Power Semiconductor Devices

1.1 INTRODUCTION

Power semiconductor devices constitute the heart of modern power electronic apparatus. They are used in power electronic converters in the form of a matrix of on-off switches, and help to convert power from ac-to-dc (rectifier), dc-to-dc (chopper), dc-to-ac (inverter), and ac-to-ac at the same (ac controller) or different frequencies (cycloconverter). The switching mode power conversion gives high efficiency, but the disadvantage is that due to the nonlinearity of switches, harmonics are generated at both the supply and load sides. The switches are not ideal, and they have conduction and turn-on and turn-off switching losses. Converters are widely used in applications such as heating and lighting controls, ac and dc power supplies, electrochemical processes, dc and ac motor drives, static VAR generation, active harmonic filtering, etc. Although the cost of power semiconductor devices in power electronic equipment may hardly exceed 20–30 percent, the total equipment cost and performance may be highly influenced by the characteristics of the devices. An engineer designing equipment must understand the devices and their characteristics thoroughly in order to design efficient, reliable, and cost-effective systems with optimum performance. It is interesting to note that the modern technology evolution in power electronics has generally followed the evolution of power semiconductor devices. The advancement of microelectronics has greatly contributed to the knowledge of power device materials, processing, fabrication, packaging, modeling, and simulation.

Today's power semiconductor devices are almost exclusively based on silicon material and can be classified as follows:

- Diode
- Thyristor or silicon-controlled rectifier (SCR)
- Triac

- Gate turn-off thyristor (GTO)
- Bipolar junction transistor (BJT or BPT)
- Power MOSFET
- Static induction transistor (SIT)
- Insulated gate bipolar transistor (IGBT)
- MOS-controlled thyristor (MCT)
- Integrated gate-commutated thyristor (IGCT)

In this chapter, we will briefly study the operational principles and characteristics of these devices.

1.2 DIODES

Power diodes provide uncontrolled rectification of power and are used in applications such as electroplating, anodizing, battery charging, welding, power supplies (dc and ac), and variable-frequency drives. They are also used in feedback and the freewheeling functions of converters and snubbers. A typical power diode has P-I-N structure, that is, it is a P-N junction with a near-intrinsic semiconductor layer (I-layer) in the middle to sustain reverse voltage.

Figure 1.1 shows the diode symbol and its volt-ampere characteristics. In the forward-biased condition, the diode can be represented by a junction offset drop and a series-equivalent resistance that gives a positive slope in the V-I characteristics. The typical forward conduction drop is 1.0 V. This drop will cause conduction loss, and the device must be cooled by the appropriate heat sink to limit the junction temperature. In the reverse-biased condition, a small
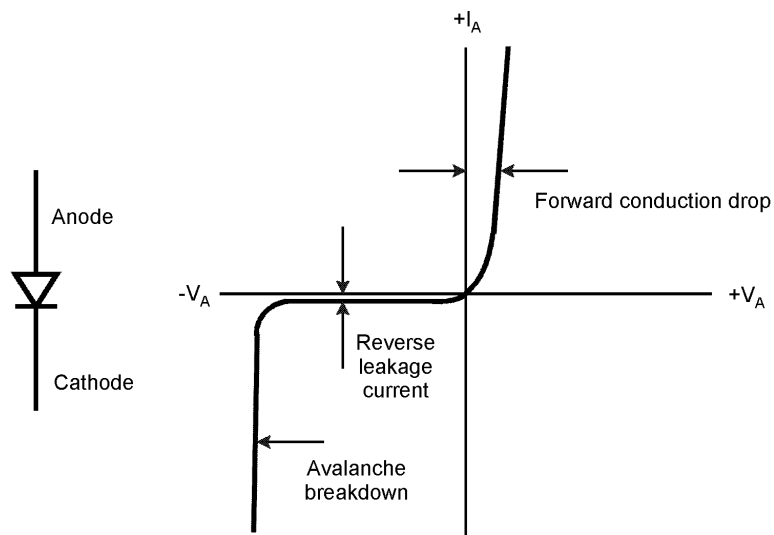

Figure 1.1   Diode symbol and volt-ampere characteristics
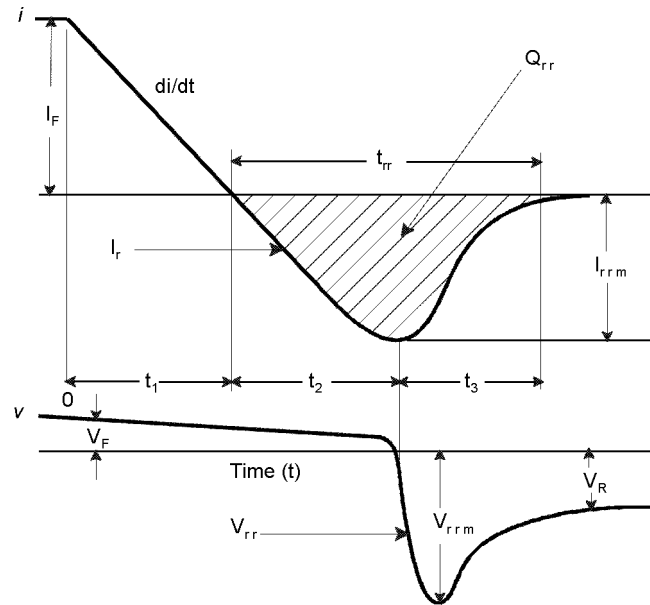
Figure 1.2 Turn-off switching characteristics of a diode

leakage current flows due to minority carriers, which gradually increase with voltage. If the reverse voltage exceeds a threshold value, called the breakdown voltage, the device goes through avalanche breakdown, which is when reverse current becomes large and the diode is destroyed by heating due to large power dissipation in the junction.

The turn-off voltage and current characteristics as functions of time, which are indicated in Figure 1.2, are particularly important for a diode. In the forward high-conduction region, the conduction drop (V_F) is small, as mentioned before. At this condition, the P and N regions near the junction and the I-layer remain saturated with minority carriers.

If the device is open-circuited, the carriers die by a recombination process, which takes a reasonably long time. Normally, a reverse dc voltage (V_R) is applied to turn off the device, as indicated in Figure 1.2. At time $t = 0$, the reverse voltage is applied when the current goes down linearly because of series-circuit inductance. During time t_2, the current is negative and the minority carriers sweep out across the junction, but the excess carrier concentration keeps the junction saturated, and therefore, the same negative current slope is maintained. The conduction drop decreases during t_1 and t_2 due to the reduction of Ohmic (equivalent resistance) drop. At the end of t_2, the device sustains voltage, and steady-state voltage appears at the end of t_3. During t_3, the reverse current falls quickly partly due to sweeping out and partly by recombination. The fast decay of negative current creates an inductive drop that adds with the reverse voltage V_R as shown. The reverse recovery time $t_{rr} = t_2 + t_3$ and the corresponding recovery charge Q_{rr} (shown by the hatched area) that are affected by the recombination process are important parameters of a diode. The snappiness by which the recovery current falls to zero determines the volt-

age boost V_{rr}. This voltage may be destructive and can be softened by a resistance-capacitance snubber, which will be discussed later. The recovery current causes additional loss (switching loss) in the diode, which can be determined graphically from Figure 1.2.

Power diodes can be classified as follows:

- Standard or slow-recovery diode
- Fast-recovery diode
- Schottky diode

Slow- and fast-recovery diodes have P-I-N geometry, as mentioned above. In a fast-recovery diode, as the name indicates, the recovery time t_{rr} and the recovery charge Q_{rr} (shown by the hatched area) are reduced by the minority carrier lifetime control that enhances the recombination process. However, the adverse effect is a higher conduction drop. For example, the POWEREX fast-recovery diode type CS340602, which has a dc current rating ($I_F(dc)$) of 20 A and a blocking voltage rating (V_{rrm}) of 600 V, has the following ratings: V_{FM} = 1.5 V, I_{rrm} = 5.0 mA, t_{rr} = 0.8 µs, and Q_{rr} = 15 µC. The standard slow-recovery diodes are used for line frequency (50/60 Hz) power rectification. They have a lower conduction drop, but a higher t_{rr}. These diodes are available with ratings of several kilovolts and several kiloamperes. A Schottky diode is basically a majority carrier diode and is formed by a metal-semiconductor junction. As a result, the diode has a lower conduction drop (typically 0.5 V) and faster switching time, but the limitations are a lower blocking voltage (typically up to 200 V) and higher leakage current. For example, the International Rectifier Schottky diode type 6TQ045 has ratings of V_{rrm} = 45 V, $I_{F(AV)}$ = 6 A, V_F = 0.51 V, and reverse leakage current I_{rm} = 0.8 mA (at 25 °C). These diodes are used in high-frequency circuits.

The electrical and thermal characteristics of diodes are somewhat similar to thyristors, which will be discussed next. Specific circuit applications of different types of diodes will be discussed in later chapters.

1.3 THYRISTORS

Thyristors, or silicon-controlled rectifiers (SCRs) have been the traditional workhorses for bulk power conversion and control in industry. The modern era of solid-state power electronics started due to the introduction of this device in the late 1950s. Chapters 3, 4, and 6 will discuss thyristor converters and their applications. The term "thyristor" came from its gas tube equivalent, thyratron. Often, it is a family name that includes SCR, triac, GTO, MCT, and IGCT. Thyristors can be classified as standard, or slow phase-control-type and fast-switching, voltage-fed inverter-type. The inverter-type has recently become obsolete and will not be discussed further.

1.3.1   Volt-Ampere Characteristics

Figure 1.3 shows the thyristor symbol and its volt-ampere characteristics. Basically, it is a three-junction P-N-P-N device, where P-N-P and N-P-N component transistors are connected in regenerative feedback mode. The device blocks voltage in both the forward and reverse directions (symmetric blocking). When the anode is positive, the device can be triggered into conduction by a short positive gate current pulse; but once the device is conducting, the gate loses its control to turn off the device. A thyristor can also turn on by excessive anode voltage, its rate of rise (dv/dt), by a rise in junction temperature (T_J), or by light shining on the junctions.

The volt-ampere characteristics of the device indicate that at gate current $I_G = 0$, if forward voltage is applied on the device, there will be a leakage current due to blocking of the middle junction. If the voltage exceeds a critical limit (breakover voltage), the device switches into conduction. With increasing magnitude of I_G, the forward breakover voltage is reduced, and eventually at I_{G3}, the device behaves like a diode with the entire forward blocking region removed. The device will turn on successfully if a minimum current, called a latching current, is maintained. During conduction, if the gate current is zero and the anode current falls below a critical limit, called the holding current, the device reverts to the forward blocking state. With reverse voltage, the end P-N junctions of the device become reverse-biased and the V-I curve becomes essentially similar to that of a diode rectifier. Modern thyristors are available with very large voltage (several KV) and current (several KA) ratings.
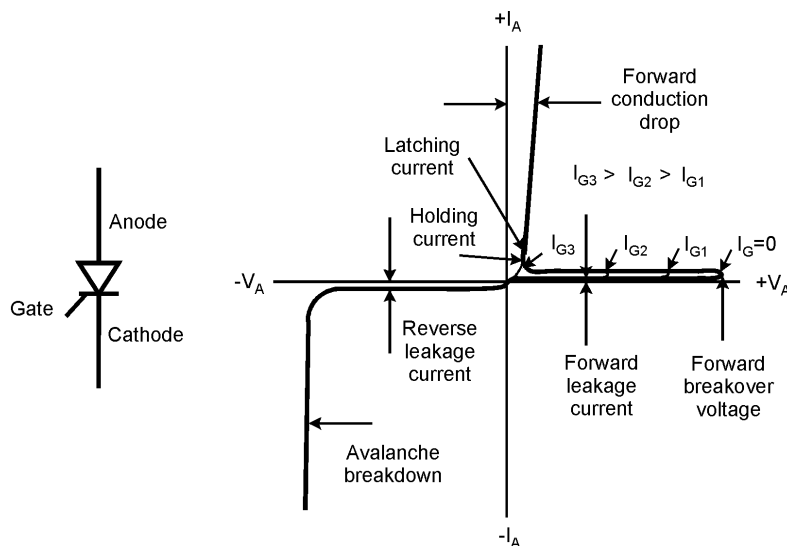

Figure 1.3   Thyristor symbol and volt-ampere characteristics

1.3.2   Switching Characteristics

Initially, when forward voltage is applied across a device, the off-state, or static *dv/dt*, must be limited so that it does not switch on spuriously. The *dv/dt* creates displacement current in the depletion layer capacitance of the middle junction, which induces emitter current in the component transistors and causes switching action. When the device turns on, the anode current *di/dt* can be excessive, which can destroy the device by heavy current concentration. During conduction, the inner P-N regions remain heavily saturated with minority carriers and the middle junction remains forward-biased. To recover the forward voltage blocking capability, a reverse voltage is applied across the device to sweep out the minority carriers and the phenomena are similar to that of a diode (see Figure 1.2). However, when the recovery current goes to zero, the middle junction still remains forward-biased. This junction eventually blocks with an additional delay when the minority carriers die by the recombination process. The forward voltage can then be applied successfully, but the reapplied *dv/dt* will be somewhat less than the static *dv/dt* because of the presence of minority carriers. For example, POWEREX SCR/diode module CM4208A2 (800 V, 25 A) has limiting *di/dt* = 100 A/μs and off-state *dv/dt* = 500 V/μs parameters. A suitably-designed snubber circuit (discussed later) can limit *di/dt* and *dv/dt* within acceptable limits. In a converter circuit, a thyristor can be turned off (or commutated) by a segment of reverse ac line or load voltage (defined as line or load commutation, respectively), or by an inductance-capacitance circuit-induced transient reverse voltage (defined as forced commutation).

1.3.3   Power Loss and Thermal Impedance

A thyristor has dominant conduction loss like a diode, but its switching loss (to be discussed later) is very small. The device specification sheet normally gives information on power dissipation for various duty cycles of sinusoidal and rectangular current waves. Figure 1.4 shows the power dissipation characteristics for a rectangular current wave. The reverse blocking loss and gate circuit loss are also included in the figure. These curves are valid up to 400 Hz supply frequency. The heat due to power loss in the vicinity of a junction flows to the case and then to the ambient through the externally mounted heat sink, causing a rise in the junction temperature T_J. The maximum T_J of a device is to be limited because of its adverse effect on device performance. For steady power dissipation P, T_J can be calculated as

$$T_J - T_A = P(\theta_{JC} + \theta_{CS} + \theta_{SA}) \tag{1.1}$$

where T_A is the ambient temperature, and θ_{JC}, θ_{CS}, and θ_{SA} represent the thermal resistance from junction to case, case to sink, and sink to ambient, respectively. The resistance θ_{SA} is determined by the cooling system design, and the methods of cooling may include heat sink with natural convection cooling, forced air cooling, or forced liquid cooling. From Equation (1.1), it is evident that for a limited T_{Jmax} (usually 125 °C), the dissipation P can be increased by reducing θ_{SA}. This means that a more efficient cooling system will increase power dissipation, that is, the
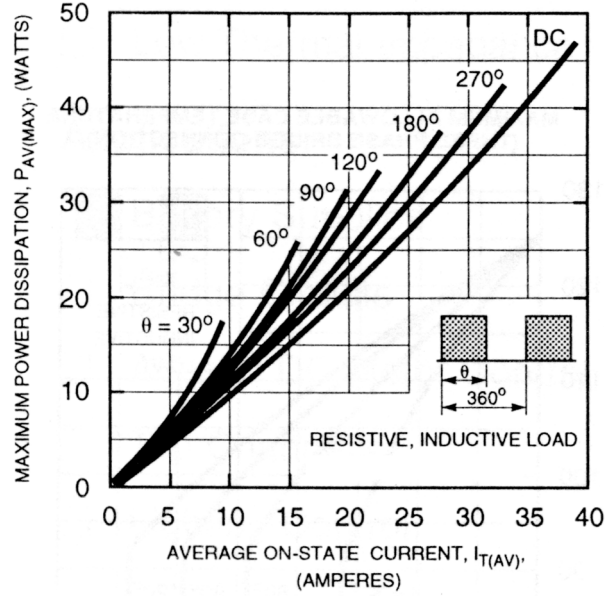
Figure 1.4 Average on-state power dissipation of thyristor for rectangular current wave
(POWEREX CM4208A2)

power-handling capability of a device. An infinite heat sink is defined when $\theta_{SA} = 0$, that is, the case temperature $T_C = T_A$.

In practical operation, the power dissipation P is cyclic, and the thermal capacitance or storage effect delays the junction temperature rise, thus permitting higher loading of the device. The transient thermal equivalent circuit can be represented by a parallel RC circuit, where P is equivalent to the current source and the resulting voltage across the circuit represents the temperature T_J. Figure 1.5(a) shows the T_J curve for the dissipation of a single power pulse. Considering the complementary nature of heating and cooling curves, the following equations can be written:

$$T_J(t_1) = T_A + P\theta(t_1) \tag{1.2}$$

$$T_J(t_2) = T_A + P[\theta(t_2) - \theta(t_2 - t_1)] \tag{1.3}$$

where $\theta(t_1)$ is the transient thermal impedance at time t_1. The device specification sheet normally gives thermal impedance between junction and case. The additional effect due to heat sink can be added if desired. Figure 1.5(b) shows typical junction temperature build-up for three repeated pulses. The corresponding T_J expressions by the superposition principle can be given as
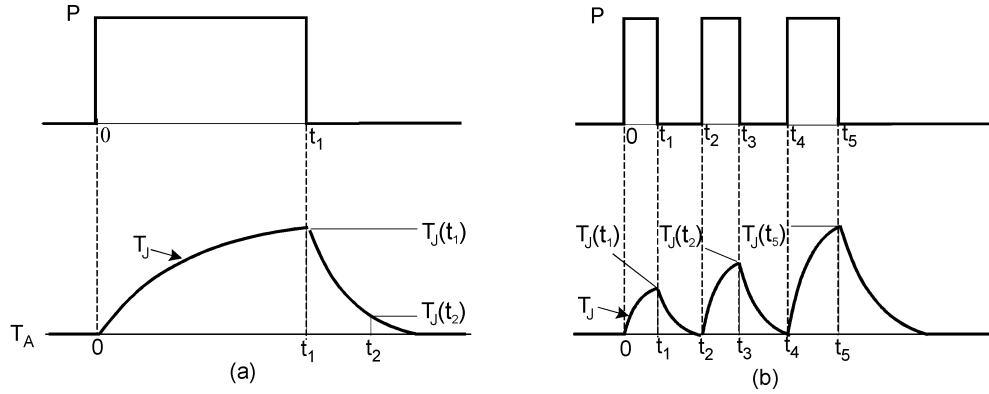
Figure 1.5 Junction temperature rise with pulsed power dissipation
(a) Single pulse, (b) Multiple pulses

$$T_J(t_1) = T_A + P\theta(t_1) \tag{1.4}$$

$$T_J(t_3) = T_A + P[\theta(t_3) - \theta(t_3 - t_1) + \theta(t_3 - t_2)] \tag{1.5}$$

$$T_J(t_5) = T_A + P[\theta(t_5) - \theta(t_5 - t_1) + \theta(t_5 - t_2) - \theta(t_5 - t_3) + \theta(t_5 - t_4)] \tag{1.6}$$

Figure 1.6 illustrates the transient thermal impedance curve ($\theta_{JC}(t)$) of a thyristor (type CM4208A2) as a function of time. The device has the rated thermal resistances of $\theta_{JC} = 0.8\ °C/W$ and $\theta_{CS} = 0.2\ °C/W$. Note that the device cooling and thermal impedance concepts discussed here are also valid for all power semiconductor devices.

1.3.4   Current Rating

Based on the criteria of limiting T_J as discussed above, Figure 1.7 shows the average current rating $I_{T(AV)}$ vs. permissible case temperature T_C for various duty cycles of rectangular current wave. For example, if T_C is limited to 110°C, the thyristor can carry 12 A average current for = 120°. If a better heat sink limits T_C to 100 °C, the current can be increased to 18 A. Figure 1.7 can be used with Figure 1.4 to design the heat sink thermal resistance.

1.4 TRIACS

A triac has a complex multiple-junction structure, but functionally, it is an integration of a pair of phase-controlled thyristors connected in inverse-parallel on the same chip. Figure 1.8(a) shows the triac symbol and (b) shows its volt-ampere characteristics. The three-terminal device can be triggered into conduction in both positive and negative half-cycles of supply voltage by applying gate trigger pulses. In I+ mode, the terminal T_2 is positive and the device is switched on by positive gate current pulse. In III- mode, the terminal T_1 is positive and it is switched on
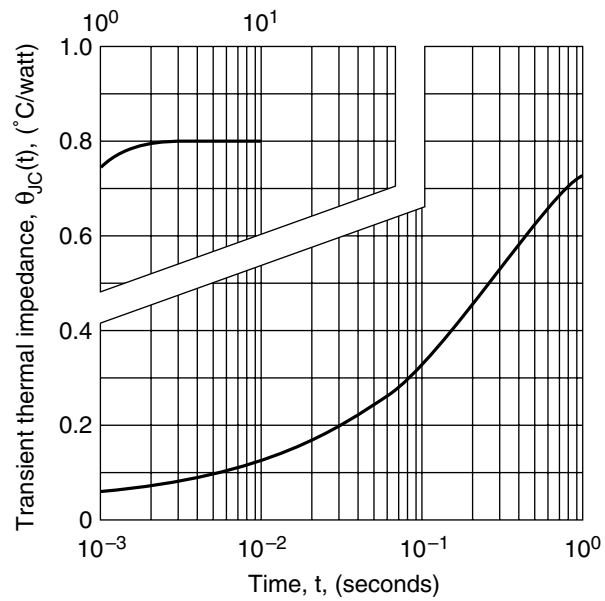
Figure 1.6   Transient thermal impedance curve of thyristor (CM4208A2)
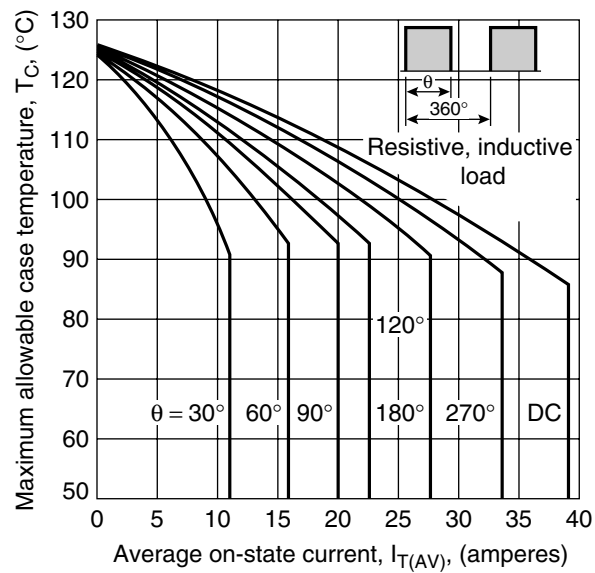
Figure 1.7   Maximum allowable case temperature for rectangular current wave
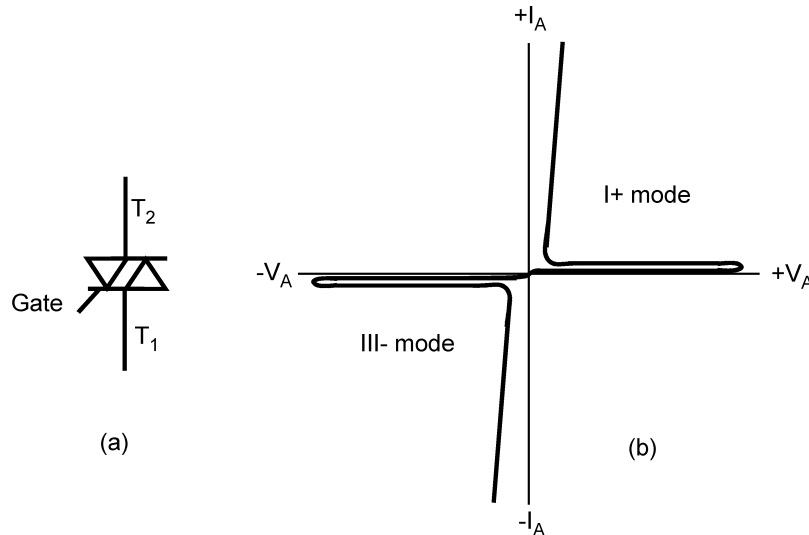(CM4208A2)

Figure 1.8   Triac symbol and volt-ampere characteristics

by negative gate current pulse. A triac is more economical than a pair of thyristors in anti-paral-lel and its control is simpler, but its integrated construction has some disadvantages. The gate current sensitivity of a triac is poorer and the turn-off time is longer due to the minority carrier storage effect. For the same reason, the reapplied *dv/dt* rating is lower, thus making it difficult to use with inductive load. A well-designed RC snubber is essential for a triac circuit. Triacs are used in light dimming, heating control, appliance-type motor drives, and solid-state relays with typically 50/60 Hz supply frequency.

Figure 1.9 shows a popular incandescent lamp dimmer circuit using a triac and the corre-sponding waveforms. The gate of the triac gets the drive pulse from an RC circuit through a diac, which is a symmetric voltage-blocking device. The capacitor voltage v_c lags the line voltage wave. When v_c exceeds the threshold voltage $\pm V_s$ of the diac, a pulse of current in either polarity triggers the triac at angle α_f, giving full-wave ac phase-controlled output to the load. The firing angle can be varied in the range α_1 to α_2 to control light intensity by varying the resistance R_1.

1.5 GATE TURN-OFF THYRISTORS (GTOS)

A gate turn-off thyristor (GTO), as the name indicates, is basically a thyristor-type device that can be turned on by a small positive gate current pulse, but in addition, has the capability of being turned off by a negative gate current pulse. The turn-off capability of a GTO is due to the diversion of P-N-P collector current by the gate, thus breaking the P-N-P / N-P-N regenerative feedback effect. GTOs are available with asymmetric and symmetric voltage-blocking capabili-ties, which are used in voltage-fed and current-fed converters, respectively. The turn-off current gain of a GTO, defined as the ratio of anode current prior to turn-off to the negative gate current required for turn-off, is very low, typically 4 or 5. This means that a 6000 A GTO requires as

Figure 1.9 (a) Triac light dimmer circuit, (b) Control waveforms

high as –1500 A gate current pulse. However, the duration of the pulsed gate current and the corresponding energy associated with it is small and can easily be supplied by low-voltage power MOSFETs. GTOs are used in motor drives, static VAR compensators (SVCs), and ac/dc power supplies with high power ratings. When large-power GTOs became available, they ousted the force-commutated, voltage-fed thyristor inverters.

1.5.1 Switching Characteristics

The switching characteristics of GTOs are somewhat different from those of thyristors and therefore require some explanation. Figure 1.10 shows a GTO chopper (dc-to-dc converter) circuit with a polarized snubber. The snubber consists of a turn-on component (L_L) called a series snubber and a turn-off component (R_s, C_s, and D_s), called a shunt snubber. This type of converter is typically used for a subway dc motor propulsion drive.

Figure 1.11 shows the turn-on and turn–off characteristics of the circuit with the snubber. The turn-on characteristics of a GTO are essentially similar to those of a thyristor. Initially, before turn-on, the capacitor C_s is charged to supply voltage V_d and the load current is flowing through the freewheeling diode. At turn-on, the series snubber limits *di/dt* through the device, and the supply voltage V_d is applied across the load. At the same time, C_s discharges through R_s
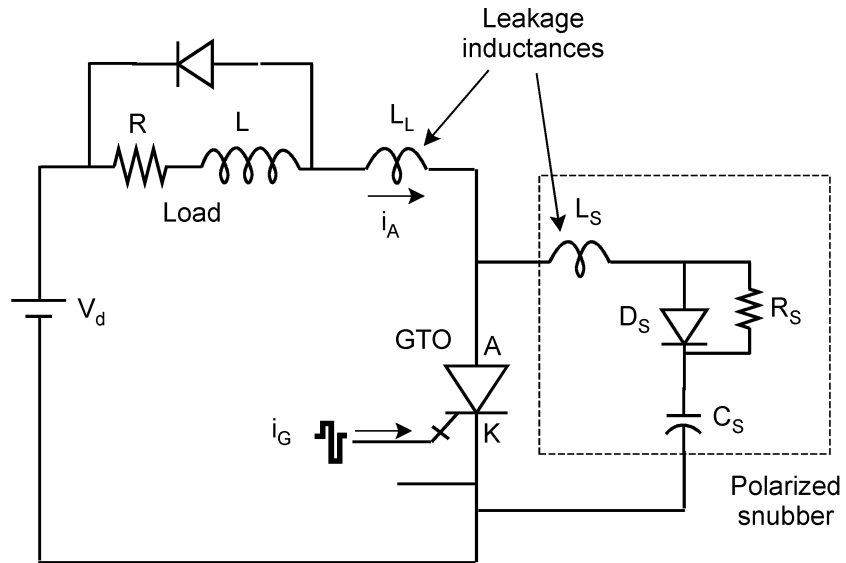
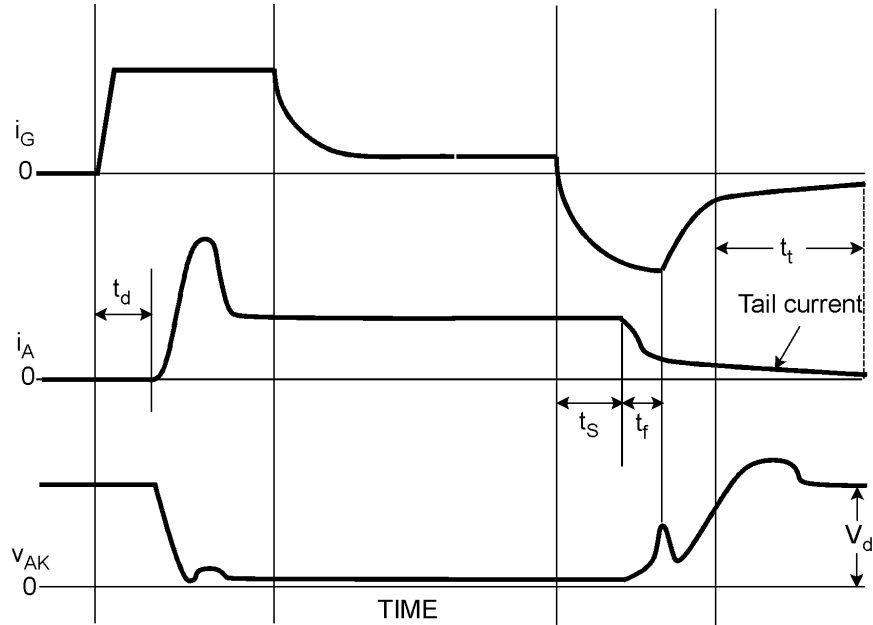**Figure 1.10**   GTO chopper with polarized snubber

Figure 0.1   GTO turn-on and turn-off characteristics with snubber (not to scale)

and the GTO in series (neglecting the L_s effect), dumping most of its energy into the resistor R_s. The power dissipation P_s in the resistor is approximately given as

$$P_s = 0.5C_s V_d^2 f \qquad\qquad (1.7)$$

where f = chopper operating frequency. Obviously, the turn-on switching loss of the device is reduced because of delayed build-up of the device current. When the GTO is turned off by negative gate current pulse, the controllable anode current i_A begins to fall after a short time delay, defined as storage time (t_s). The fall time t_f is somewhat abrupt, and is typically less than 1.0 μs. As the forward voltage begins to develop, anode current tends to bypass through the shunt capacitor, limiting dv/dt across the device. The leakage inductance L_s in the snubber creates a spike voltage, as shown. A large voltage spike is extremely harmful because current concentration may create localized heating, causing what is known as second breakdown failure. This emphasizes the need to minimize the shunt snubber leakage inductance. After the spike voltage, the anode voltage overshoots due to underdamped resonance before settling to normal forward blocking voltage V_d. GTO has a long tail current, as shown, mainly due to sweeping out of the minority carriers. This tail current at large anode voltage causes large turn-off switching loss unless voltage build-up is slowed with large C_s.

However, large C_s increases snubber dissipation, as given by Equation (1.7). The trade-off between snubber loss and turn-off switching loss, and the corresponding total loss curves with increasing snubber capacitance are given approximately by Figure 1.12. The curves indicate that
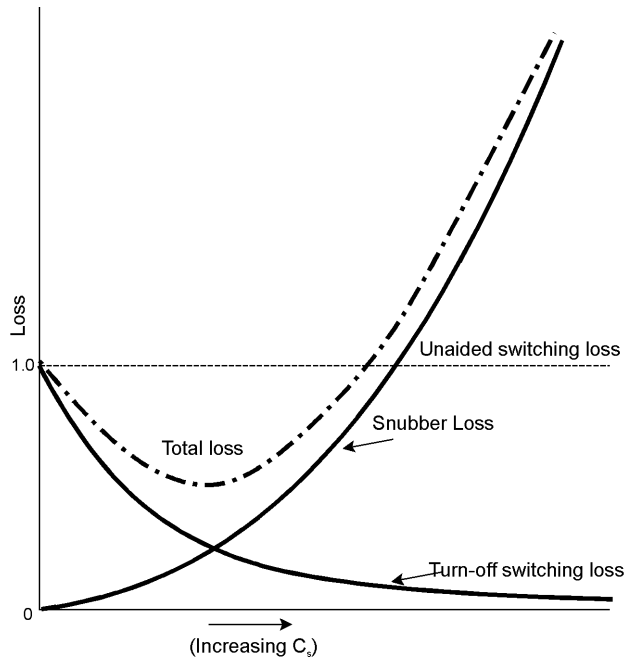

Figure 1.11   Trade-off between snubber loss and turn-off switching loss
with increasing capacitor

the device-switching loss is diverted to snubber loss, and the total loss may be higher than the intrinsic switching loss of the device. Since GTO power losses are somewhat higher during switching, the converter switching frequency is low and is typically restricted within 1.0 kHz.

1.5.2   Regenerative Snubbers

The snubber loss may be substantial in a high-power and/or high-frequency converter. This, in turn, may reduce the converter's efficiency and put a burden on the cooling system. To combat this problem, various regenerative or energy recovery schemes have been proposed where the stored energy in the snubber capacitor is pumped back to the source or load. Figure 1.13(a) shows a passive energy recovery scheme. When the GTO is turned off, the snubber capacitor C_s charges to the full supply voltage, as usual. At the subsequent turn-on of the GTO, the stored energy is transferred to capacitor C resonantly through the inductance L and diode D. When the GTO turns off again, the energy in C is absorbed in the load and C_s charges again to voltage V_d. Figure 1.13(b) shows a regenerative snubber that uses an auxiliary chopper. At GTO turn-off, the snubber capacitor C_s charges to supply voltage. At subsequent turn-on of the device, the energy is resonantly transferred to capacitor C, as before. The energy in C is then pumped to the source through a dc-to-dc boost converter.

The discussion on dissipative and regenerative snubbers given in this section is also valid for other devices. The idea of a regenerative snubber appears very attractive, but its application should be carefully weighed against the extra cost, loss, complexity, and equipment reliability. High-power GTO converters normally use regenerative snubbers. Otherwise, RC snubbers are commonly used. Snubberless converters, which will be discussed later, are also possible.

1.6   BIPOLAR POWER OR JUNCTION TRANSISTORS (BPTS OR BJTS)

A bipolar junction transistor (BPT or BJT), unlike a thyristor-like device, is a two-junction, self-controlled device where the collector current is under the control of the base drive current. Bipolar junction transistors have recently been ousted by IGBTs (insulated gate bipolar transistors) in the higher end and by power MOSFETs in the lower end. The dc current gain (h_{FE}) of a power transistor is low and varies widely with collector current and temperature. The gain is increased to a high value in the Darlington connection, as shown in Figure 1.14. However, the disadvantages are higher leakage current, higher conduction drop, and reduced switching frequency. The shunt resistances and diode in the base-emitter circuit help to reduce collector leakage current and establish base bias voltages. A transistor can block voltage in the forward direction only (asymmetric blocking). The feedback diode, as shown, is an essential element for chopper and voltage-fed converter applications. Double or triple Darlington transistors are available in module form with matched parallel devices for higher power rating.

Power transistors have an important property known as the second breakdown effect. This is in contrast to the avalanche breakdown effect of a junction, which is also known as first breakdown effect. When the collector current is switched on by the base drive, it tends to crowd on the base-emitter junction periphery, thus constricting the collector current in a narrow area of the
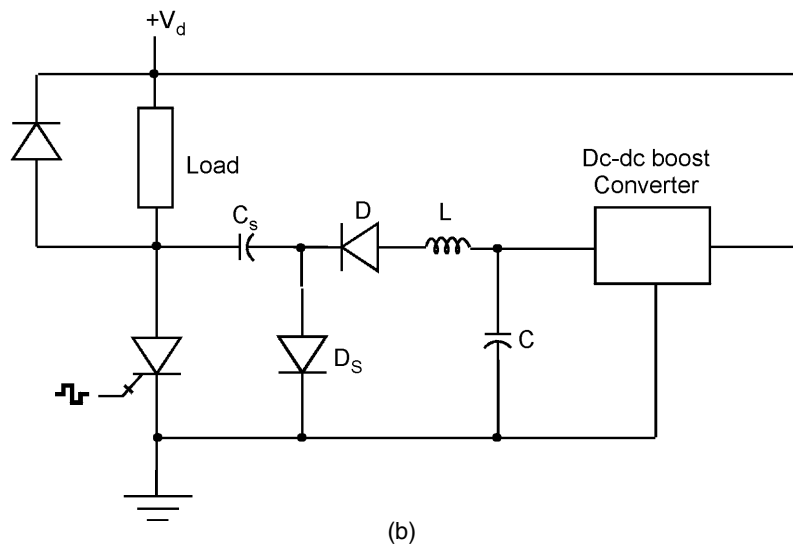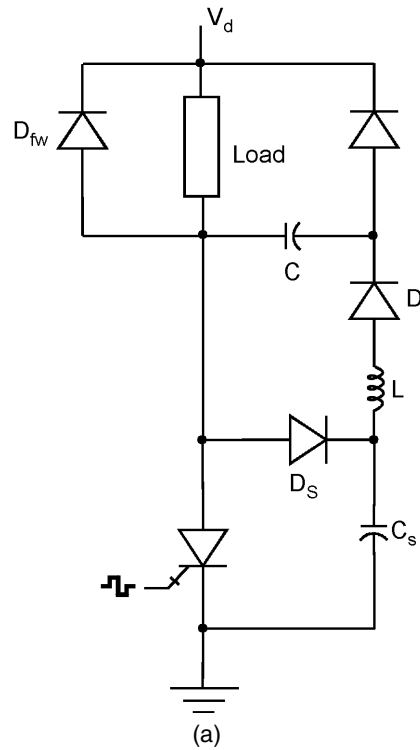
(a)

(b)

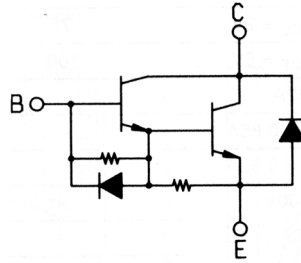**Figure 1.12**   Regenerative snubbers (a) Passive, (b) Active

Figure 1.13   Darlington transistor symbol

reverse-biased collector junction. This tends to create a hot spot and the junction fails by thermal runaway, which is known as second breakdown. The rise in junction temperature at the hot spot accentuates the current concentration owing to the negative temperature coefficient of the drop, and this regeneration effect causes collapse of the collector voltage, thus destroying the device. A similar problem arises when an inductive load is turned off. As the base-emitter junction becomes reverse-biased, the collector current tends to concentrate in a narrow area of the collector junction.

Manufacturers provide specifications in the form of safe operating areas (SOAs) during turn-on (FBSOA) and turn-off (RBSOA), as shown in Figure 1.15. Obviously, a well-designed polarized RC snubber is indispensable in a transistor converter.
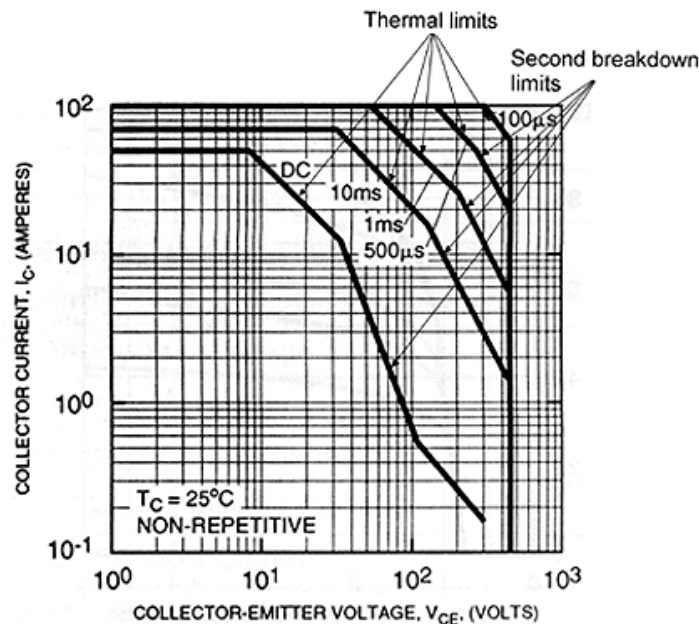

Figure 1.14   Forward-bias safe operating area (SOA) of a transistor (POWEREX KS524505)
(600 V, 50 A)

1.7 POWER MOSFETS

1.7.1 V-I Characteristics

Unlike the devices discussed so far, a power MOSFET (metal-oxide semiconductor field-effect transistor) is a unipolar, majority carrier, "zero junction," voltage-controlled device. Figure 1.16(a) shows the symbol of an N-type MOSFET and (b) shows its volt-ampere characteristics. If the gate voltage is positive and beyond a threshold value, an N-type conducting channel will be induced that will permit current flow by majority carrier (electrons) between the drain and the source. Although the gate impedance is extremely high at steady state, the effective gate-source capacitance will demand a pulse current during turn-on and turn-off. The device has asymmetric voltage-blocking capability, and has an integral body diode, as shown, which can carry full current in the reverse direction. The diode is characterized by slow recovery and is often bypassed by an external fast-recovery diode in high-frequency applications.

The V-I characteristics of the device have two distinct regions, a constant resistance ($R_{DS(on)}$) region and a constant current region. The $R_{DS(on)}$ of a MOSFET is an important parameter which determines the conduction drop of the device. For a high voltage MOSFET, the longer conduction channel makes this drop large ($R_{DS(on)} \propto V^{2.5}$). It is interesting to note that modern trench gate technology tends to lower the conduction resistance [10]. The positive temperature coefficient of this resistance makes parallel operation of MOSFET easy. In fact, large MOSFETS are fabricated by parallel connection of many devices.

While the conduction loss of a MOSFET is large for higher voltage devices, its turn-on and turn-off switching times are extremely small, causing low switching loss. The device does not have the minority carrier storage delay problem associated with a bipolar device, and its switching times are determined essentially by the ability of the drive to charge and discharge a tiny input capacitance $C_{ISS} = C_{GS} + C_{GD}$ (defined as Miller capacitance) with C_{DS} shorted, where C_{GS} = gate-to-source capacitance, C_{GD} = gate-to-drain capacitance, and C_{DS} = drain-to-source capacitance. Although a MOSFET can be controlled statically by a voltage source, it is normal practice to drive it by a current source dynamically followed by a voltage source to minimize switching delays. MOSFETs are extremely popular in low-voltage, low-power, and high-frequency (hundreds of kHz) switching applications. Application examples include switching mode power supplies (SMPS), brushless dc motors (BLDMs), stepper motor drives, and solid-state dc relays.

1.7.2 Safe Operating Area (SOA)

An important property of a MOSFET is that it does not have the second breakdown problem of a BJT. If localized and potentially destructive heating occurs within the device, the positive temperature coefficient effect of resistance forces local current concentration to be uniformly distributed across the total area. The maximum SOA of a MOSFET is shown in Figure 1.17. The device in the figure has a maximum dc current rating of 8 A at saturated condition, which can be
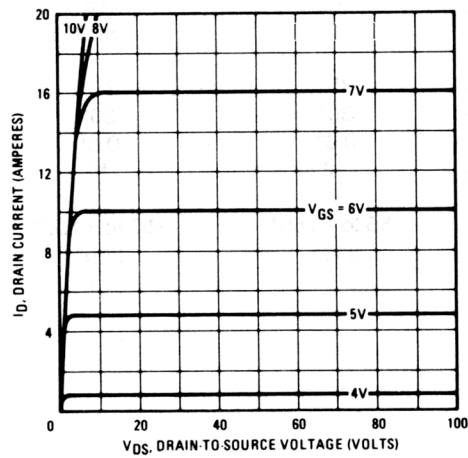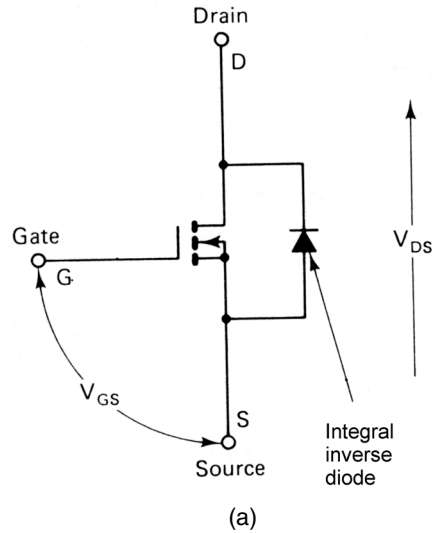
(a)

(b)

Figure 1.15   (a) Power MOSFET symbol, (b) Volt-ampere characteristics (Harris 2N6757);
(150 V, 8 A)

increased to an absolute maximum value of 12 A on a single-pulse basis. The maximum drain-to-source voltage V_{DS} is limited to 150 V without causing avalanche breakdown.

The SOAs of a MOSFET are determined solely by the junction temperature (T_J) rise, which can be calculated from thermal impedance information. As shown in Figure 1.17, the dc current can be carried in the full voltage range by 75 watts of power dissipation. This corresponds to junction-to-case thermal resistance $\theta_{JC} = 1.7$ °C/W for $T_{Jmax} = 150$ °C and infinite
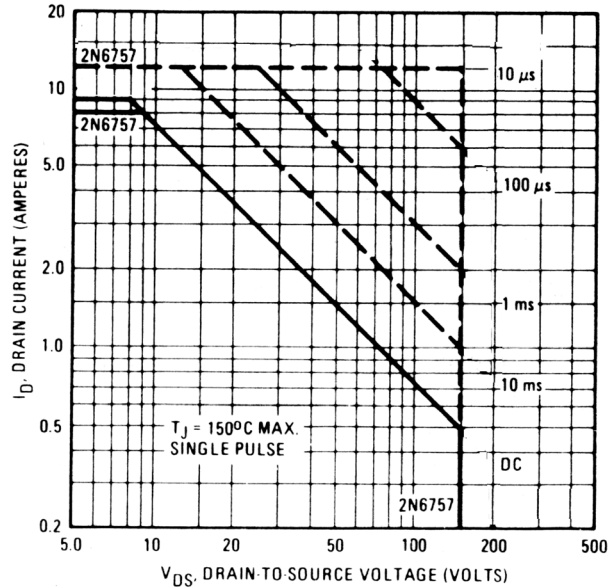
Figure 1.16   MOSFET safe operating area (SOA)

heat sink with ambient temperature $T_A = T_C = 25\ °C$ (see Equation 1.4). If the case temperature increases due to finite heat sink thermal resistance, the power dissipation is to be linearly derated, as shown in Figure 1.18. Note that there is no secondary slope on the SOA curves, indicating the absence of second breakdown as commonly observed on BJT SOA curves (Figure 1.15). Figure 1.17 also shows SOA curves based on single current pulse-operation. For example, at $V_{DS} = 100$ V, a dc current of 0.75 A (75 W) can be increased to 9.0 A (900 W) with 100 μs pulse. With the transient thermal impedance information of a device, safe dissipation limits for multi-pulse operation on a duty-cycle basis within the constraint of T_{Jmax} can be easily calculated. With square SOA and the absence of second breakdown effect, MOSFET converters with minimal stray inductance can be designed without snubbers if desired.

1.8 STATIC INDUCTION TRANSISTORS (SITS)

A static induction transistor (SIT) is a high-voltage, high-power, high-frequency device that can be considered essentially the solid-state version of a triode vacuum tube, which has been known for a long time. It is a short N-channel majority carrier device where the P-type gate electrodes are buried within the drain and source N-type layers. A drawback of the device is that it is normally on, but if gate voltage is negative, the reverse-biased P-N junction will inhibit drain current flow. Functionally, it is almost identical to a junction-FET, except that its lower channel resistance causes lower conduction drop. The reliability, noise, and radiation hardness of an SIT are claimed to be superior to a MOSFET. Although the conduction drop of the device is lower than that of an equivalent series-parallel combination of MOSFETs, the excessively large con-
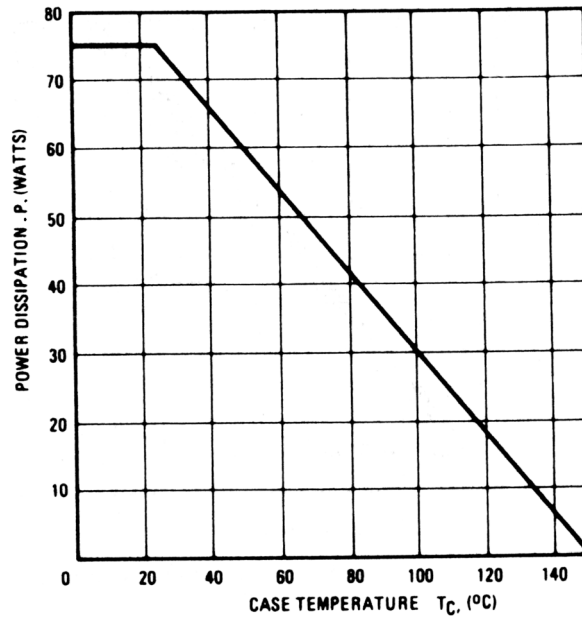
Figure 1.17   MOSFET power vs. temperature derating curves

duction drop makes it unsuitable in most power electronics applications unless justified by a need for FET-like switching frequency. These devices have been used in AM/FM transmitters, high-frequency induction heating, high-voltage, low-current power supplies, ultrasonic genera-tors, and linear power amplifiers.

1.9 INSULATED GATE BIPOLAR TRANSISTORS (IGBTS)

The introduction of insulated gate biploar transistors (IGBTs) in the mid-1980s was an important milestone in the history of power semiconductor devices. They are extremely popular devices in power electronics up to medium power (a few kWs to a few MWs) range and are applied extensively in dc/ac drives and power supply systems. They ousted BJTs in the upper range, as mentioned before, and are currently ousting GTOs in the lower power range. An IGBT is basically a hybrid MOS-gated turn-on/off bipolar transistor that combines the advantages of both a MOSFET and BJT. Figure 1.19(a) shows the basic structure of an IGBT and (b) shows the device symbol.

Its architecture is essentially similar to that of a MOSFET, except an additional P^+ layer has been added at the collector over the N^+ drain layer of the MOSFET. The device has the high-input impedance of a MOSFET, but BJT-like conduction characteristics. If the gate is positive with respect to the emitter, an N-channel is induced in the P region. This forward-biases the base-emitter junction of the P-N-P transistor, turning it on and causing conductivity modulation of the N^- region, which gives a significant reduction of conduction drop over that of a MOSFET.
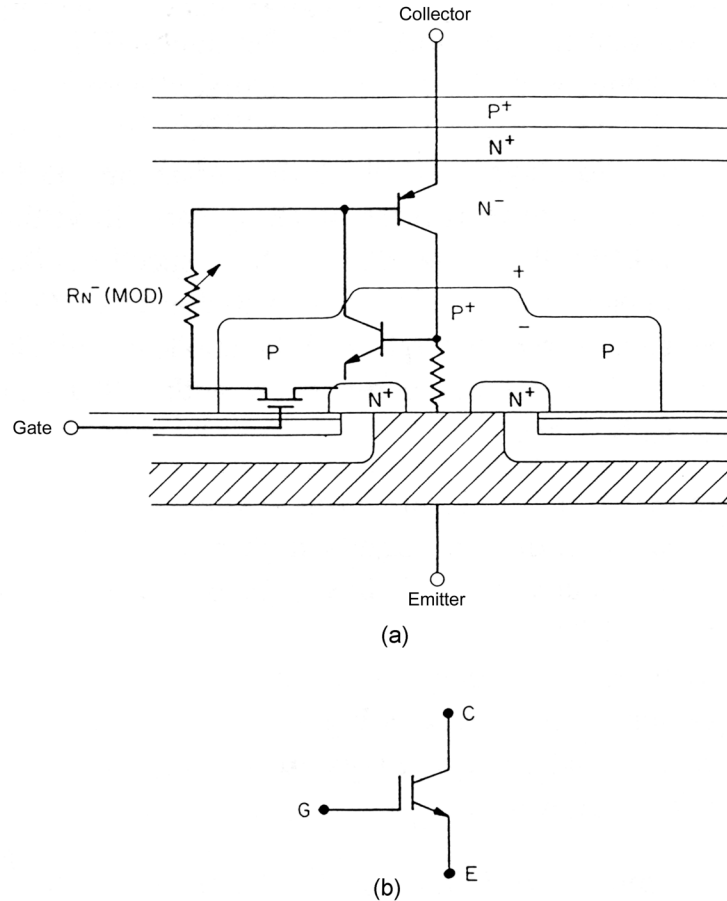
Figure 1.18   (a) IGBT structure with equivalent circuit, (b) Device symbol

At the on-condition, the driver MOSFET in the equivalent circuit of the IGBT carries most of the total terminal current. The thyristor-like latching action caused by the parasitic N-P-N transistor is prevented by sufficiently reducing the resistivity of the P^+ layer and diverting most of the current through the MOSFET. The device is turned off by reducing the gate voltage to zero or negative, which shuts off the conducting channel in the P region. The device has higher current density than that of a BJT or MOSFET. Its input capacitance (C_{iss}) is significantly less than that of a MOSFET. Also, the ratio of gate-collector capacitance to gate-emitter capacitance is lower, giving an improved Miller feedback effect.

Figure 1.20 shows the volt-ampere characteristics of an IGBT near the saturation region, indicating its BJT-like characteristics. A modern IGBT uses trench-gate technology to reduce the conduction drop further. The device does not show any second breakdown characteristics of a BJT and its square SOA is limited thermally like a MOSFET. Therefore, an IGBT converter can be designed with or without a snubber.
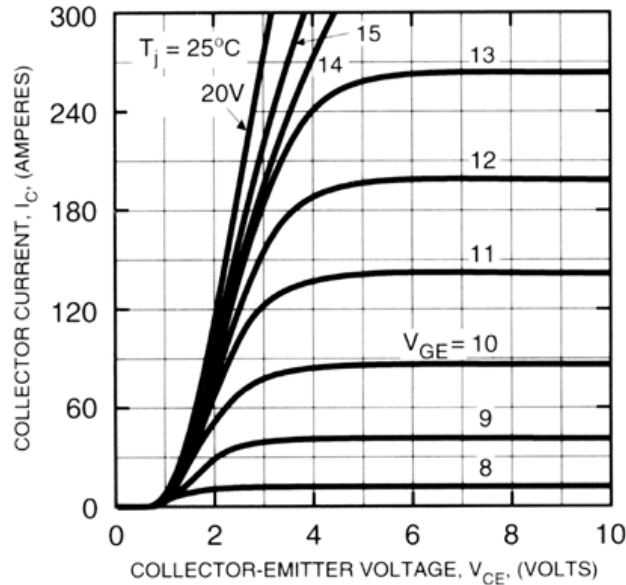
Figure 1.19   Volt-ampere characteristics of an IGBT (POWEREX IPM CM150TU-12H);
(600 V, 150 A)

1.9.1   Switching Characteristics and Thermal Impedance

Figure 1.21(b) shows the typical switching voltage and current waves for the "hard-switched," snubberless, half-bridge converter shown in (a) of the same figure. The profile of conduction and switching losses is indicated in the lower part of (b). Initially, the IGBT Q_1 is off and the inductive load current is taken by the free wheeling diode D_2. When Q_1 is turned on, the load current is initially taken by the device at full voltage (with a small leakage inductance drop), as shown. In fact, the diode D_2 recovery current is added to it before the diode sustains reverse voltage and Q_1 voltage falls to zero. Similarly, at turn-off, the device voltage builds up at full current and then the diode D_2 takes over the line current as shown. The fall time t_f is very short and is dictated by turn-off of the MOSFET section of the IGBT. The device shows a tail time t_t, which is due to minority carrier storage in the N$^-$ region. The loss curve indicates that the average switching loss becomes high at high switching frequency. Obviously, a turn-on/turn-off snubber can reduce the device's switching losses, as discussed before.

Figure 1.22 shows the transient thermal impedance characteristics of an IGBT in normalized form, which indicates that $\theta_{JC}(t)$ is always a fraction of the corresponding thermal resistance $\theta_{JC}(dc)$. For this particular device (POWEREX CM150TU-12H), $\theta_{JC}(dc) = 0.21$ °C/W. This figure helps to design heat sink for certain duty cycle power pulses, as indicated in Figure 1.5. The power rating (currently 3500 V, 1200 A) and electrical characteristics of the device are
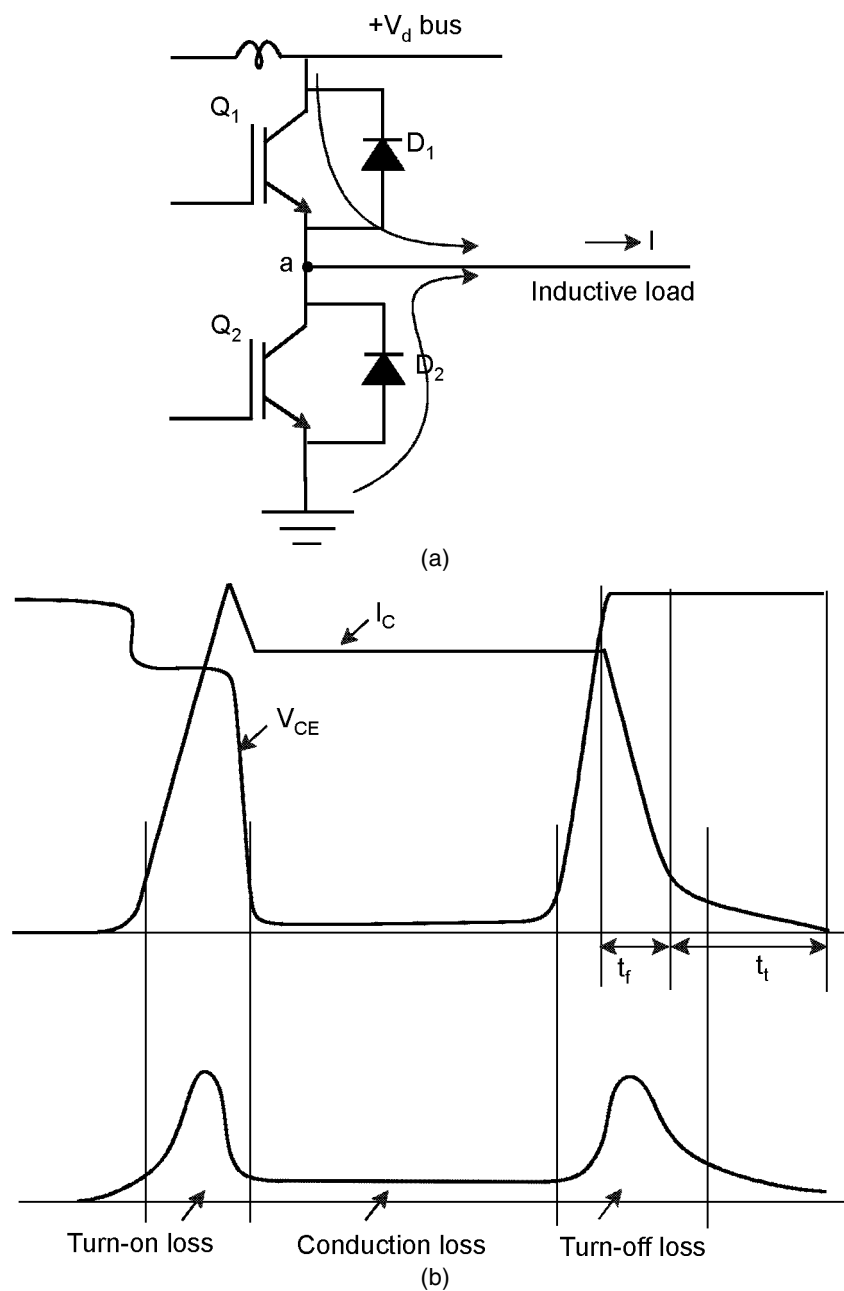
Figure 1.20 (a) Half-bridge converter configuration, (b) Typical switching characteristics of an IGBT

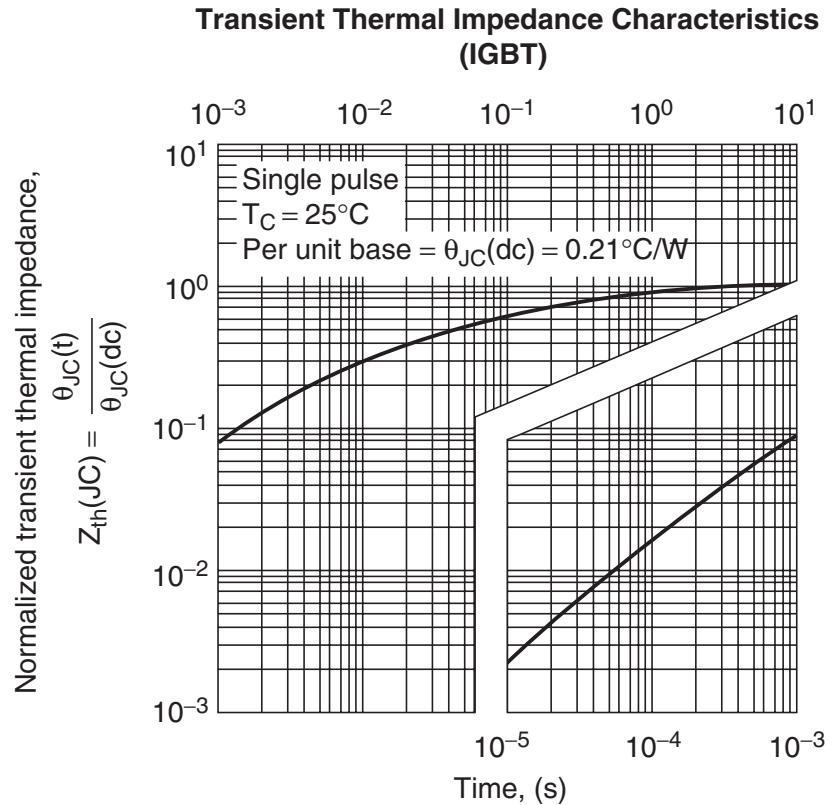**Transient Thermal Impedance Characteristics (IGBT)**

Figure 1.21   Transient thermal impedance characteristics of an IGBT (CM150TU-12H)

continuously improving. IGBT intelligent power modules (IPMs) are available with built-in gate drivers, controls, and protection for up to a several hundred kW power rating.

1.10 MOS-CONTROLLED THYRISTORS (MCTS)

An MOS-controlled thyristor (MCT), as the name indicates, is a thyristor-like, trigger-into-conduction hybrid device that can be turned on or off by a short voltage pulse on the MOS gate. The device has a microcell construction, where thousands of microdevices are connected in parallel on the same chip. The cell structure is somewhat complex. Figure 1.23 shows the equivalent circuit and symbol of the device. It is turned on by a negative voltage pulse at the gate with respect to the anode and is turned off by a positive voltage pulse. The MCT has a thyristor-like P-N-P-N structure, where the P-N-P and N-P-N transistor components are connected in regenerative feedback, as shown in the figure. However, unlike a thyristor, it has unipolar (or asymmetric) voltage-blocking capability. If the gate of an MCT is negative with respect to the anode, a P-channel is induced in the P-FET, which causes forward-biasing of the N-P-N transistor. This
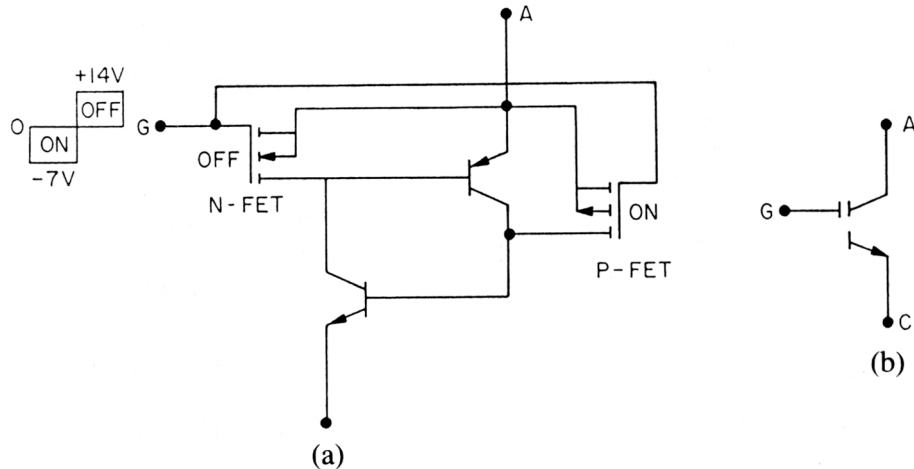
Figure 1.22   MCT symbol and equivalent circuit

also forward-biases the P-N-P transistor and the device goes into saturation by positive feedback effect. At conduction, the drop is around one volt (like a thyristor). If the gate is positive with respect to the anode, the N-FET will saturate and short-circuit the emitter-base junction of the P-N-P transistor. This will break the positive feedback loop for thyristor operation and the device will turn off. The turn-off occurs purely by recombination effect and therefore the tail time of the MCT is somewhat large. The device has a limited SOA, and therefore a snubber circuit is mandatory in an MCT converter. Recently, the device has been promoted for "soft-switched" converter applications (to be discussed in Chapter 5), where the SOA is not utilized. In spite of complex geometry, the current density of an MCT is high compared to a power MOSFET, BJT, and IGBT, and therefore it needs a smaller die area.

The MCT was commercially introduced in 1992, and currently, medium-power devices are available commercially. The future acceptance of the device remains uncertain at this point.

1.11 INTEGRATED GATE-COMMUTATED THYRISTORS (IGCTS)

The integrated gate-commutated thyristor (IGCT) is the newest member of the power semiconductor family at this time, and was introduced by ABB in 1997 [12]. Basically, it is a high-voltage, high-power, hard-driven, asymmetric-blocking GTO with unity turn-off current gain. This means that a 4500 V IGCT with a controllable anode current of 3000 A requires turn-off negative gate current of 3000 A. Such a gate current pulse of very short duration and very large di/dt has small energy content and can be supplied by multiple MOSFETS in parallel with ultra-low leakage inductance in the drive circuit. The gate drive circuit is built-in on the device module. The device is fabricated with a monolithically integrated anti-parallel diode. The conduction drop, turn-on di/dt, gate driver loss, minority carrier storage time, and turn-off dv/dt of the device are claimed to be superior to GTO. Faster switching of the device permits snubberless

operation and higher-than-GTO switching frequency. Multiple IGCTs can be connected in series or in parallel for higher power applications. The device has been applied in power system inter-tie installations (100 MVA) and medium-power (up to 5 MW) industrial drives.

1.12 LARGE BAND-GAP MATERIALS FOR DEVICES

So far, all the power semiconductor devices discussed exclusively use silicon as the basic raw material, and this will possibly continue, at least in the near future. However, new types of large band-gap materials, such as silicon carbide and semiconducting diamond, are showing high promise for the future generation of power devices. Silicon carbide is particularly more promising because its technology is more "mature" than for diamond. The material has high carrier mobility, faster minority carrier lifetime, and high electrical and thermal conductivities. These properties permit high-voltage and high-power capabilities, fast switching (i.e., high switching frequency), low conduction drop, good radiation hardness, and high junction temperature. All key devices, such as diodes, power MOSFETs, thyristors, GTOs, etc. are possible with this new material.

Silicon carbide power MOSFETs with T_{Jmax} up to 350 °C appear particularly interesting as replacements for high-power silicon IGBTs in the future. High-voltage silicon carbide Schottky diodes with close to one-volt drop and negligible leakage and recovery current are available at this time.

1.13 POWER INTEGRATED CIRCUITS (PICS)

A discussion on power semiconductor devices is incomplete without some mention of power integrated circuits (PICs). In a PIC, the control and power electronics are generally integrated monolithically on the same chip. Loosely, a PIC is defined as "smart power." The motivations behind a PIC are reductions in size and cost, and improvement in reliability. The main problems in PIC fabrication are isolation between high-voltage and low-voltage devices and thermal management. A PIC is often differentiated from a high-voltage integrated circuit (HVIC), where the voltage is high but the current is small, that is, the loss is low. Low-voltage NMOS, CMOS, and bipolar devices can be conveniently integrated with MOS-gated power devices. Recently, a large family of PICs that includes power MOSFETs or IGBT smart switches, half-bridge inverter drivers, H-bridge inverters, two-phase step motor drivers, one-quadrant choppers for dc motor drives, three-phase brushless dc motor drivers, etc. has become available. Figure 1.24 shows a monolithic PIC (within the dotted rectangle) for driving a brushless dc motor. The simplified block diagram of the40 V, 2 A PIC consists of a six-switch power stage, Hall sensor decoding logic, current-regulated PWM (pulse width modulated) control of the lower switches, and thermal/undervoltage protection features.
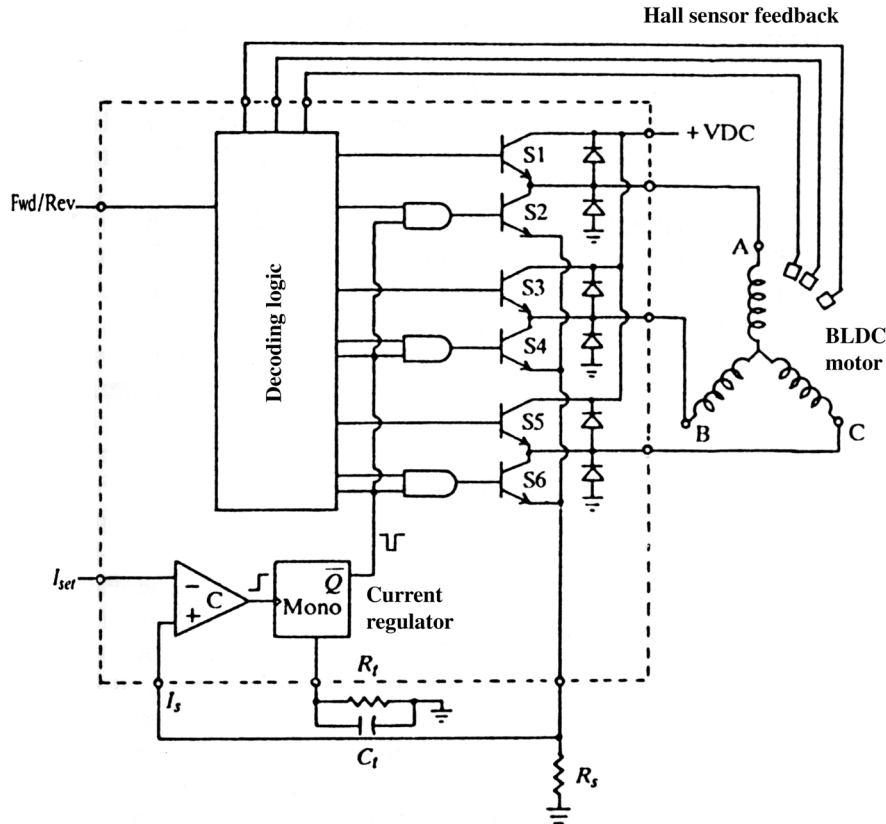
Figure 1.23   Monolithic PIC for brushless dc motor (BLDC) drive (Unitrode UC3620)

1.14 SUMMARY

This chapter has given a brief, but comprehensive review of the different types of power semiconductor devices that are used in power electronic systems. The devices covered include the diode, thyristor, triac, GTO, BJT, power MOSFET, IGBT, MCT, and IGCT. Power semiconductor devices constitute a vast and complex subject, and the technology is going through continuous evolution. Within the scope of this chapter, we only gave brief descriptions of the devices and their characteristics. It is needless to say that a power electronics engineer responsible for designing an apparatus should be thoroughly familiar with the different devices to achieve optimum cost and the performance goals of the system. Traditionally, thyristor-type devices have been very popular in power electronic systems and many applications can be found in this area. Therefore, these types of devices and their characteristics were described at the beginning of the chapter. MOS-gated devices, particularly power MOSFETs and IGBTs, have been applied extensively in recent years, and therefore these devices were covered in more

detail. Although the BJT is now practically obsolete, and SIT and MCT devices are seldom used, these were briefly described for completeness of the subject. The IGCT is a recent member in the device family with good potential, and we are yet to see its growth of applications in competition with IGBTs and GTOs. Finally, large band-gap materials and PICs were discussed. It is interesting to see that the advent of new power semiconductor devices, growth of their power ratings, and improvement of their characteristics are continually driving the power electronics and motor drives technologies forward. Suffice it to say that if the device evolution would have stopped at the SCR level, the power electronics technology would have stalled hopelessly in the primitive stage. In the next several chapters, we will gradually develop applications of power semiconductor devices.

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