickness of this region. The design of a fast diode is therefore the result of a trade-off between maximum voltage V_{DRM}, forward voltage drop V_F and speed (t_{rr}) - see figure 3.

Figure 4 shows losses introduced by a frewheel diode. Using a faster diode reduces these losses, but it is not always possible to have an ultra fast diode with a high voltage rating. Instead it could be possible to use several low voltage ultra-fast diodes in series - see reference /3/.

When the diode switches off in series with an inductance L, a supplementary energy $L \cdot I^2_{RM}$ is dissipated in the circuit. For this reason the choice of circuit configuration is very important (figure 5).

2.4 Schottky Power Diodes

Schottky power diodes, which use only majority carriers, have a different behaviour; they have a smaller voltage drop and no recovery charge, and are many times faster than PN diodes. However, they have the disadvantages of a limited voltage range (60 to 100V) and a very high internal capacitance. The leakage current is also large, and becomes larger at high temperatures.

3 THE BIPOLAR TRANSISTOR
see figure 6.

3.1 Current

The current capability is defined by:

$$V_{CE(sat)} < 1.5V@ \qquad \text{If } I_C = I_{C(sat)}$$
$$\text{If } I_B = I_{B(sat)}$$

If $I_C < I_{C(sat)}$, the voltage drop V_{CE} is proportional to it, and can be very small.

If $I_C > I_{C(sat)}$, V_{CE} remains relatively constant with changing I_C, and so the transistor can be considered as a current source.

The bipolar transistor has no overcurrent capability (I_C cannot exceed $I_{C(max)}$), and this maximum operating current is defined by the gain, not by thermal considerations.
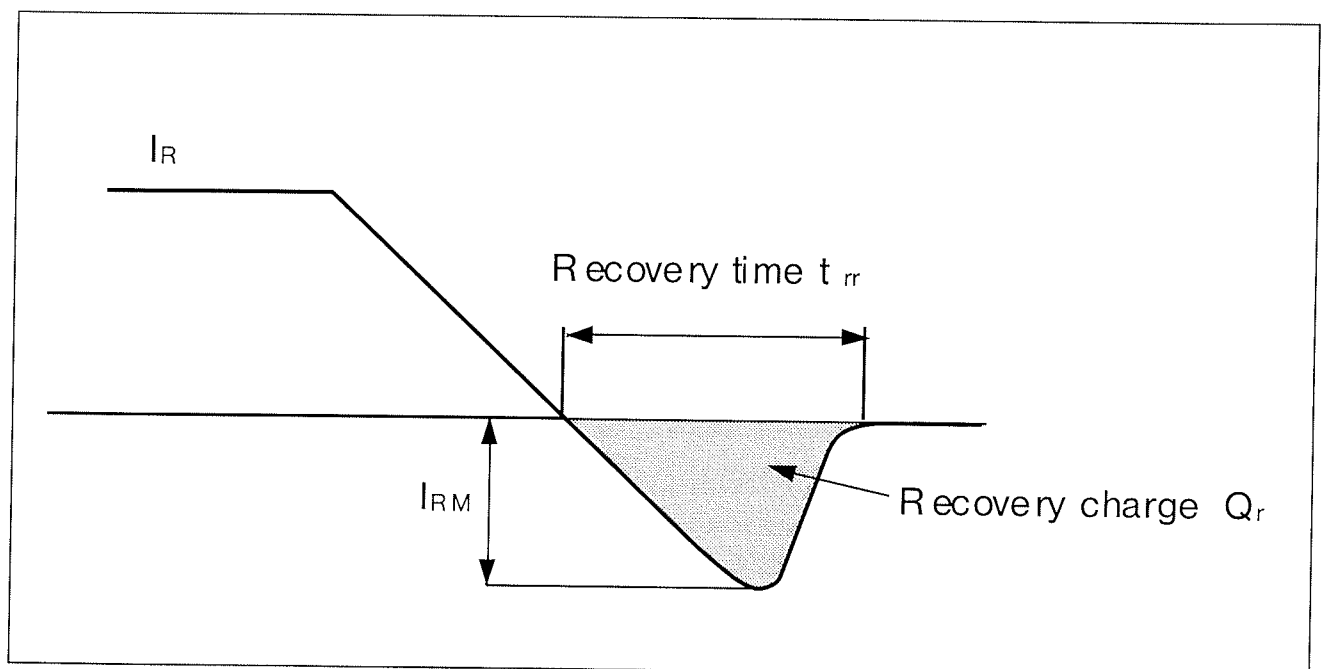

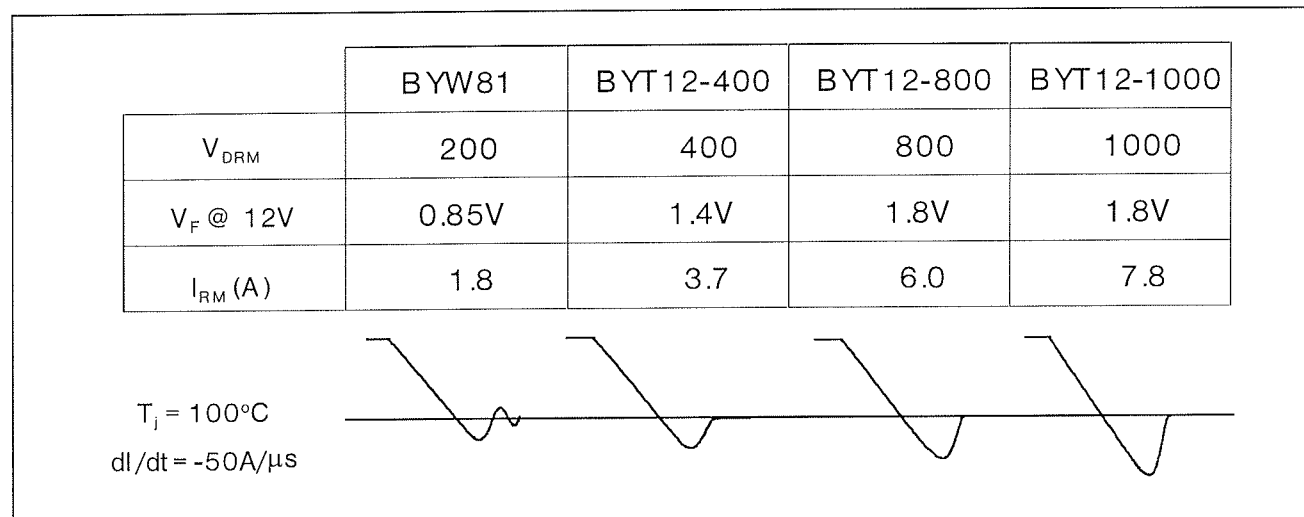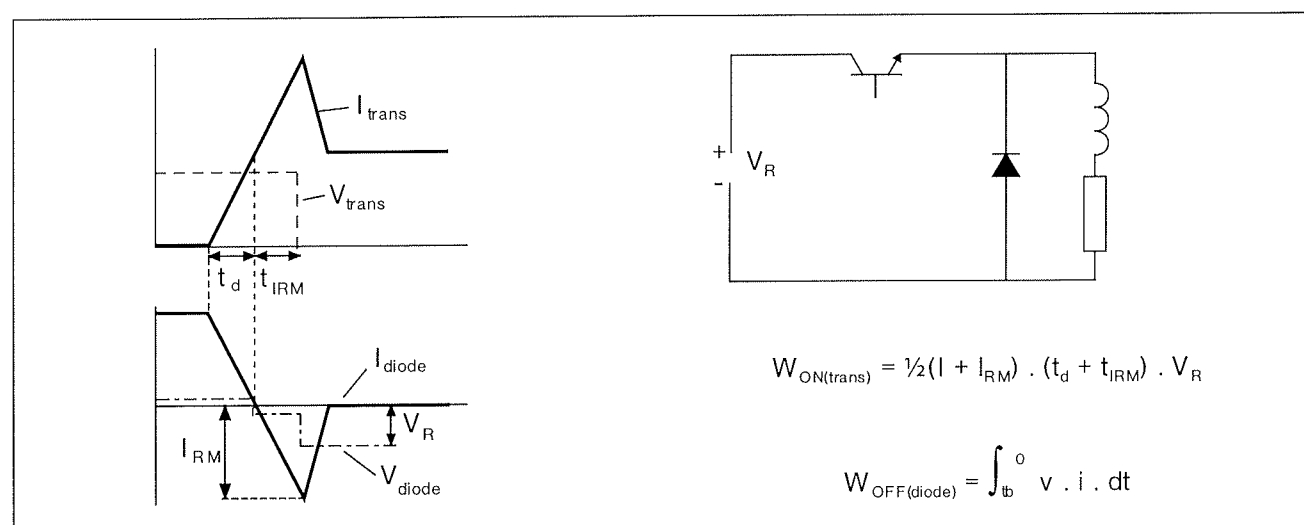Figure 2.   Diode turn-off behaviour

	BYW81	BYT12-400	BYT12-800	BYT12-1000
V_{DRM}	200	400	800	1000
V_F @ 12V	0.85V	1.4V	1.8V	1.8V
I_{RM} (A)	1.8	3.7	6.0	7.8

$T_j = 100°C$

$dl/dt = -50A/\mu s$

Figure 3.   Speed versus VDRM

$$W_{ON(trans)} = \tfrac{1}{2}(I + I_{RM}) \cdot (t_d + t_{IRM}) \cdot V_R$$

$$W_{OFF(diode)} = \int_{tb}^{0} v \cdot i \cdot dt$$

Figure 4.   Freewheel diode losses

$$W_{OFF(diode)} = \int v \cdot i \cdot dt$$

$$W_{ON(trans)} = W_D + \tfrac{1}{2} I \cdot I^2_{RM}$$
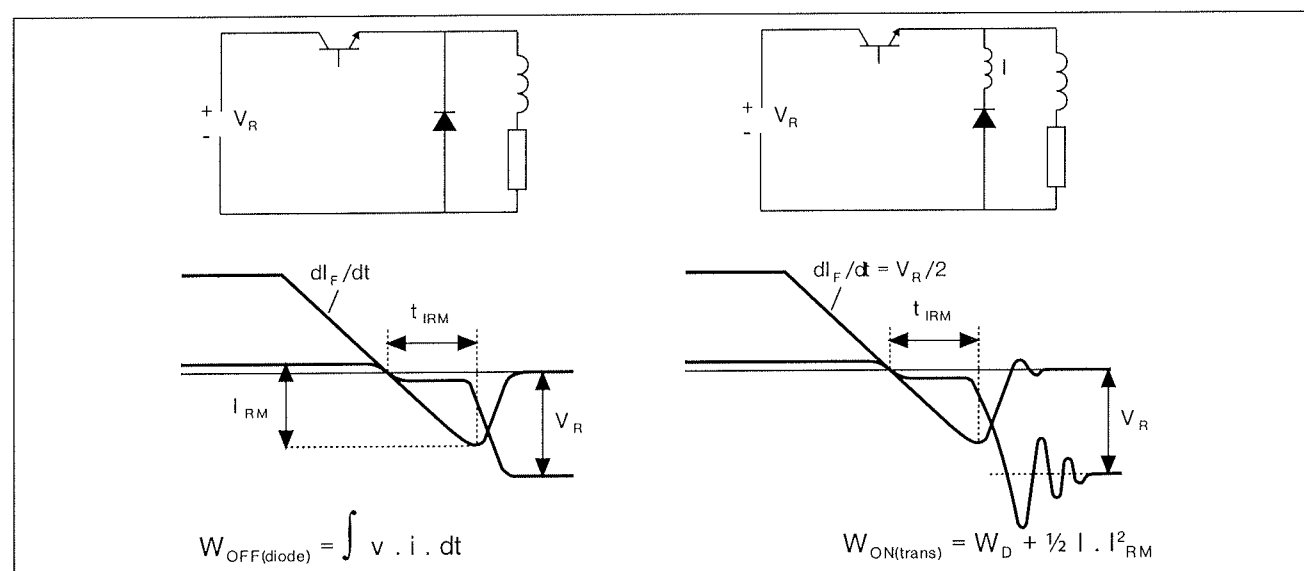
Figure 5.   Effect of circuit topology on diode behaviour
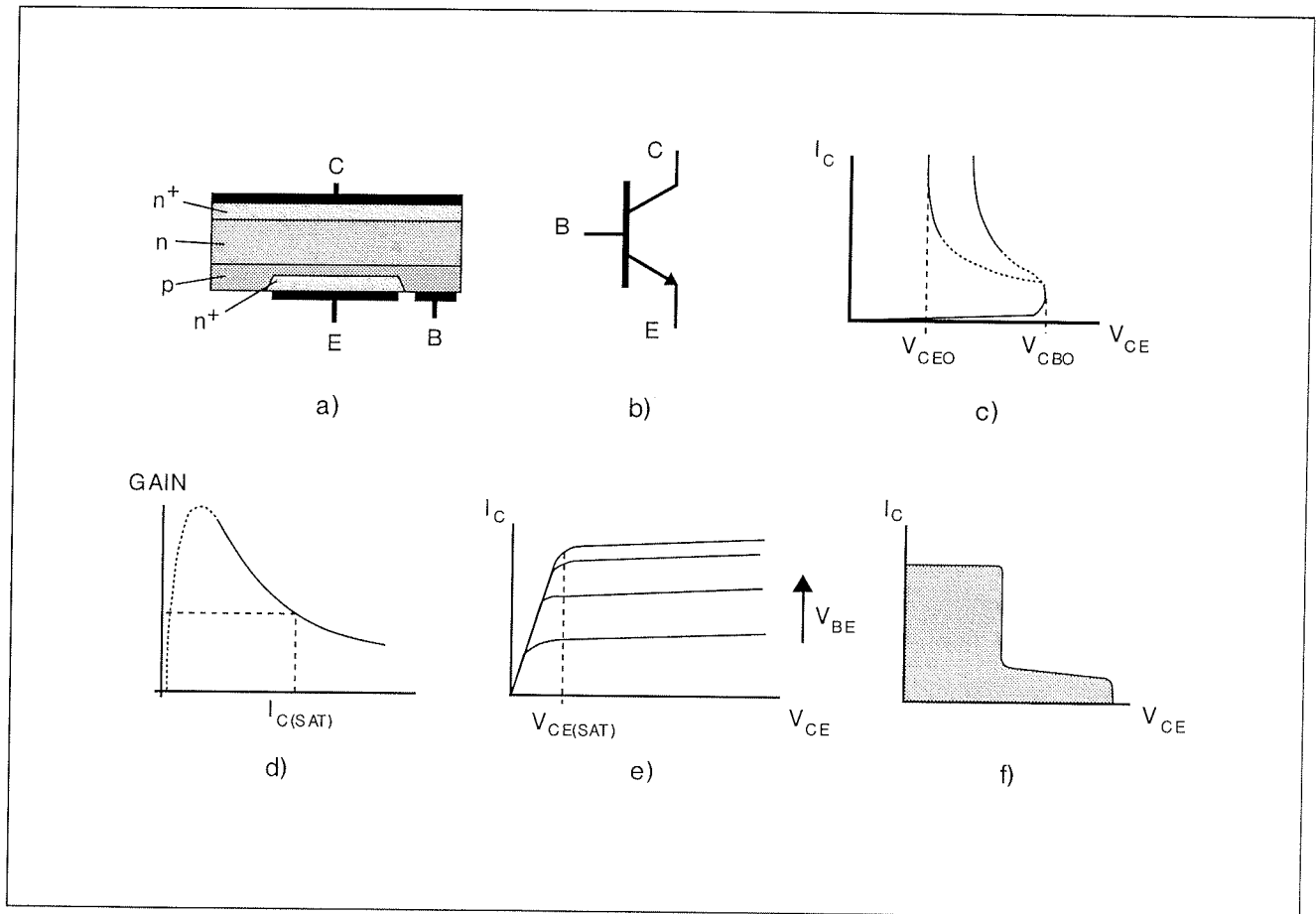
Figure 6. The Bipolar Transistor: a) *Simplified structure*   d) *Output characteristics*
b) *Circuit symbol*   e) *Forward breakdown characteristics*
c) *Gain characteristics*   f)*Forward-bias safe operating area (FBSOA)*

3.2 Voltage

Two parameters define bipolar transistor voltage capability:

- V_{CEV}, the maximum voltage with the base emitter junction blocked ($V_{CEV} = V_{CBO}$, the maximum collector-base voltage).

- V_{CEO}, the maximum voltage with base open.

For switching applications, voltage limits are defined by the Safe Operating Area (SOA). (V_{CEW}, the working voltage at high current, is often equal to V_{CEO}).

Maximum capabilities for the early 1990s

	V_{CEO}	V_{CEV}	$I_{C(sat)}$
Fast transistors	800V	1300V	60A
Slow transistors	1000V	1400V	400A

Voltage drop: If $I_C < I_{C(sat)}$ the voltage drop (with optimised drive) is very low.

$$V_{CE} = \frac{I_C}{I_{C(sat)} \cdot V_{CE(sat)}}$$

3.3 Drive requirements

See figure 7.

The BJT is a current-driven device: during the conducting phase its necessary to deliver a base current

$$I_{B1} = \frac{I_C}{\beta} \qquad \beta = gain$$

At nominal current the gain specified for low voltage transistors ($V_{CEO} < 250V$) is around 10, and for high voltage transistors is around 5, near $I_{C(sat)}$ as defined in the data sheets.

The following empirical relation can be used to estimate gain at other current levels.

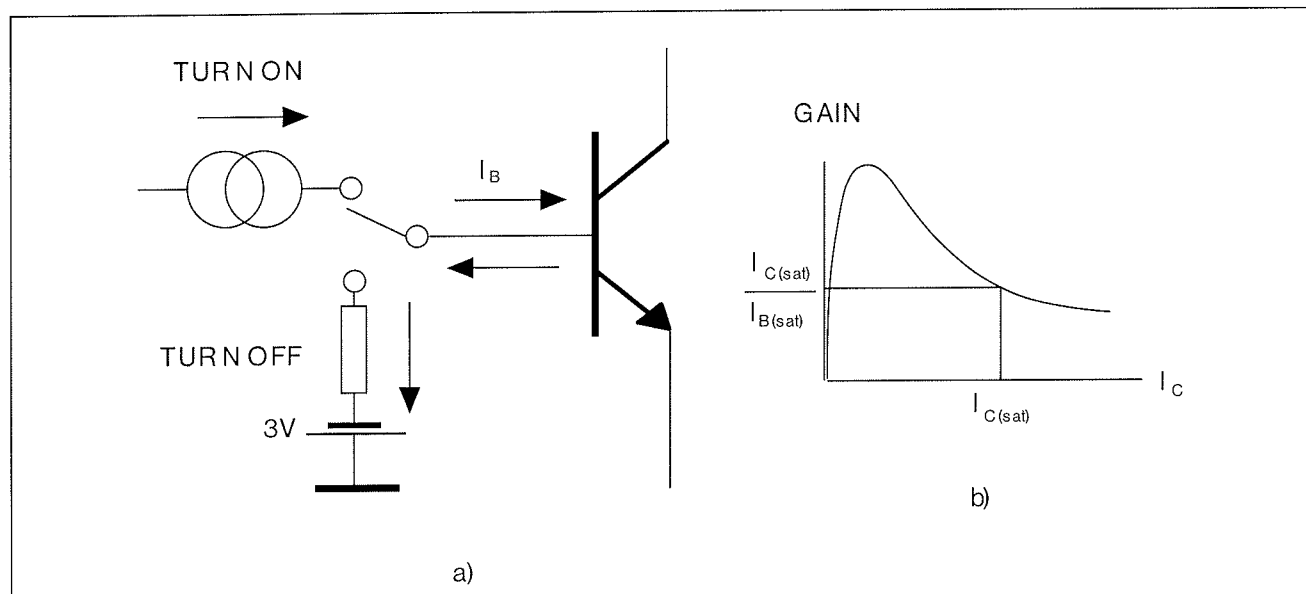$$\beta @ I_C = [\beta @ I_{C(sat)}] \cdot \frac{I_C}{I_{C(sat)}}$$

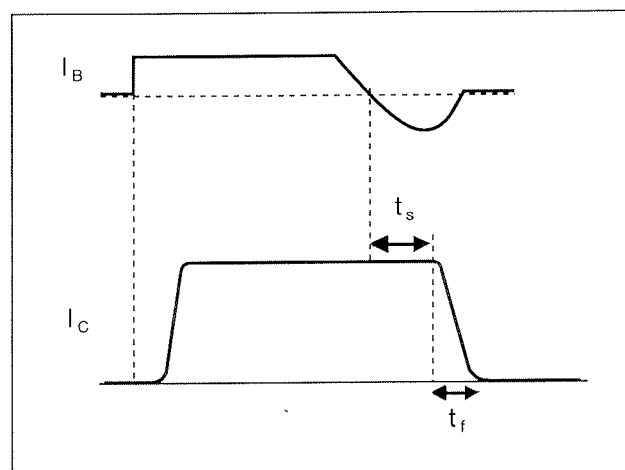Figure 7. Driving a bipolar transistor: a) Driving circuit b) Choosing the base drive current

Figure 8. Bipolar transistor switching times

3.4 Switching times

The total turn-off time toff is the sum of two components (see figure 8):

- The storage time t_s. This is a "memory" effect, due to the storage of minority carriers in the base. (1s for V_{CEO} = 100V, 3s for V_{CEO} = 400V).

- The fall time t_f. The majority of switching losses are due to the fall time (but modern transistors using cellular technology have very small fall times).

To ensure fast turn-off, it is necessary to force a negative current I_{B2} in the base to increase the rate of recombination of minority carriers.

3.5 The Darlington

This is a structure which behaves like two bipolar transistors connected, as shown in figure 9: the first acting as a driver, and the second as a power stage.

The Darlington offers higher gain than a conventional BJT, and the ability to operate at higher current density (because the gain of the power stage can be very high), but these advantages are offset by a higher voltage drop:

$$V_{CE(sat)} \text{ Darlington} = 0.8V + V_{CE(sat)} \text{ BJT}$$

and also the increased turn-off time - the power stage transistor can only begin to turn off after the driver has turned off.
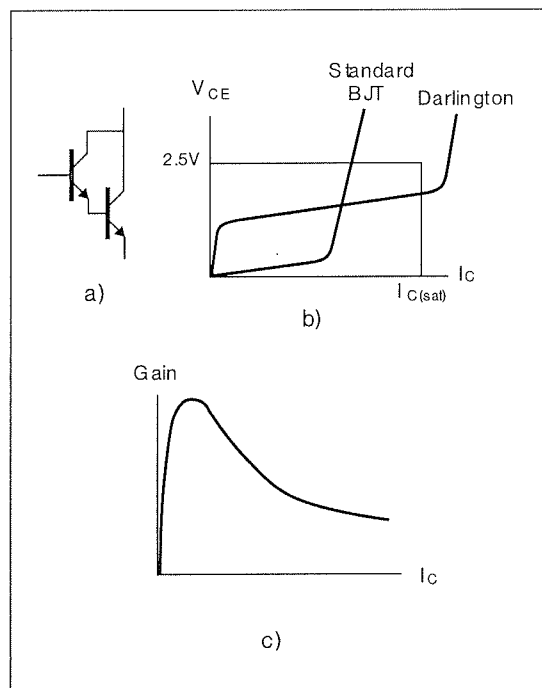

Figure 9. Darlington Transistor characteristics
a) Equivalent structure
b) Output characteristics
c) Gain characteristics

4.   THE THYRISTOR

»Thyristor« is a generic term for a semiconductor device having four or more layers. The two main members of the family are the Silicon Controlled Rectifier, or SCR (often simply called a thyristor) and the TRIAC (derived from TRIode for Alternating Current). Both share similar current and voltage characteristics. The structure and characteristics of the SCR are shown in figure 10.

The thyristor operates using positive feedback - once the device is turned on or "fired" by applying the current pulse to the gate, it continues to conduct until the current through it falls below a certain small fixed value, known as the holding current. This effect occurs because, as shown in figure 10b, the SCR behaves like two bipolar transistors connected back to back, which once fired effectively provide their own base drive current.

4.1   Current

The maximum operating current is defined, like the power diode, by the rate at which the device is cooled. The thyristor can withstand very high surge currents (within the capabilities of the cooling arrangements).

4.2   Voltage

The blocking voltage can be very high - up to 5kV. Its voltage drop is around 0.8V at low current, rising to 1.2V at nominal current.

4.3   Drive requirements - see figure 11.

Because of the positive feedback, the thyristor needs only a very low current for a short time at turn-on (firing). In practice a small "holding current" is required to maintain the device in conduction. However it has the disadvantage that the device cannot be turned off by controlling the gate current - instead the anode current must be forced to zero, by forcing the anode-cathode voltage to zero. In switching or AC circuits this can be achieved using a resonant LC circuit connected in series or parallel.

4.4   Switching times

When the anode current is forced to zero, the thyristor turns off. However, it is necessary to wait for a time tq (the turn-off time, like the fall time of a bipolar device) before the anode voltage is reapplied - otherwise the device will continue to conduct.

4.5   The TRIAC

The TRIAC is effectively two SCRs connected in anti-parallel, with a single gate - see figure 12. This device can conduct current in both directions (ie from A1 to A2 and from A2 to A1) and so can be used to control the flow of AC currents - the current through the device will fall below the holding current every half cycle, and at this point the device will turn off automatically unless it is refired. Hence for continuous conduction the device must be refired at twice the frequency of the current it is conducting.
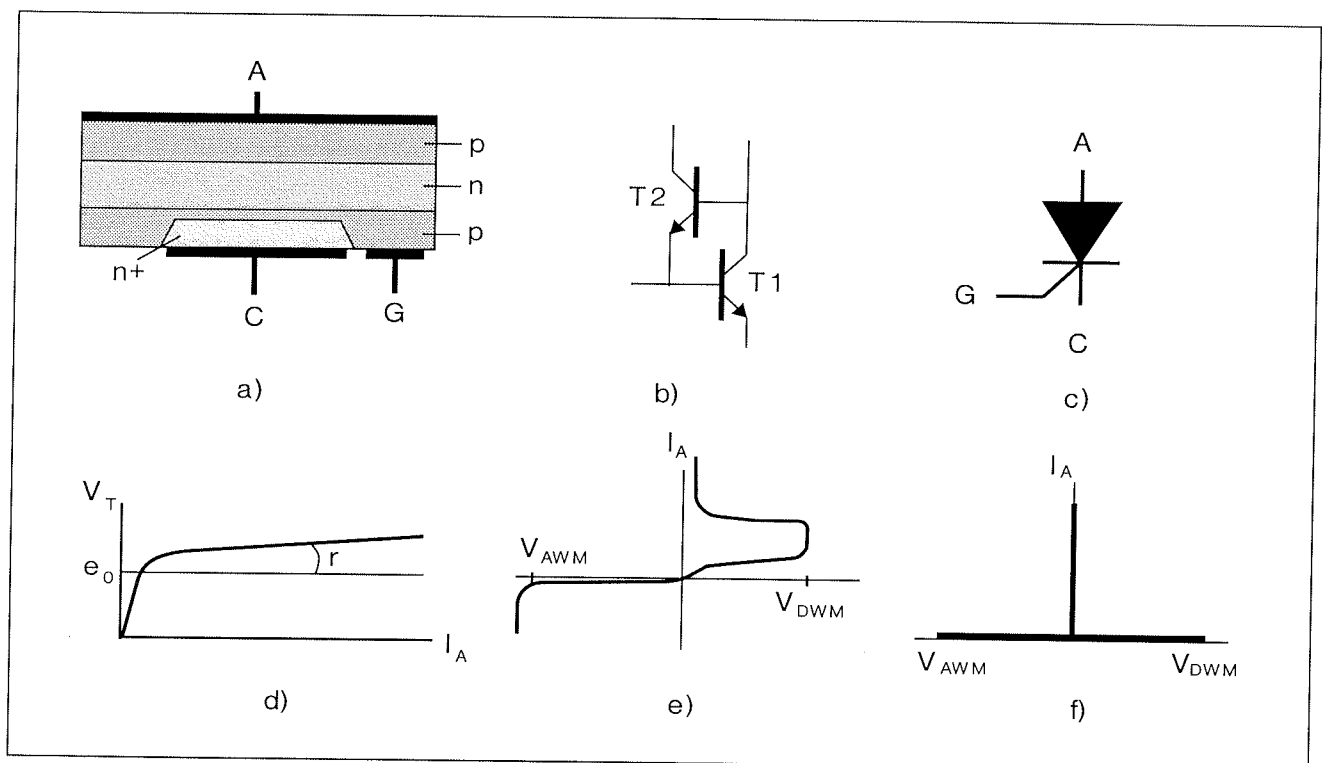

Figure 10.   The SCR: a) Simplified structure   d) Current limits
                          b) Equivalent circuit   e) Voltage limits
                          c) Circuit symbol   f) Switching Safe Operating Area
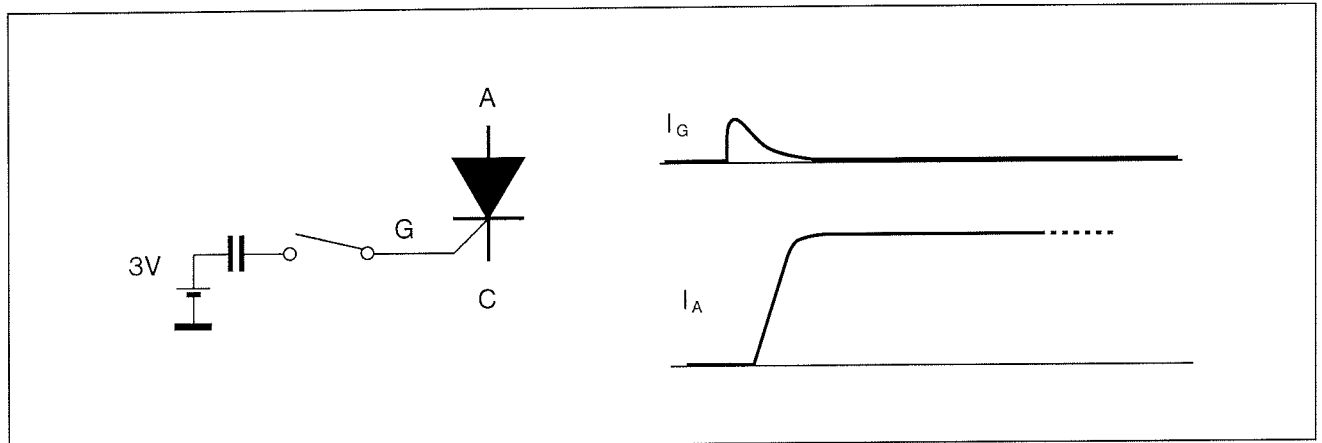
Figure 11.   Thyristor drive requirements

As shown in figure 13, the TRIAC can operate in one of two ways:

a)   The device is fired on only for a certain proportion of AC half waves, or

b)   The firing of the device can be delayed such that only a portion of each half wave is allowed through. This is known as phase control.

Operating in the first way, the device can be used as a simple on-off AC switch, while used in the second way, the device can be used to control AC power - for example as a speed control for an AC motor.
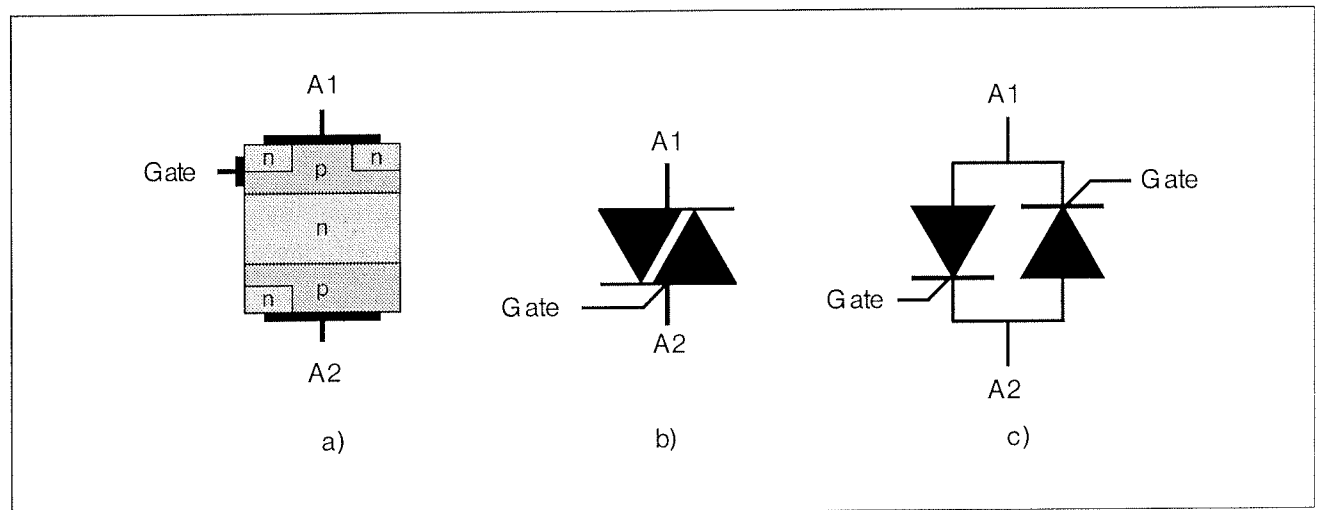

Figure 12. The TRIAC   a) Simplified structure   b) Circuit symbol   c) Equivalent circuit

5   THE GTO see figure14.

The GTO is another "positive feedback" component and is similar to the thyristor, but it has an interdigitated structure, as shown in figure 14. Consequently it has similar characteristics to the thyristor, but it can be blocked like a transistor.

5.1   Voltage

GTOs can support up to around 4kV with a maximum rated current of 1kA. During turn-off the maximum voltage is defined by the SOA. The GTO has a poor S.O.A. when operating at high currents. Its voltage drop is marginally higher than that of the thyristor.

5.2   Drive requirements see figure 15.

The GTO requires a very high negative gate current to turn-off quickly; its has a gain of only 3 which means it requires a sophisticated and expensive gate drive if it is to be run at any speed. This means that it is often impractical to use a charge extracting drive circuit, and so the device has a "tail effect" whereby the device still conducts while the minority carriers combine naturally.
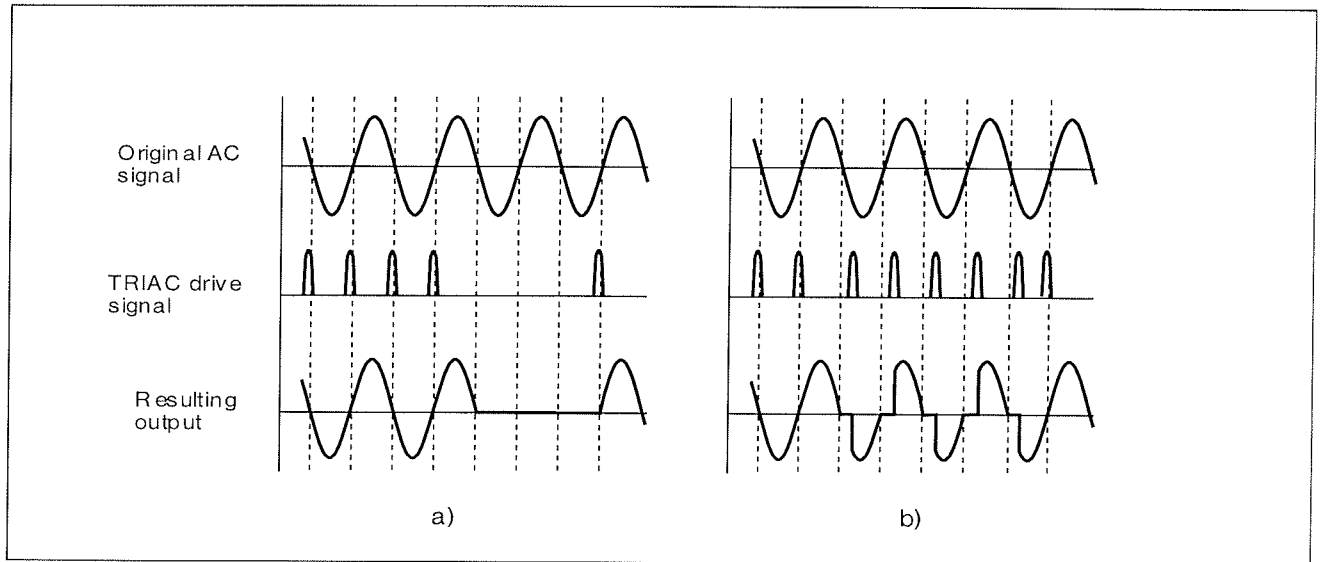
Figure 13. Driving a TRIAC: a) Using as an on-off switch   b) Phase control

5.3 Switching times - see figure 16

Like the bipolar transistor the GTO has a storage time, and during the fall time its tail effect considerably increases the turn-off losses.

6 THE POWER MOSFET see figure 17.

This component uses only majority carriers in conduction, which accounts for its specific behaviour.

The majority carriers flow into the component due to the influence of gate voltage; the current cannot be limited by a "gain phenomenon". Hence the voltage drop depends only on the resistance of the silicon path between the drain and source, $R_{DS(ON)}$.

6.1 Current

The maximum operating current is defined, as for a diode, by the rate at which it is cooled. Its surge current capabil-
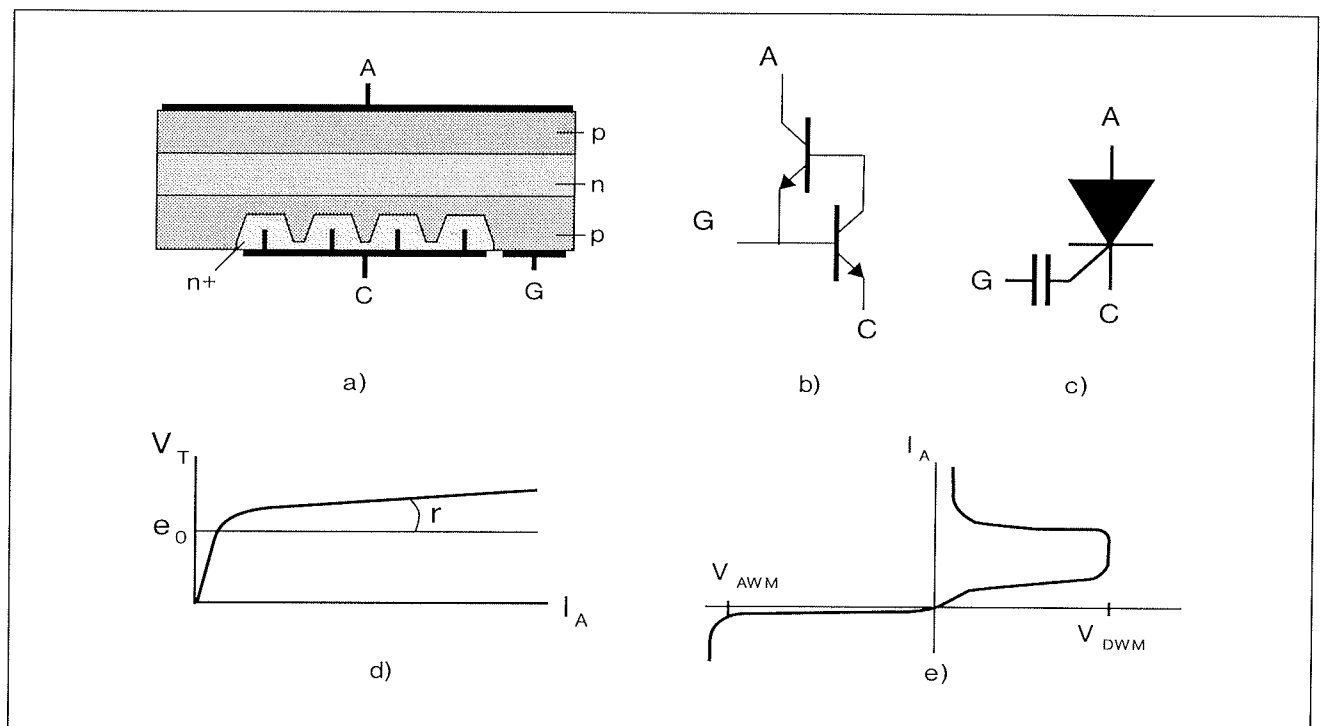

Figure 14. The Gate Turn-Off Thyristor: a) Simplified structure   d) Current limits
                                                   b) Equivalent circuit   e) Voltage limits
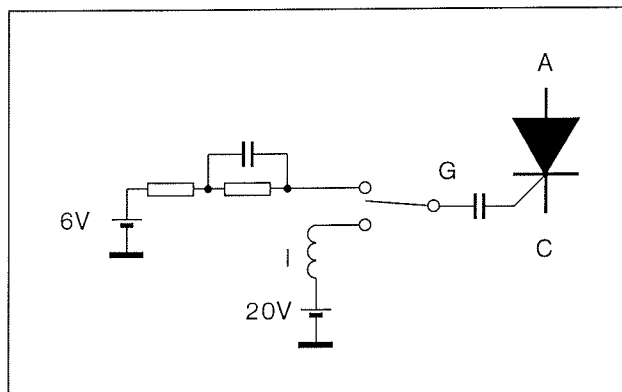   c) Circuit symbol
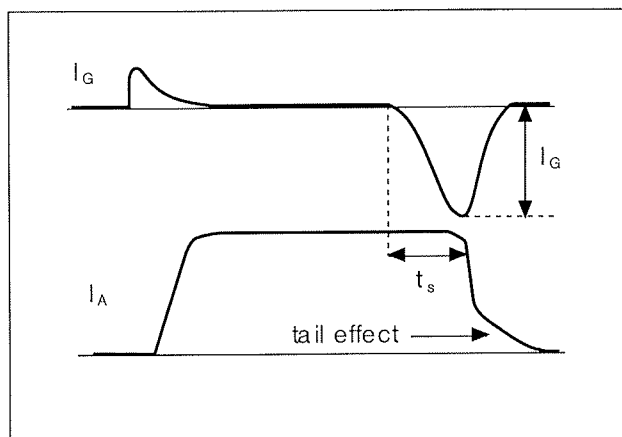
Figure 15.   Driving a GTO

Figure 16.   GTO switching times

ities are defined by the thermal time constant of cooling arrangements (figure 18).

6.2   Voltage

Because the area of silicon used and hence $R_{DS(ON)}$ increase considerably with the maximum rated voltage, this voltage is currently limited to around 1000V.

The MOSFET has a large S.O.A, as it is able to sustain its maximum rated voltage during turn-off.

Present technology current ratings are governed by the following $R_{DS(ON)}$ (25°C) values for the relevant voltage ranges.

$R_{DS(ON)}$ @ 25°C (mW)	Max. rated voltage (V)
77	100
850	500
3500	1000

It is frequently said that the MOSFET has a very high voltage drop, but this is not correct. The MOSFET voltage drop,

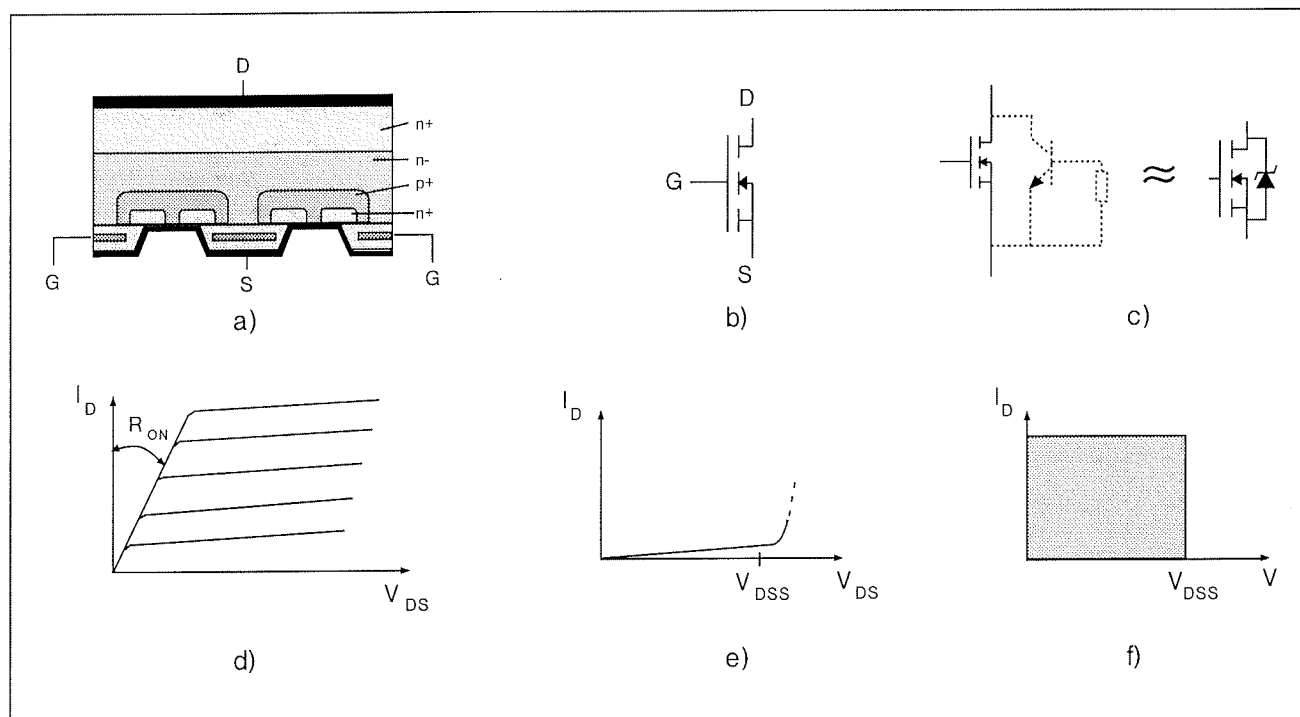Figure 17. The Power MOSFET: a) Simplified structure
                                  b) Circuit symbol
                                  c) Equivalent circuit

d) Output characteristics
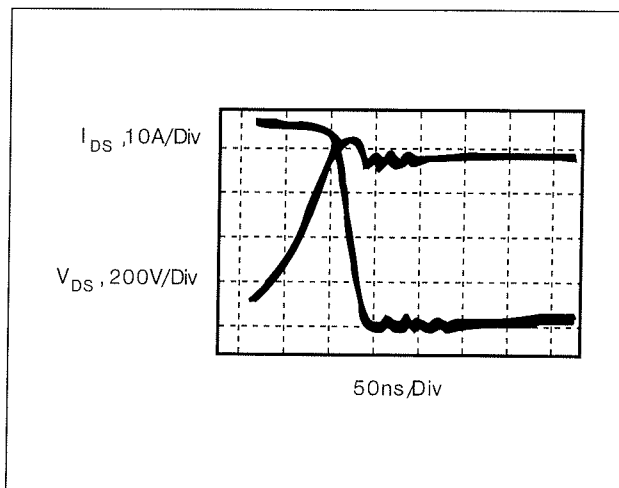e)Forward breakdown characteristics
f) Switching Safe Operating Area

Figure 18.   Turnoff with high current

$R_{DS(ON)}$.I, can be very low at a low current density, though that would be compensated by the need for a large silicon surface area.

The $R_{DS(ON)}$ is (unfortunately) specified in manufacturers datasheets at 25°C. At a more realistic operating temperature:

$$R_{DS(ON)} @ 100°C \approx 1.7 \times R_{DS(ON)} @ 25°C$$

6.3   Drive requirements

During conduction the gate requires only a voltage (approximately 15V) without any significant energy consumption - see figure 19.

MOSFETs turn off very quickly when the gate-source voltage falls to zero. However, the prescence of a capacitance between the gate and source means that to switch the device, charge must be supplied or removed to make the gate voltage rise or fall.

The designer must consider losses due to the charge/ discharge of this capacitance at each turn-on/off.

6.4   Switching times

The MOSFET, a majority carrier device, has no storage time. This is very important for many applications. Fall time (depending on drive) can be very small, but for a rated voltage higher than 300V, it is approximately the same for both fast bipolar and MOSFET devices.

7   THE IGBT see figure 20.

The IGBT can be considered as a pseudo-Darlington with a MOSFET as driver and a bipolar transistor as the power stage.

7.1   Current

The maximum current is generally limited by cooling. It has over-current capability.

7.2   Voltage

At present, the maximum rated voltage is 1.2kV. This limit is rapidly increasing towards 1800V and a maximum rated current of 500A. The SOA is approximately rectangular.

The voltage drop across the IGBT is relatively constant with respect to the current. This means that at high current levels, conduction losses are lower than those of a MOSFET, but at low current levels they are considerably higher. This causes a limit to the efficiency of IGBT circuits.

7.3   Drive requirements

Similar to the MOSFET drive (figure 21).
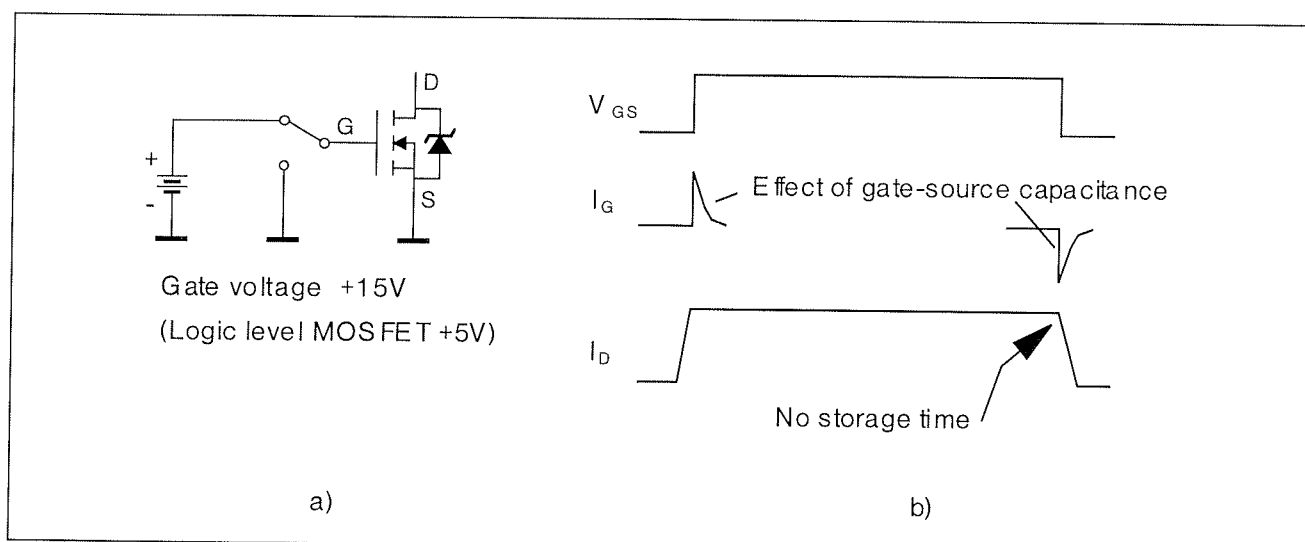

Figure 19:   a) Driving a Power MOSFET   b) MOSFET switching waveforms
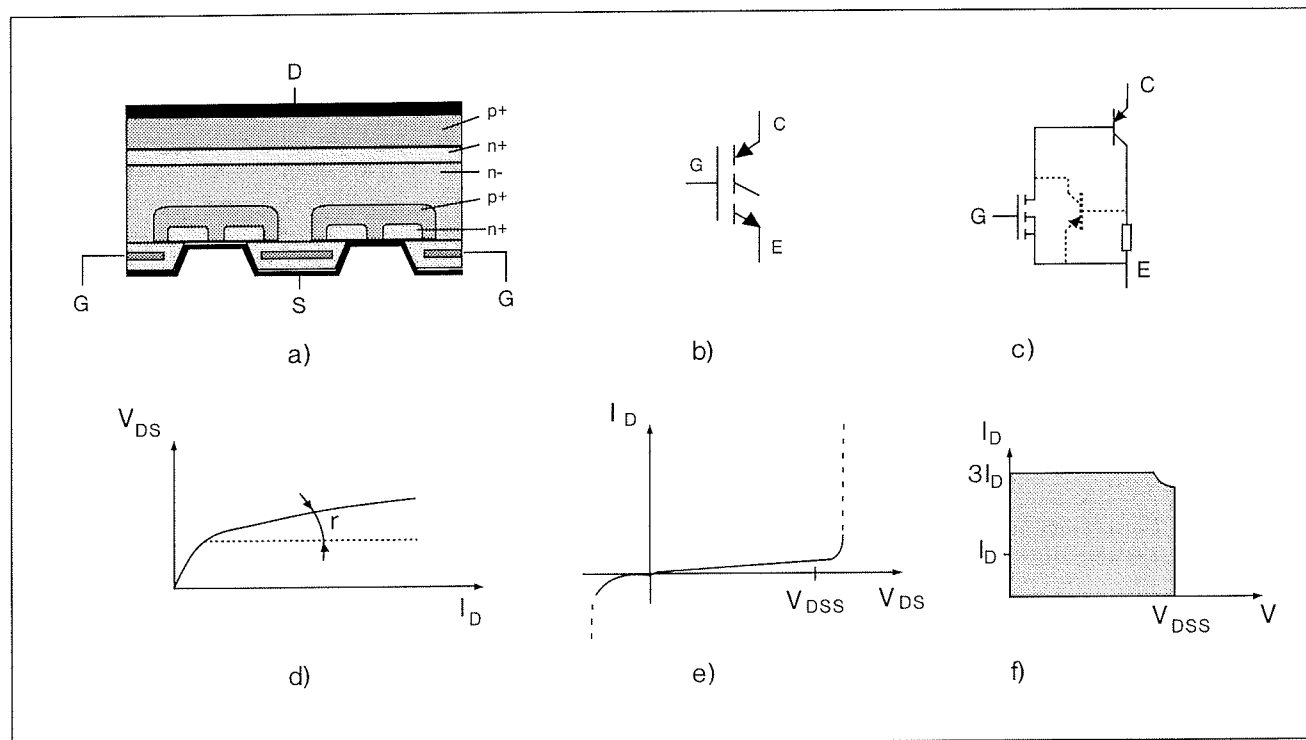
Figure 20. The IGBT:
   a) Simplified structure
   b) Circuit symbol
   c) Equivalent circuit

d) Output characteristics
e) Forward breakdown characteristics
f) Switching Safe Operating Area

7.4 Switching times

The MOSFET stage has practically no storage time, but the bipolar section causes a tail current like that in the GTO, where the device continues to conduct due to the presence of residual minority carriers in the base. As the base section of the device cannot be accessed externally to remove these charges, this tail current persists until the carriers recombine naturally. This current causes switching losses, which increase with operating frequency.
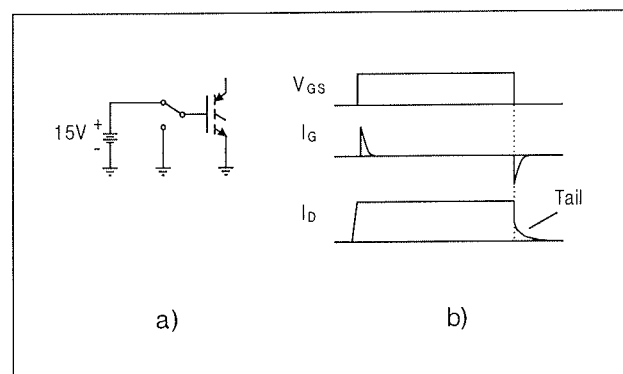

Figure 21.   Driving an IGBT.
    a) Driving circuit
    b) Switching waveforms

8. LIMITS AND MAXIMUM RATINGS

The absolute maximum ratings are defined by the semiconductor manufacturer. These ratings must not be exceeded under any circumstances - to do so risks destroying the component. Examples of maximum ratings are the maximum junction temperature $T_{j(max)}$, the maximum current and the maximum blocking voltage.

It should be noted that the user cannot measure these parameters, as the device will probably be destroyed in the attempt. Characteristics which may be measured are for example the collector-emitter saturation voltage $V_{CE(sat)}$, and the switching times.

The manufacturer specifies a maximum and/or minimum value, depending on the parameter. In the design of circuits it is important to take into account the "worst case" value of the component, and to verify that the circuit operates correctly with the spread of all parameters.

9. CHOOSING THE RIGHT SEMICONDUCTOR

When selecting the type of semiconductor device to use in a particular application, the designer must take into account a number of factors, such as:

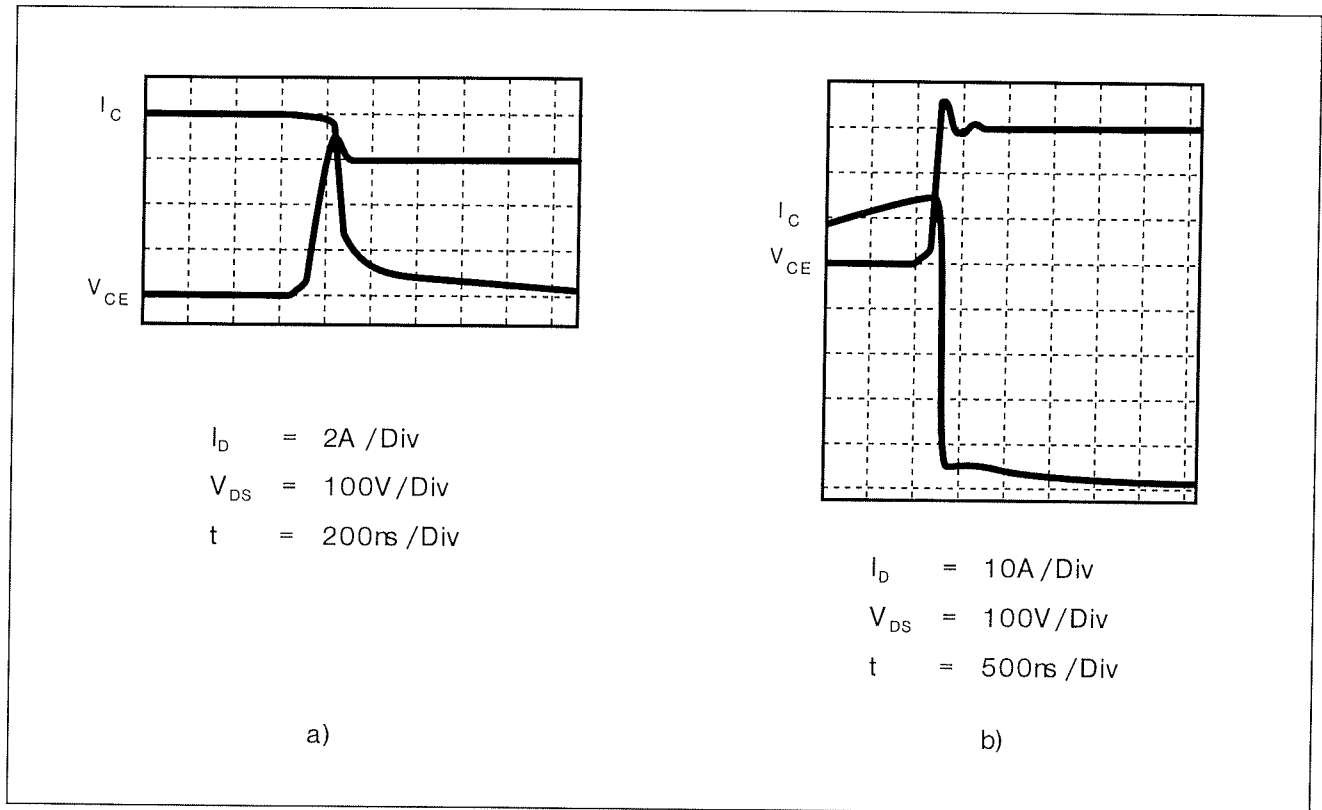i)   The cost of the device, and the cost constraints on the application.

I_D = 2A /Div

V_{DS} = 100V/Div

t = 200ns /Div

a)

I_D = 10A/Div

V_{DS} = 100V/Div

t = 500ns /Div

b)

Figure 22. IGBT Switch-off behaviour: a) Normal current   b) Very high surge current

ii)   The magnitude of voltages and currents encountered.

iii)   The drive requirements of the device - the need for a complex drive circuit can increase design time and the cost of the circuit.

iv)   The frequency at which the device will switch.

9.1   Typical applications of each type

9.1.1 Bipolar transistors

In general terms bipolar transistors compete with Power MOSFETs and IGBTs. Their main advantage over these types is the lower cost, particularly for high voltage devices, while their main disadvantages are the cost of the drive circuit and the limit on their switching speed imposed by the storage and fall times. The applications in which they are used are typically characterised by low to medium operating frequency and high voltage, where they result in a cheaper solution than the equivalent MOSFET or IGBT. Examples are in electronic lamp ballasts, automotive ignition switches, and horizontal deflection circuits in TVs and monitors.

9.1.2 Power MOSFETs

The main advantages of Power MOSFETs are their minimal drive requirements and ability to operate at high frequencies. In power supplies, operation at high frequencies allows the size of circuit magnetics to be reduced, decreasing the circuit cost. In compact fluorescent lamp ballasts (such as those used in domestic environments)

operating at high frequencies leads to smaller overall dimensions. The low currents and relatively low voltages in this application means that in this case the Power MOSFET leads to a cheaper solution than the power bipolar.

Power MOSFETs are also frequently used as power actuators (solid-state relays) in automotive circuits, because of the low voltages involved means that they are inexpensive, and types are available which can be driven directly from a microprocessor, which are increasingly being used to control automotive systems.

9.1.3 IGBTs

The main applications of IGBTs are in motor control and automotive ignition - again these are characterised by high voltages and relatively low operating frequencies. In these applications they compete with bipolars. Although the basic device is more expensive than a bipolar transistor, the minimal drive requirements can lead to a cheaper overall solution, particularly where there is a need to interface with a microprocessor. Its main disadvantage is the unavoidable losses caused by the tail current (which become more significant at high frequencies),

9.1.4 GTOs

GTOs are used in conditions of very high voltage and very high current, and low switching frequencies. An example of their use is in electric trains.

9.1.5 Thyristors

This component is very cheap, but its use is limited by the difficulty of turning it off. It can be used to control devices which can be fed with half-wave rectified AC current, for example DC motors (when it will turn off automatically every half cycle, like the TRIAC), and also to protect other devices, for example in power supplies.

9.1.6 TRIACs

TRIACs are unique in their ability to conduct and control current in both directions. They are the cheapest way of controlling AC currents, for example in AC motor speed controls or lamp dimmers.

11. CONCLUSION

"Power MOSFET has very high voltage drop"

"Bipolar ... an old technology"

"Epitaxial is better..."

This type of commercial jargon does not help the designer to produce optimal circuits. At the present time the designer has a choice between a lot of components. Which is the best solution? The answer is, there is no best solution - this is the field of technical design, not scientific research.

For some applications, for example 1MHz Switch Mode Power Supplies, only one solution (MOSFET) is possible. For most applications, there are always several solutions. The designer's job is to optimize the "switching function"after thorough analysis. Experience shows that the quality of this analysis, and the work done by the designer (drive, protection, etc.) play a bigger role in the total cost than the actual price of the component.

REFERENCES

/1/   Transistors and Diodes in Power Processing THOMSON SEMI-CONDUCTOR 1985

/2/   Power Transistor application manual SGS-THOMSON 1989

/3/   Parallel Operation of Fast Rectifiers SGS-THOMSON Application Note