SECTION 13

POWER ELECTRONICS

Power electronics deals with the application of electronic devices and associated components to the conversion, control, and conditioning of electric power. The primary characteristics of electric power, which are subject to control, include its basic form (ac or dc), its effective voltage or current (including the limiting cases of initiation and interruption of conduction), and its frequency and power factor (if ac). The control of electric power is a means for achieving control or regulation of one or more nonelectrical parameters, e.g., the speed of a motor, the temperature of an oven, the rate of an electrochemical process, or the intensity of lighting.

Aside from the obvious difference in function, power-electronics technology differs markedly from the technology of low-level electronics for information processing in that much greater emphasis is required on achieving high-power efficiency. Few low-level circuits exceed a power efficiency of 15 percent, but few power circuits can tolerate a power efficiency less than 85 percent. High efficiency is vital, first, because of the economic and environmental value of wasted power and, second, because of the cost of dissipating the heat it generates. This high efficiency cannot be achieved by simply scaling up low-level circuits; a different approach must be adopted.

This different approach is attained by using electronic devices as switches, e.g., approximating ideal closed (no voltage drop) or open (no current flow) switches. This differs from low-level digital switching circuits in that digital systems are primarily designed to deliver two distinct small voltage levels while conducting small currents (ideally zero). Power electronic circuits, though, must have the capability of delivering large currents and be able to withstand large voltages. Power can be controlled and modified by controlling the timing of repetitive switch action. Because of wear and limited switching speed, mechanical switches are ordinarily not suitable, but electronic switches have made this approach feasible into the multigigawatt power region while maintaining high-power efficiencies over wide ranges of control. However, the inherent nonlinearity of the switching action leads to the generation of transients and spurious frequencies that must be considered in the design process.

Reliability of the power electronics circuits is just as important as efficiency. Modern power converter and control circuits must be extremely robust, with MTBF (mean time between failure) for typical systems in the order of 1,000,000 h of operation.

Power electronic circuits are often divided into categories depending on their intended function. Converter circuits that change ac into dc are called rectifiers, circuits that change the dc operating voltage or current are called dc-to-dc converters, circuits that convert dc into ac power are called inverters, and those that change the amplitude and frequency of the ac voltage and/or current without using an intermediate dc stage are ac-to-ac converters (also called cycloconverters).

Rectifiers are used in many power electronics applications because of the widespread availability of ac power sources, and rectification is often a first step in the power conditioning scheme. Rectifiers are used in very low voltage systems (e.g., 3 V logic circuits) as well as very high voltage applications of commercial utilities. The control and circuit topology can vary according to the application requirements.

Dc–dc converters have many implementations that depend on the intended application, and can make use of different types of input power sources. Often, ac power is rectified and filtered to supply the requisite input dc levels. An inverter section is then used to transform the dc power to high frequency ac voltage or current, which a transformer then steps up or down. The new ac from the transformer secondary is then rectified and filtered to provide the desired output dc level. Other dc–dc converters step voltage up or down without the intervening transformer.

Inverters convert dc into ac power. Many applications require the production of three-phase power waveforms for speed control of large motors used in industry. The reconstruction of single-frequency, near-sinusoidal voltage, or current waveforms requires precisely controlled switching circuits. The exact mode and timing of the switching action in the associated power electronic devices can be complex, especially when regenerative schemes are employed to recover energy from the mechanical system and convert it back to electrical energy for more efficient operation. Inverter circuit design and control has been the subject of much research and development over the past several decades.

Ac–ac power control, without changing frequency, is accomplished by simple converters that allow conduction to begin at a time past the zero-crossing of the voltage or current waveform (referred to as phase control), or more complex converters that create completely new amplitudes and frequencies for the output ac power.

Note: Original contributions to this section were made by W. Newell. Portions of the material on diodes were contributed by P. F. Pittman, J. C. Engel, and J. W. Motto. D.C.

In This Section:

CHAPTER 13.1
POWER ELECTRONIC DEVICES

Jerry L. Hudgins

POWER ELECTRONIC DEVICE FAMILIES

Power electronic devices have historically been separated into three broad categories: diodes, transistors, and thyristors. Modern devices can still be classified in this way, though there is increasing overlap in device design and function. Also, new materials as well as novel designs have increased the suitability and broadened the applications of semiconductor switches in energy conversion circuits and systems. Diodes are two-terminal devices that perform functions such as rectification and protection of other components. Diodes are not controllable in the sense that they will conduct current when a positive forward voltage is applied between the anode and cathode. Transistors are three-terminal devices that include the traditional power bipolar (two types of charge carriers), power MOSFETs (metal-oxide-semiconductor field-effect transistor), and hybrid devices that have some aspect of a control-FET element integrated with a bipolar structure, such as an IGBT (insulated-gate bipolar transistor). Thyristors are also three-terminal devices that have a four-layer structure (several *p-n* junctions) for the main power handling section of the device. All transistors and thyristor types are controllable in switching from a forward blocking state (very little current flows) into a forward conduction state (large forward current flows). All transistors and most thyristors (except SCRs) are also controllable in switching from forward conduction back to a forward blocking state.

Typically, thyristors are used at the highest energy levels in power conditioning circuits because they are designed to handle the largest currents and voltages of any device technology (systems approximately with voltages above 3 kV or currents above 100 A). Many medium-power circuits (systems operating at less than 3 kV or 100 A) and particularly low-power circuits (systems operating below 100 V or several amperes) generally make use of transistors as the main switching elements because of the relative ease in controlling them. IGBTs are also replacing thyristors (e.g., GTEs) in industrial motor drives and traction applications as the IGBT voltage blocking capability improves. Diodes are used throughout all levels of power conditioning circuits and systems.

COMMON DEVICE CHARACTERISTICS

A high-resistivity region of silicon is present in all power semiconductor devices. It is this region that must support the large applied forward voltages that occur when the switch is in its off state (nonconducting). The higher the forward blocking voltage rating of the device, the thicker this region must be. Increasing the thickness of this high-resistivity region results in slower turn-on and turn-off (i.e., longer switching times and/or lower frequency of operation). For example, a device rated for a forward blocking voltage of 5 kV will by its physical construction switch much more slowly than one rated for 100 V. In addition, the thicker high-resistivity region of the 5 kV device will cause a larger forward voltage drop during conduction than the 100 V device carrying the same current. There are other effects associated with the relative thickness and layout of the various regions that make up modern power devices, but the major trade-off between forward blocking voltage rating and switching times and between forward blocking voltage and forward voltage drop during conduction should be kept in mind. Another physical aspect of the semiconductor material is that the maximum breakdown voltage achievable using a semiconductor is proportional to the energy difference between the conduction and valence bands (bandgap). Hence, a material with a larger bandgap energy than that in silicon (Si) can in principle achieve the same blocking voltage rating with a thinner high-resistivity region. This is one of the reasons that new semiconductor devices are being designed and are recently becoming available in materials such as silicon carbide (SiC).

The time rate of rise of device current (*di*/*dt*) during turn-on and the time rate of rise of device voltage (*dv*/*dt*) during turn-off are important parameters to control for ensuring proper and reliable operation. Many power electronic devices have maximum limits for *di*/*dt* and *dv*/*dt* that must not be exceeded. Devices capable of conducting large currents in the on-state are necessarily made with large surface areas through which the current flows. During turn-on, localized regions of a device begin to conduct current. If the local current density becomes too large, then heating will damage the device. Sufficient time must be allowed for the entire area to begin conducting before the localized currents become too high and the device's *di*/*dt* rating is exceeded. The circuit designer sometimes adds series inductance to limit *di*/*dt* below the recommended maximum value.

During turn-off, current is decreasing while voltage across the device is increasing. If the forward voltage becomes too high while sufficient current is still flowing, then the device will drop back into its conduction mode instead of completing its turn-off cycle. Also, during turn-off, the power dissipation can become excessive if the current and voltage are simultaneously too large. Both of these turn-off problems can damage the device as well as other portions of the circuit. Another problem that occurs is associated primarily with thyristors. Thyristors can self-trigger into a forward conduction mode from a forward blocking mode if their *dv*/*dt* rating is exceeded (because of excessive displacement current through parasitic capacitances). Protection circuits, known as snubbers, are used with power semiconductor devices to control *dv*/*dt*.

The snubber circuit specifically protects devices from a large *di*/*dt* during turn-on and a large *dv*/*dt* during turn off. A general snubber topology is shown in Fig. 13.1.1. The turn-on snubber is made by inductance L_1 (often L_1 is stray inductance only). This protects the device from a large *di*/*dt* during the turn-on process. The auxiliary circuit made by R_1 and D_1 allows the discharging of L_1 when the device is turned off. The turn-off snubber is made by resistor R_2 and capacitance C_2. This circuit protects the power electronic device from large *dv*/*dt* during the turn-off process. The auxiliary circuit made by D_2 and R_2 allows the discharging of C_2 when the device is turned on. The circuit of capacitance C_2 and inductance L_1 also limits the value of *dv*/*dt* across the device during forward blocking. In addition, L_1 protects the device from reverse overcurrents.

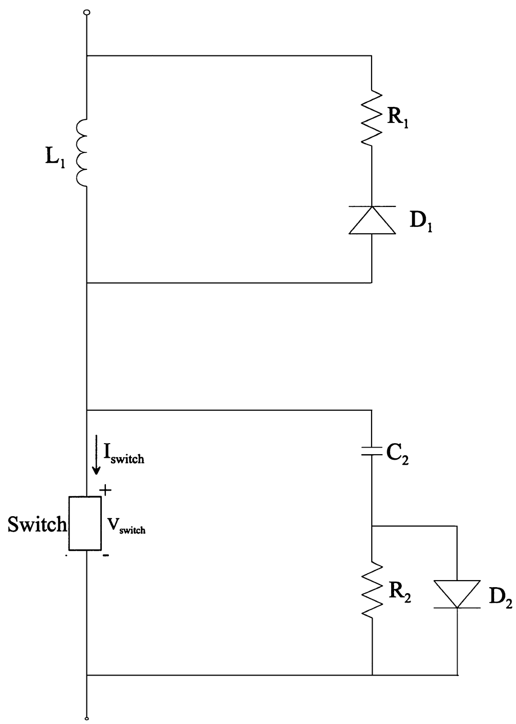


FIGURE 13.1.1 Turn-on (top elements) and turn-off (bottom elements) snubber circuits for typical power electronic devices.

All power electronic devices must be derated (e.g., power dissipation levels, current conduction, voltage blocking, and switching frequency must be reduced), when operating above room temperature (defined as about 25°C). Bipolar-type devices have thermal runway problems, in that if allowed to conduct unlimited current, these devices will heat up internally causing more current to flow, thus generating more heat, and so forth until destruction. Devices that exhibit this behavior are *pin* diodes, bipolar transistors, and thyristors. MOSFETs must also be derated for current conduction and power dissipation when heated, but they do not suffer from thermal runaway as other device types do. IGBTs fall in between the behavior of MOSFETs and bipolar transistors. At low current levels they behave similar to bipolar transistors, whereas operating at high currents causes them to behave more like MOSFETs.

There are many subtleties of power device fabrication and design that are made to improve the switching times, forward voltage drop during conduction, *dv*/*dt*, *di*/*dt*, and other ratings. Many of these improvements cause the loss of the ability of the device to hold-off large applied reverse voltages. In other devices the inherent structure itself precludes reverse blocking capability. In general, only some versions of two types of thyristors have equal (symmetric) forward and reverse voltage hold-off capabilities: GTOs (gate turn-off thyristor) and SCRs (silicon controlled rectifier).

A simple diagram of the internal structure of the major power semiconductor devices, the corresponding circuit symbols, some simple equivalent circuits, and a summary of the principal characteristics of each device are shown in Fig. 13.1.2. A comparison between types of devices illustrating the useable switching frequency range and switched power capability is shown in Fig. 13.1.3. Switched power capability is defined here as the maximum forward hold-off voltage obtainable multiplied by the maximum continuous conduction current. Further information on power electronic devices can be obtained from manufacturer's databooks and applications notes, textbooks (Baliga, 1987, 1996; Ghandi, 1977; Sze, 1981), and in many technical journal publications (including Azuma and Kurata, 1988; Hower, 1988; Hudgins, 1993).

DIODES

Diode Types

Schottky and *pin* diodes are used extensively in power electronic circuits. Schottky diodes are formed by placing a metal layer directly on a lightly doped (usually *n*-type) semiconductor. The naturally occurring potential barrier at the metal-semiconductor interface gives rise to the rectifying properties of the device. A *pin* diode is a *pn*-junction device with a lightly doped (near intrinsic) region placed between the typical diode *p*- and *n*-type regions. The lightly doped region is necessary to support large applied reverse voltages. The diode characteristic is such that current easily flows in one direction while it is blocked in the other. Power Schottky diodes are limited to about 200 V reverse blocking capability because the forward voltage drop becomes excessive in the high-resistivity region of the semiconductor and the lowering of the interface potential barrier (and associated increase in reverse leakage current) owing to the applied reverse voltage also increases (Sze, 1981). However, new Schottky structures made from SiC material are commercially available that have much higher voltage blocking capability. It is likely that these SiC diodes will be available with multi-kV ratings soon.

Reverse blocking of up to 10 kV is obtainable with a *pin* structure in Si. These types of diodes can easily handle surge currents of tens of thousands of amperes and rms currents of several thousand amperes. The *pin* diode has the advantages of much higher voltage and current capabilities than the Schottky diode, though the new SiC Schottky diodes are moving into higher power ratings all the time. Also, *pin* diodes are inherently slower in switching speed than Schottky devices, and for low reverse-blocking values, they have a larger forward voltage drop than Schottky diodes. For devices rated for 50 V reverse blocking, a Schottky diode has a forward drop of about 0.6 V as compared to a *pin* diode's forward drop of about 0.9 V at the same current density. The fast switching of the Schottky structure can be used to advantage in high-frequency power converter circuits. The Schottky's low forward drop can be used to advantage on the output rectifiers of low-voltage converter circuits, also. There have been several structures proposed that merge the features of the *pin* (for high reverse-blocking capability) and Schottky (for fast switching and low forward drop) diodes (Hower, 1988; Baliga, 1987). This concept is beginning to be implemented into the newer SiC diodes.

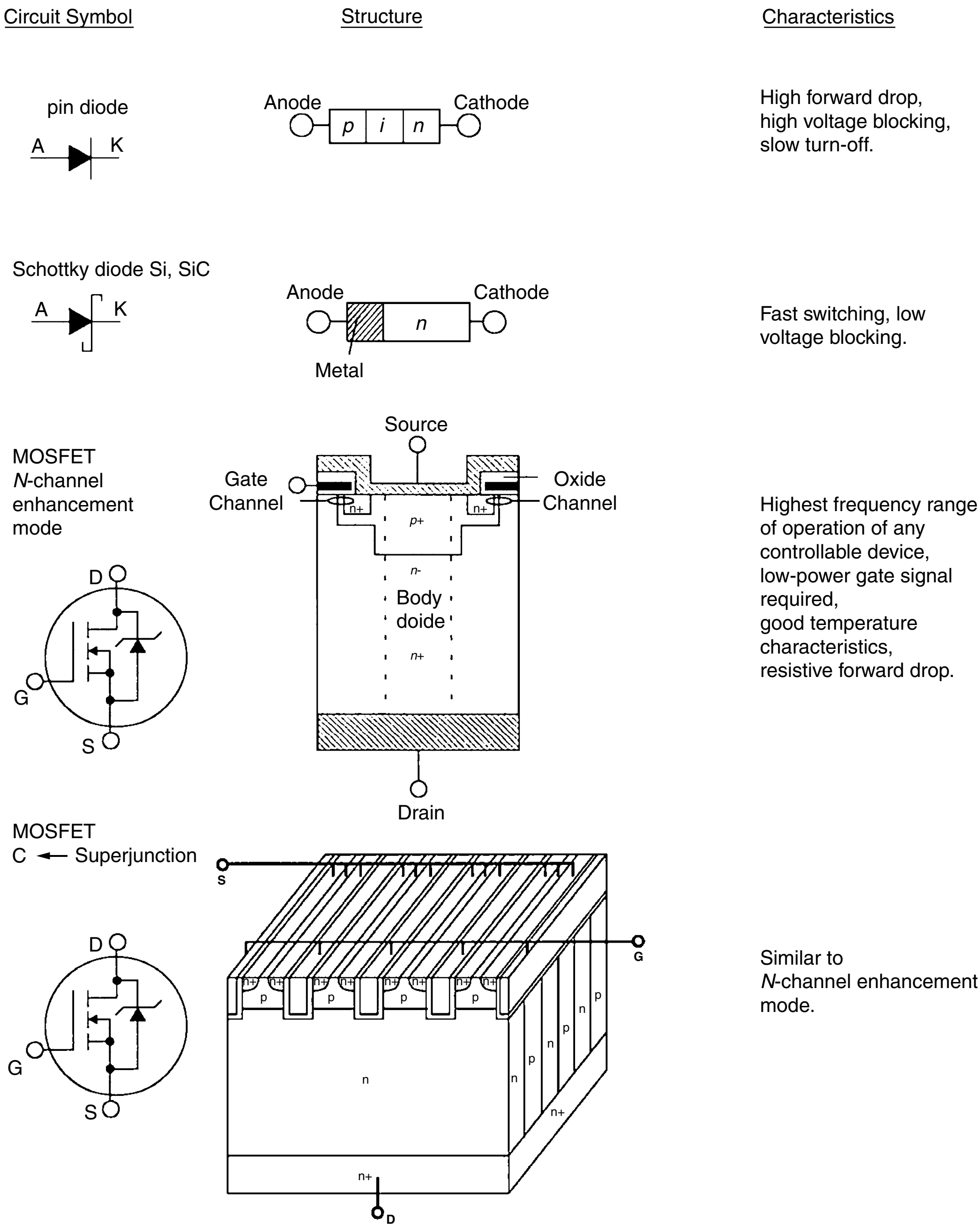
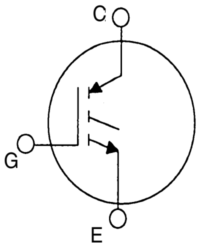


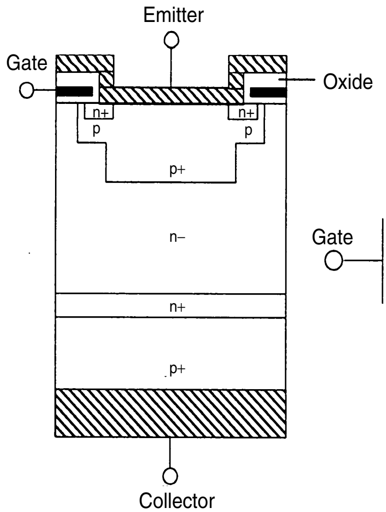
FIGURE 13.1.2 Commonly used power electronic devices showing their circuit symbols, simplified internal structures, equivalent circuits (where appropriate), and some major characteristics.

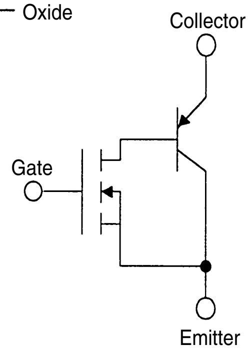
Circuit Symbol | Structure | Equivalent Circuit | Characteristics

IGBT

N-channel, punch-through with lateral gate.

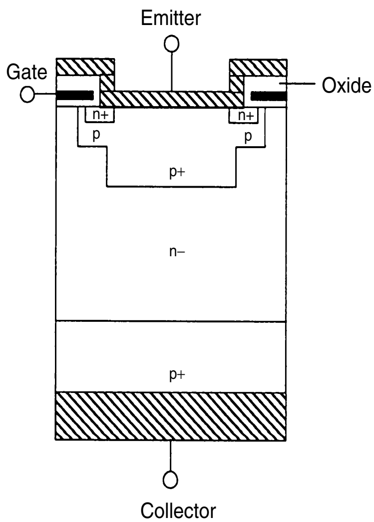






Good behavior with respect to temperature variations, moderately good range of operating frequencies, moderately good forward drop characteristics, good SOA characteristics

N-channel, nonpunch-through with lateral gate.



Similar to above.

FIGURE 13.1.2 (*Continued*)

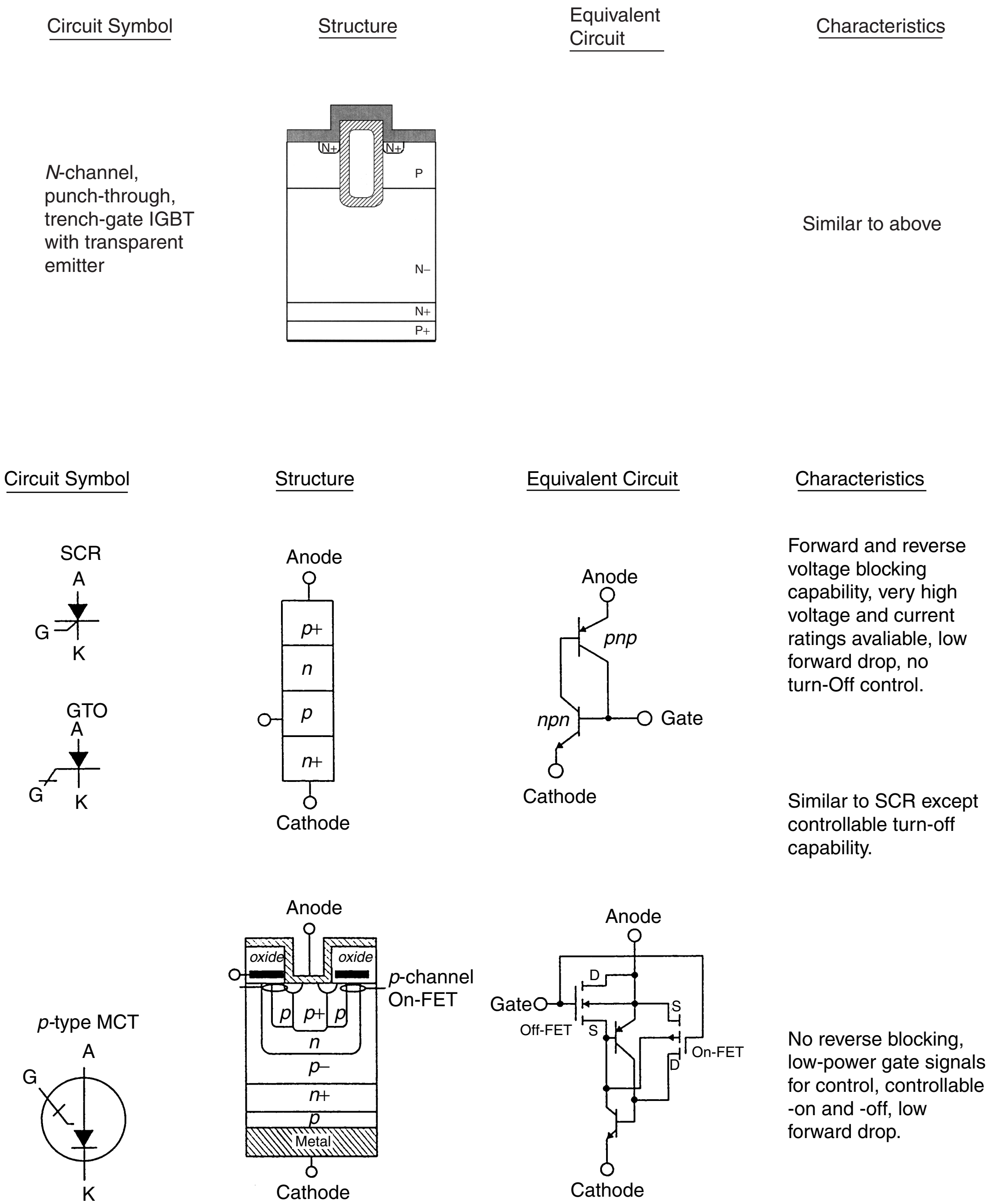


FIGURE 13.1.2 (*Continued*)

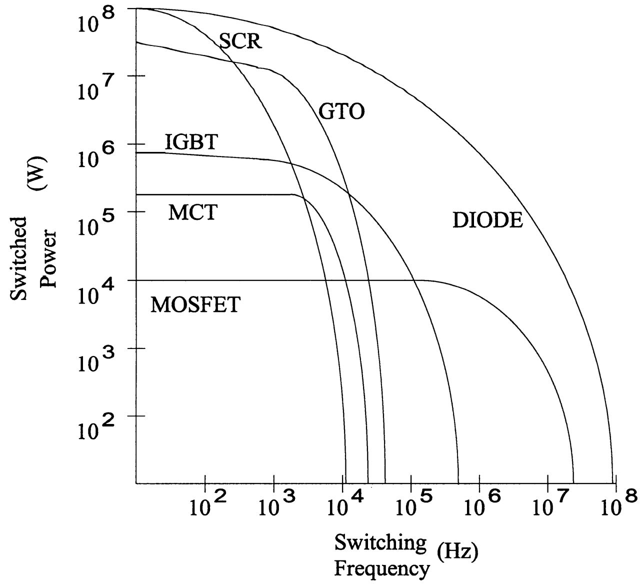


FIGURE 13.1.3 Comparison between major power electronic devices of their maximum switched power capability in terms of associated switching frequency. The switched power refers to the maximum forward blocking voltage multiplied by the maximum forward conduction current that each device is capable of handling.

Diode Ratings*

Silicon diode ratings include voltage, current, and junction temperature. A list of some of the more important parameters is shown in Table 13.1.1. The device current rating I_F is primarily determined by the area of the silicon die, power dissipation, and the method of heat sinking, while the spread of voltage ratings V_{RRM} is determined by silicon resistivity and die thickness.

Reverse voltage ratings are designated as repetitive V_{RRM} and nonrepetitive V_{RSM}. The repetitive value pertains to steady-state operating conditions, while the nonrepetitive peak value applies to occasional transient or fault conditions. Care must be exercised when applying a device to ensure that the voltage rating is never exceeded, even momentarily. When the blocking capability of a conventional diode is exceeded, leakage currents flow through the localized areas at the edge of the crystal. The resulting localized heating can cause rapid device failure.

Although even low-energy reverse overvoltage transients are likely to be destructive, the silicon diode is remarkably rugged with respect to forward current transients. This property is demonstrated by the I_{FSM} rating that permits one-half-cycle peak surge current of over ten times the I_F rating. For shorter current pulses, less than 4 ms, the surge current is specified by an I^2t rating similar to that of a fuse.

Proper circuit design must ensure that the maximum average junction temperature will never exceed its design limit of typically 150°C. Good design practice for high reliability, however, limits the maximum junction temperature to a lower value. The average junction-temperature rise above ambient is calculated by multiplying the average power dissipation, given approximately by the product of V_F and I_F, by the thermal resistance $R_{\theta JC}$. Transient junction temperatures can be computed from the transient thermal-impedance curve.

Device ratings are normally specified at a given case temperature and operating frequency. The proper use of a device at other operating conditions requires an appreciation of certain basic device characteristics.

*Major portions of this subsection were originally contributed by P. F. Pittman, J. C. Engel, and J. W. Motto.

TABLE 13.1.1 Symbols for Some Diode Ratings and Characteristics

Maximum Ratings	
V_{RRM}	Peak repetitive reverse voltage
V_{RSM}	Peak nonrepetitive reverse voltage
$I_{F(RMS)}$	RMS forward current
$I_{F(AV)}$	Average forward current
I_{FSM}	Surge forward current
I^2t	Nonrepetitive pulse overcurrent capability
T_j	Junction temperature
Characteristics	
V_F	Forward voltage drop (at specified temperature and forward current)
I_R	Maximum reverse current (at specified temperature and reverse voltage)
t_{RR}	Reverse recovery time (under specified switching of forward and reverse currents)
$R_{\theta jC}$	Junction-to-case thermal resistance

This is especially true in applications where the operating conditions of a number of devices are interdependent, as in series and parallel operation. For example, the forward voltage drop of a silicon diode has a negative temperature coefficient of 2 mV/°C for currents below the rated value. This variation in forward drop must be considered when devices are to be operated in parallel.

The reverse blocking voltage of a diode, at a specified reverse current, effectively decreases with an increase in temperature. The tendency to decrease comes from the fact that the reverse leakage current of a junction increases with temperature, thereby decreasing the voltage attained at a given measuring-current level. If the leakage current is very low, the maximum reverse voltage will be determined by avalanche breakdown (which has a coefficient of approximately 0.1 percent per °C in silicon). Thus, the voltage required to cause avalanche actually increases as the temperature rises. It should be noted that the reverse blocking voltage of a conventional diode is usually determined by imperfections at the edge of the die, and thus an ideal avalanche breakdown is usually not observed.

The reverse recovery time of a diode causes its performance to degrade with increasing frequency. Because of this effect, the rectification efficiency of a conventional diode used in a power circuit at high frequency is poor. In order to serve this application, a family of fast-recovery diodes has been developed. The stored charge of these devices is low, with the result that the amplitude and duration of the sweep-out current are greatly reduced compared with those of a conventional diode. However, improved turnoff characteristics of the fast-recovery diodes are obtained at some sacrifice in blocking voltage and forward drop compared with a conventional diode.

TRANSISTORS

Power MOSFETs

MOSFETs and IGBTs have an insulating oxide layer separating the gate contact and the silicon substrate. This insulating layer provides a large effective input resistance so that the control power necessary to switch these devices is considerably lower than that for a comparable bipolar transistor. The oxide layer also makes MOSFETs and IGBTs subject to damage from electrostatic charge build-up at the gate so that care must be exercised in their handling. Because of the internal structure of the power MOSFET, a *pn* junction (referred to as the "body diode") is present that conducts when a reverse voltage is applied across the drain and source. Power MOSFETs do not suffer from second breakdown as bipolar transistors do and generally switch much faster, particularly during turn-off. Power MOSFETs have a large, voltage-dependent, effective input capacitance (combination of the gate-to-source and gate-to-drain capacitances) that can interact with stray circuit inductance in the gate-drive circuit to create oscillations. An external, small-valued resistor is usually placed in series with the gate lead to damp the oscillatory behavior. Even with a fairly large input capacitance, power MOSFETs can be made to turn on and off faster than any other type of power electronic device.

Power MOSFETs are enhancement-type devices; a nonzero gate-to-source voltage must be applied to form a conducting channel between the drain and source to allow external current to flow. *N*-channel MOSFETs require a positive applied voltage at the gate with respect to the source for turn-on, while *p*-channel MOSFETs require a negative gate-source voltage. The gate electrode must be externally shorted to the source electrode for the device to support the maximum drain-source voltage V_{DS}, and keep the device in its forward-blocking mode. Drain current will flow if the gate-source voltage V_{GS} is above some minimum value (threshold voltage $V_{GS(TH)}$) necessary to form the conducting channel between the drain and source. In the saturated-mode of operation (i.e., drain current I_D, primarily dependent only on the gate-source voltage V_{GS}) the most important device characteristic is the forward transconductance g_{fs} usually specified by the manufacturer with a graph showing the value as a function of I_D.

The linear-mode of operation is preferred for switching applications. Here, V_{GS} is typically in the range of 10 to 20 V. In this mode, I_D is approximately proportional to the applied V_{DS} for a given value of V_{GS}. The proportionality constant defines the on-resistance $r_{DS(ON)}$. The on-resistance is the total resistance between the source and drain electrodes in the on-state and it determines the maximum I_D rating (based on power dissipation restrictions). As temperature increases, the ability of charge to move through the conduction channel from source to drain decreases. The effect appears as an increase in $r_{DS(ON)}$. The increase in $r_{DS(ON)}$ as a function of temperature goes approximately as $T^{2.3}$. Because of the positive temperature exponent, power MOSFETs can be operated in parallel, for increased current capacity, with relative ease. In addition, the safe operating area (SOA) of MOSFETs is relatively large and the devices can be operated reliably near the SOA limits.

Power MOSFETs can be obtained with a forward voltage hold-off capability BV_{DSS} of around 1.2 kV (*n*-channel) and current handling capacity of up to 100 A at lower BV_{DSS} values. *P*-channel devices typically have less spread in ratings and are generally not available in extremes of current handling or hold-off voltage values like *n*-channel devices. MOSFETs can be obtained as discretely packaged parts or with several die configured together to form various half-bridge or full H-bridge topologies in a module. Advanced MOSFETs have integrated features that provide capabilities such as current limiting, voltage clamping, and current sensing for more intelligent system design. Trench- or buried-gate technology has contributed to the reduction of the $R_{on} \times$ Area product in power MOSFETs (and IGBTs) by a factor of 3 or more compared to surface gate devices (see Fig. 13.1.2). The trench-gate technology has been further adapted into the newest structure called the Superjunction MOSFET (see Fig. 13.1.2). The horizontal distribution of alternating *p*- and *n*-regions modifies the electric field distribution in the forward blocking mode such that the *n*-regions can be designed with a smaller vertical dimension, for the same blocking capability, as the trench-gate structure. Hence, the shorter current path causes the forward drop to be greatly reduced during conduction. At 100 A/cm^2 the SJ-MOSFET has been shown to have a forward drop of 0.6 V as compared to 0.9 V for the traditional MOSFET (Fujihira, 1998). Table 13.1.2 lists some of the more important power MOSFET ratings and characteristics.

IGBTs. Insulated-gate bipolar transistors are designated as *n*-type or *p*-type. The *n*-type of device dominates the marketplace because of its ease of use (it is controlled by a positive gate-emitter voltage). The *n*-type device can be thought of as an *n*-channel enhancement-mode MOSFET controlling the base current of a *pnp* bipolar transistor, as shown in Fig. 13.1.2. The naming convention is somewhat confusing because the external leads are labeled with the idea of an IGBT being a direct replacement for an *npn* transistor with a gate lead replacing the base lead (i.e., the emitter of the equivalent *pnp*, in Fig. 13.1.2, is the collector of the IGBT, and so forth).

Applying a positive gate voltage above the threshold value, $V_{GE(TH)}$, turns the IGBT on. For switching applications, V_{GE} is typically in the range of 10 to 20 V. The IGBT has a saturated mode of operation (similar to a MOSFET), where the collector current is relatively independent of collector-to-emitter voltage V_{CE}. The base-collector junction, of the equivalent *pnp*, can never become forward biased because of drain current flow through the equivalent MOSFET. Therefore, the IGBT always has a forward drop, during conduction, of at least one *pn* junction (typically around 1 V). This is why the forward voltage drop $V_{CE(ON)}$ of the IGBT is greater than a comparable bipolar transistor, but less than a pure MOSFET structure at rated current flow. The switching times of the IGBT are shorter than comparable bipolar transistors (resulting in higher frequency of operation) and are not as susceptible to failure modes as are bipolars. The turn-off of an IGBT is characterized by two distinct portions of its current waveform. The first portion is characterized by a steep drop associated with the interruption of base-current to the equivalent *pnp* transistor (i.e., the internal MOSFET turns off). The second

TABLE 13.1.2 Symbols for Some MOSFET Ratings and Characteristics

Maximum Ratings	
V_{DS}	Drain-source voltage
I_D	Continuous drain current
I_{DM}	Pulsed drain current
T_j	Junction temperature
P_D	Maximum power dissipation
Characteristics	
BV_{DSS}	Drain-source breakdown voltage
$V_{GS(TH)}$	Gate threshold voltage
I_{DSS}	Zero gate-voltage drain current
$I_{D(on)}$	On-state drain current
$r_{DS(ON)}$	Static drain-source on-state resistance
g_{fs}	Common-source forward transconductance
C_{ISS}	Input capacitance
C_{OSS}	Output capacitance
C_{RSS}	Reverse transfer capacitance
$t_{d(on)}$	Turn-on delay time
t_r	Rise time
$t_{d(off)}$	Turn-off delay time
t_f	Fall time
Q_g	Total gate charge (gate-source + gate-drain)
Q_{gs}	Gate-source charge
Q_{gd}	Gate-drain ("Miller") charge
L_D	Internal drain inductance
L_S	Internal source inductance
$R_{\theta JC}$	Junction-to-case thermal resistance
Body Diode Ratings	
I_S	Continuous source current
I_{SM}	Pulse source current
V_{SD}	Diode forward voltage drop
t_{rr}	Reverse recovery time
Q_{RR}	Reverse recovered charge
t_{ON}	Forward turn-on time

portion is known as the current-tail and can be very long in time. This is associated with final turn-off of the bipolar transistor structure. Much of the IGBT design efforts are aimed at modifying this current-tail to control switching time and/or power dissipation during turn-off.

If a large collector current is allowed to flow, the self-heating can cause the internal parasitic thyristor structure to latch into conductance (the gate thus loses the ability to turn the device off). This behavior is known as the short-circuit, shoot-through, or latch-up current limit. The maximum current that can flow (limited only by the device impedance), before latch-up occurs, must usually be limited to less than 10 μs duration. The behavior as a function of temperature is complicated for IGBTs. At low collector current values, the forward drop dependency as a function of temperature is similar to bipolar transistors. At high collector current values, the forward drop dependency on temperature is closer to that of a MOSFET. The exact design and fabrication steps used in the production of the device plays a strong role in the exact behavior because of temperature changes. Further details are available from Baliga (1987) and Hefner (1992).

IGBTs can now be obtained with hold-off voltage ratings of up to 6.3 kV and pulsed forward current capability of over 200 A. These devices can be obtained as discrete components or with several parallel die (to form one switch) and then several sets of switches configured into bridge or half-bridge topologies in modules. They are also available with an integrated current sensing feature for active monitoring of device performance. There are two types of IGBT designs—punch through (PT) and non-punch through (NPT). NPT structures have no n^+ buffer layer next to the p^+ emitter (see Fig.13.1.2). This means that the applied forward blocking voltage can extend the associated depletion region all the way across the n^- base causing breakdown at the *p*-emitter/*n*-base junction if the applied voltage is high enough. In a PT structure (shown in Fig. 13.1.2) the depletion region is pinned to the n^+ buffer layer, thus allowing a thinner n^- base (high-resistivity region) to be used in the device design.

Previous generation IGBTs have a punch-through structure designed around a p^+ Si substrate with two epitaxial regions (n^- base region and n^+ buffer layer). Carrier lifetime reduction techniques are often used in the drift region to modify the turn-off characteristics. Recently, trench-gate devices have been designed with local lifetime control in the buffer layer (Motto, 1998). High-voltage devices (>1.2 kV) have been created using a non-punch-through structure beginning with the n^- base region as the substrate upon which a shallow (transparent) p^+ emitter is formed (Cotorogea, 2000). Cross-sections of typical unit cells for planar-gate IGBTs are shown in Fig. 13.1.2.

Third-generation IGBTs make use of improved cell density and shallow diffusion technologies that create fast switching devices with lower forward drops than have been achieved with previous devices. These lateral channel structures have nearly reached their limit for improvements. New trench-gate technologies offer the promise of greatly improved operation (Santi, 2001). Trench technologies can create an almost ideal IGBT structure because it connects in series the MOSFET and a *p*-*n* diode. There is no parasitic JFET as is created by the diffused *p*-wells in a lateral channel device (see Fig. 13.1.2). A simplified cross-section of the trench-gate IGBT is shown in Fig. 13.1.2. The forward drop in a trench-gate device is reduced significantly from the value in a third-generation lateral-gate IGBT. For example, in devices rated for 100 A and 1200 V, the forward drop, V_{CE}, is 1.8 V in a trench-gate IGBT as compared to 2.7 V in a lateral-gate (third generation) IGBT at the same current density, gate voltage, and temperature (Motto, 1998.) Local lifetime control is obtained in the n^+ base layer by using proton irradiation. This helps decrease the effective resistance in the n^- base by increasing the on-state carrier concentration. The surface structure of the gate is such that the MOS-channel width is increased (causing a decrease in channel resistance). The trend is for devices to be of the PT type as processing technology is improved. Table 13.1.3 lists some of the more important IGBT ratings and characteristics.

Bipolar Transistors. Power bipolar transistors and bipolar Darlingtons are seldom used in modern converter systems because of the amount of power required by the control signal and the limited SOA of the traditional

TABLE 13.1.3 Symbols for Some IGBT Ratings and Characteristics

Maximum Ratings	
V_{CES}	Collector-emitter voltage
V_{CGR}	Collector-gate voltage
V_{GE}	Gate-emitter voltage
I_C	Continuous collector current
T_j	Junction temperature
P_D	Maximum power dissipation
Characteristic	
BV_{CES}	Collector-emitter breakdown voltage
$V_{GE(TH)}$	Gate threshold voltage
I_{CES}	Zero gate-voltage collector current (at specified T_j and V_{CE} value)
$V_{CE(ON)}$	Collector-emitter on-voltage (at specified T_j, I_C, and V_{GE} values)
$Q_{G(ON)}$	On-state gate charge (at specified I_C and V_{CE} values)
$t_{D(ON)}$	Turn-on delay time (for specified test)
t_{RI}	Rise time (for specified test)
$t_{D(OFF)}$	Turn-off delay time (for specified test)
t_{FI}	Fall time (or specified test)
W_{OFF}	Turn-off energy loss per cycle
$R_{\theta JC}$	Junction-to-case thermal resistance

power bipolar transistor. Because of their declining use, no further discussion will be given. Further details should be obtained from manufacturers' databooks.

THYRISTORS

There are four major types of thyristors: (*i*) silicon-controlled rectifier (SCR), (*ii*) gate turn-off (GTO) thyristor, (*iii*) MOS-controlled thyristor (MCT) and related forms, and (*iv*) static induction thyristor (SITh). MCTs are so-named because many parallel enhancement-mode, MOSFET structures of one charge type are integrated into the thyristor for turn-on and many more MOSFETs of the other charge type are integrated into the thyristor for turn-off. A static induction thyristor (SITh), or field-controlled thyristor (FCTh), has essentially the same construction as a power diode with a gate structure that can pinch-off anode current flow. The advantage of using MCTs, derivative forms of the MCT, or SIThs is that they are essentially voltage-controlled devices, (e.g., little control current is required for turn-on or turn-off) and therefore require simplified control circuits attached to the gate electrode (Hudgins, 1993). Less important types of thyristors include the Triac (a pair of low-power, anti-parallel SCRs integrated together to form a bi-directional current switch) and the programmable unijunction transistor (PUT).

A thyristor used in some ac power circuits (50 or 60 Hz in commercial utilities or 400 Hz in aircraft) to control ac power flow can be made to optimize internal power loss at the expense of switching speed. These thyristors are called phase-control devices, because they are generally turned from a forward-blocking into a forward-conducting state at some specified phase angle of the applied sinusoidal anode-cathode voltage waveform. A second class of thyristors is used in association with dc sources or in converting ac power at one amplitude and frequency into ac power at another amplitude and frequency, and must generally switch on and off relatively quickly. The associated thyristors used are often referred to as inverter thyristors.

SCRs and GTOs. The voltage hold-off ratings for SCRs and GTOs is above 6 kV and continuing development will push this higher. The pulsed current rating for these devices is easily tens of kiloamperes. A gate signal of 0.1 to 100 A peak is typical for triggering an SCR or GTO from forward blocking into forward conduction. These thyristors are being produced in silicon with diameters greater than 100 mm.

The large wafer area places a limit on the rate of rise of anode current, and hence a di/dt limit (rating) is specified. The depletion capacitances around the *pn* junctions, in particular the center junction, limit the rate of rise in forward voltage that can be applied even after all the stored charge, introduced during conduction, is removed. The associated displacement current under application of forward voltage during the thyristor blocking state sets a dv/dt limit. Some effort in improving the voltage hold-off capability and over-voltage protection of conventional SCRs is underway by incorporating a lateral high-resistivity region to help dissipate the energy during breakover. Most effort, though, is being placed in the further development of high-performance GTO thyristors because of their controllability and to a lesser extent in optically triggered structures that feature gate circuit isolation.

Optically gated thyristors have traditionally been used in power utility applications where series stacks of devices are necessary to achieve the high voltages required. Isolation between gate-drive circuits for circuits such as static VAR compensators and high voltage dc to ac inverters have driven the development of this class of devices. One of the most recent devices can block 6 kV forward and reverse, conduct 2.5 kA average current, and maintain a di/dt capability of 300 A/μs and a dv/dt capability of 3000 V/μs, with a required trigger power of 10 mW.

High-voltage GTO thyristors with symmetric blocking capability require thick *n*-base regions to support the high electric field. The addition of an n^+ buffer-layer next to the p^+-anode allows high voltage blocking capability and yet produces a low forward voltage drop during conduction because of the thinner n^--base required. Many other design modifications have been introduced by manufacturers so that GTOs with a forward blocking capability of around 8 kV and anode conduction of 1 kA have been produced. Also, a reverse conducting GTO has been fabricated that can block 6 kV in the forward direction, interrupt a peak current of 3 kA, and has a turn-off gain of about 5.

A modified GTO structure, called a gate-commutated thyristor (GCT), has been designed and manufactured that commutates all of the cathode current away from the cathode region and diverts it out the gate contact. The GCT is similar to a GTO in structure except that it has a low-loss *n*-buffer region between the *n*-base and *p*-emitter. The GCT device package is designed to result in very low parasitic inductance and is integrated with a specially designed gate-drive circuit (IGCT). The specially designed gate drive and ring-gate package circuit allows the GCT to be operated without a snubber circuit and switch with higher anode *di*/*dt*, than a similar GTO. At blocking voltages of 4.5 kV and higher, the IGCT seems to provide better performance than a conventional GTO. The speed at which the cathode current is diverted to the gate (di_{GQ}/dt) is directly related to the peak snubberless turn-off capability of the GCT. The gate-drive circuit can sink current for turn-off at di_{GQ}/dt values in excess of 7000 A/μs. This hard gate drive results in a low-charge storage time of about 1 μs. The low storage time and the fail-short mode makes the IGCT attractive for high-voltage series applications.

The bi-directional control thyristor (BCT) is an integrated assembly of two anti-parallel thyristors on one Si wafer. The intended application for this switch is VAR compensators, static switches, soft starters, and motor drives. These devices are rated up to 6.5 kV blocking. Cross-talk between the two halves has been minimized. The small gate-cathode periphery necessarily restricts the BCT to low-frequency applications because of its *di*/*dt* limit.

The continuing improvement in GTO performance has caused a decline in the use of SCRs, except at the very highest power levels. In addition, the improvement in IGBT design further reduces the attractiveness of SCRs. These developments make the future use of SCRs seemingly diminish.

MCTs. There is a *p*-channel and an *n*-channel MOSFET integrated into the MCT, one FET-structure for turn-on and one for turn-off. The MCT itself comes in two varieties: *p*-type (gate voltage applied with respect to the anode) and an *n*-type (gate voltage applied with respect to the cathode). Just as in a GTO, the MCT has a maximum controllable cathode current value. The inherent optimization for good switching and forward conduction characteristics make the MCT unable to block reverse applied voltages.

MCTs are presently limited to operation at medium power levels. The seeming variability in fabrication of the turn-off FET structure continues to limit the performance of MCTs, particularly current interruption capability, though these devices can handle two to five times the conduction current density of IGBTs. All MCT device designs center on the problem of current interruption capability. Turn-on is relatively simple, by comparison, with it and conduction properties approaching the one-dimensional thyristor limit. Other types of integrated MOS-thyristor structures can be operated at high power levels, but these devices are not commonly available or are produced for specific applications. Typical MCT ratings are for 1 kV forward blocking and a peak controllable current of 75 A. A recent version of the traditional MCT design is a diffusion-doped (instead of the usual epitaxial growth) device. They are rated for 3 kV forward blocking, have a forward drop of 2.5 V at 100 A, and are capable of interrupting around 300 A with a recovery time of 5 μs.

An MCT that uses trench-gate technology, called a depletion-mode thyristor (DMT), has been designed. A similar device is the base resistance controlled thyristor (BRT). Here, a *p*-channel MOSFET is integrated into the *n*-drift region of the MCT. These devices operate in an “IGBT” mode until the current is large enough to cause the thyristor structure to latch.

Another new MCT-type structure is called an emitter switched thyristor (EST), and uses an integrated lateral MOSFET to connect a floating thyristor *n*-emitter region to an n^+ thyristor cathode region. All thyristor current flows through the lateral MOSFET so it can control the thyristor current. Integrating an IGBT into a thyristor structure has been proposed. One device, called an IGBT triggered thyristor (ITT), is similar in structure and operation to the EST. The best designed EST, however, is the dual gate emitter switched thyristor (DG-EST). The device has two gate electrodes. One gate controls an integrated IGBT section, while the other gate controls a thyristor section. The DG-EST is intended to be switched in IGBT mode, to exploit the controllability and snubberless capabilities of an IGBT. During forward conduction, the thyristor section takes over and thus the DG-EST takes advantage of a low forward drop and the latching nature of a thyristor.

Static Induction Thyristors. A static induction thyristor (SITh) or field controlled thyristor (FCTh) is essentially a *pin* diode with a gate structure that can pinch-off anode current flow. High-power SITHs have a subsurface gate (buried-gate) structure to allow larger cathode areas to be used, and hence larger current densities can be conducted. Other SITh configurations have surface gate structures.

Planar gate devices have been fabricated with blocking capabilities of up to 1.2 kV and conduction currents of 200 A, while step-gate (trench-gate) structures have been produced that are able to block up to 4 kV and conduct 400 A. Similar devices with a “Verigrid” structure have been demonstrated that can block 2 kV and conduct 200 A, with claims of up to 3.5 kV blocking and 200 A conduction. Buried gate devices that block 2.5 kV and conduct 300 A have also been fabricated.

An integrated light-triggered and light-quenched SITh has been produced that can block 1.2 kV and conduct up to 20 A (at a forward drop of 2.5 V). This device is an integration of a normally off buried-gate static induction photothyristor and a normally off *p*-channel Darlington surface-gate static induction phototransistor. The optical trigger and quenching power required is less than 5 and 0.2 mW, respectively.

Thyristor Behavior. The thyristor is a three-terminal semiconductor device comprising four layers of silicon so as to form three separate *pn* junctions. In contrast to the linear relation that exists between load and control currents in a transistor, the thyristor is bistable. The four-layer structure of the thyristor is shown in Fig. 13.1.2. The anode and cathode terminals are connected in series with the load to which power is to be controlled. The thyristor is turned on by application of a low-power control signal between the third terminal, or gate, and the cathode (between gate and anode for *p*-type MCT).

The reverse characteristic is determined by the outer two junctions, which are reverse-biased in this operating mode. With zero gate current, the forward characteristic in the off- or blocking-state is determined by the center junction, which is reverse biased. However, if the applied voltage exceeds the forward blocking voltage, the thyristor switches to its on- or conducting state. The effect of gate current is to lower the blocking voltage at which switching takes place.

This behavior can be explained in terms of the two-transistor analog shown in Fig. 13.1.2. The two transistors are regeneratively coupled so that if the sum of their current gains (α's) exceeds unity, each drives the other into saturation. In the forward blocking-state, the leakage current is small, both α's are small, and their sum is less than unity. Gate current increases the current in both transistors, increasing their α's. When the sum of the two α's equals 1, the thyristor switches to its on-state (latches).

The form of the gate-to-cathode *VI* characteristic of SCRs and GTOs is similar to that of a diode. With positive gate bias, the gate-cathode junction is forward-biased and permits the flow of a large current in the presence of a low voltage drop. When negative gate voltage is applied to an SCR, the gate-cathode junction is reverse-biased and prevents the flow of current until the avalanche breakdown voltage is reached. In a GTO, a negative gate voltage is applied to provide a low impedance for anode current to flow out of the device instead of out of the cathode. In this way the cathode region turns off, thus pulling the equivalent *npn* transistor out of conduction. This causes the entire thyristor to return to its blocking state. The problem with the GTO is that the gate-drive circuitry is typically required to sink from 5 to 10 percent of the anode current to achieve turn-off. The MCT achieves turn-off by internally diverting current through an integrated MOSFET. Switching the equivalent MOSFET only requires a voltage signal to be applied at the gate electrode.

A summary is provided in Table 13.1.4 of some of the ratings which must be considered when choosing a thyristor for a given application. Both forward and reverse repetitive and nonrepetitive voltage ratings must be considered, and a properly rated device must be chosen so that the maximum voltage ratings are never exceeded. In most cases, either forward or reverse voltage transients in excess of the nonrepetitive maximum ratings result in destruction of the device.

The maximum rms or average current ratings given are usually those which cause the junction to reach its maximum rated temperature. Because the maximum current will depend on the current waveform and on thermal conditions external to the device, the rating is usually shown as a function of case temperature and conduction angle. The peak single half-cycle surge-current rating must be considered, and in applications where the thyristor must be protected from damage by overloads, a fuse with an I^2t rating smaller than the maximum rated value for the device must be used. Maximum ratings for both forward and reverse gate voltage, current, and power also must not be exceeded.

The maximum rated operating junction temperature T_J must not be exceeded, since device performance, in particular voltage-blocking capability, will be degraded. Junction temperature cannot be measured directly but must be calculated from a knowledge of steady-state thermal resistance $R_{\theta JC}$ and the average power dissipation. For transients or surges, the transient thermal impedance ($Z_{\theta JC}$) curve must be used. The maximum average power dissipation P_T is related to the maximum rated operating junction temperature and the case temperature by the steady-state thermal resistance. In general, both the maximum dissipation and its derating with increasing case temperature are provided.

The number of thyristor characteristics specified varies widely from one manufacturer to another. Some characteristics are given only as typical values of minima or maxima, while many characteristics are displayed graphically. Table 13.1.4 summarizes some of the characteristics provided. Thyristor types shown in parentheses

TABLE 13.1.4 Symbols for Some Thyristor Ratings and Characteristics

Maximum Ratings	
V_{RRM}	Peak repetitive reverse voltage
V_{RSM} (SCR & GTO)	Peak nonrepetitive reverse voltage
V_{DRM}	Peak repetitive forward off-state voltage
V_{DSM} (SCR & GTO)	Peak nonrepetitive forward off-state voltage
$I_{T(RMS)}$	RMS forward current
$I_{T(AV)}$ (I_K for MCT)	Average forward current
I_{TSM} (I_{KSM} for MCT)	Surge forward current
I_{TGO} (I_{KC} for MCT)	Peak controllable current
I^2t (SCR & GTO)	Nonrepetitive pulse overcurrent capability
P_T (MCT)	Maximum power dissipation
di/dt	Critical rate of rise of on-state current
dv/dt	Critical rate of rise of off-state voltage
P_{GM}(P_{FGM} for GTO)	Peak gate forward power dissipation
P_{RGM} (GTO)	Peak gate reverse power dissipation
V_{FGM}	Peak forward gate voltage
V_{RGM}	Peak reverse gate voltage
I_{FGM} (SCR & GTO)	Peak forward gate current
I_{RGM} (GTO)	Peak reverse gate current
T_j	Junction temperature
Characteristics	
V_{TM}	On-state voltage drop (at specified temperature and forward current)
I_{DRM}	Maximum forward off-state current (at specified temperature and forward voltage)
I_{RRM}	Maximum reverse blocking current (at specified temperature and reverse voltage)
C_{ISS} (MCT)	Input capacitance (at specified temperature and gate and anode voltages)
V_{GT} (SCR & GTO)	Gate trigger voltage (at specified temperature and forward applied voltage)
V_{GD} (SCR & GTO)	Gate nontrigger voltage (at specified temperature and forward applied voltage)
I_{GT} (SCR & GTO)	Gate trigger current (at specified temperature and forward applied voltage)
t_{gt} (GTO)	Turn-on time (under specified switching conditions)
t_q (SCR & GTO)	Turn-off time (under specified switching conditions)
$t_{D(ON)}$ (MCT)	Turn-on delay time (for specified test)
t_{RI} (MCT)	Rise time (for specified test)
$t_{D(OFF)}$ (MCT)	Turn-off delay time (for specified test)
t_{FI} (MCT)	Fall time (for specified test)
W_{OFF} (MCT)	Turn-off energy loss per cycle
$R_{\theta JC}$	Junction-to-case thermal resistance

indicate a characteristic unique to that device or devices. Gate conditions of both voltage and current to ensure either nontriggered or triggered device operation are included.

The turn-on and turn-off transients of the thyristor are characterized by switching times like the turn-off time listed in Table 13.1.4. The turn-on transient can be divided into three intervals—gate-delay interval, turn-on of initial area, and spreading interval. The gate-delay interval is simply the time between application of a turn-on pulse at the gate and the time the initial area turns on. This delay decreases with increasing gate drive current and is of the order of a few microseconds. The second interval, the time required for turn-on of the initial area, is quite short, typically less than 1 μs. In general, the initial area turned on is a small percentage of the total useful device area. After the initial area turns on, conduction spreads (spreading interval) throughout the device in tens of microseconds.

It is during this spreading interval that the di/dt limit must not be exceeded. Typical di/dt values range from 100 to 1000 A/μs. Special inverter-type SCRs and GTOs are made that have increased switching speed (at the expense of higher forward voltage drop during conduction) with di/dt values in the range of 2000 A/μs. The rate of application of forward voltage is also restricted by the *dv/dt* characteristic. Typical values range from 100 to 1000 V/μs.

Thyristors are available in a wide variety of packages, from small plastic ones for low-power (i.e., TO-247), to stud-mount packages for medium-power, to press-pack (also called flat-pack) for the highest power devices. The press-packs must be mounted under pressure to obtain proper electrical and thermal contact between the device and the external metal electrodes. Special force-calibrated clamps are made for this purpose.

OTHER POWER SEMICONDUCTOR DEVICES

Semiconductor materials such as silicon carbide (SiC), gallium arsenide (GaAs), and gallium nitride (GaN) are being used to develop *pn*-junction and Schottky diodes, power MOSFET structures, some thyristors, and other switches. SiC diodes are commercially available now. No other commercial power devices made from these materials yet exist, but will likely be available in the future. Further information about advanced power semiconductor materials and device structures can be found in (Baliga, 1996) and (Hudgins, 1993, 1995, 2003).

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