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Power Semiconductor Devices

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POWER SEMICONDUCTOR DEVICES

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For variable speed drives

BY JERRY L. HUDGINS
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HISTORICALLY, POWER SEMICONductor devices have been divided into three broad categories: diodes, transistors, and thyristors. Although modern devices can be classified in this way, there is an increasing overlap in device design and function. Also semiconductors, such as silicon carbide (SiC), gallium nitride (GaN), and other materials, as well as novel device designs have increased the suitability and broadened the applications of semiconductor switches in megawatt (MW) power conversion circuits and systems.

Modern Transistors

Transistors include the traditional power bipolar (nonsilicon materials being considered for the future), power metal-oxide-semiconductor field-effect transistors (MOSFETs), and hybrid devices that have some aspect of a control FET element integrated with a bipolar structure, such as an insulated-gate bipolar transistor (IGBT). Because of power limitations, MOSFETs are not used in MW drives and converter circuits. Thyristors are three-terminal devices that have a four-layer structure (typically, three p-n junctions) for the main power handling section of the device. All transistors and thyristor types are controllable and can be switched from a forward-blocking state (little or no current flows) into a forward-conduction state (large forward current flows). Transistors and most modern

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thyristors [except silicon-controlled thyristors (SCRs)] are also controllable in switching from a forward conduction back into a forward-blocking state. Some thyristors are able to block forward and reverse voltages (symmetric blocking) when compared with others that only block voltage in forward direction (asymmetric blocking). Transistor-type devices are generally asymmetric components, though some work on symmetric IGBTs has also been done [1].

Basic Design of Power Devices

Modern bipolar power devices are designed around a common theme: the p-i-n structure (approximated as p^+-n^--n^+), as shown in Figure 1, during the off-state or blocking condition of full applied voltage. One of the desirable attributes of a high-power switch is the ability to withstand (block) large off-state voltages. The relationship between the maximum sustainable blocking voltage, V_{Blk}, and impurity (dopant) concentration in the center region (base), N_{base}, is given in

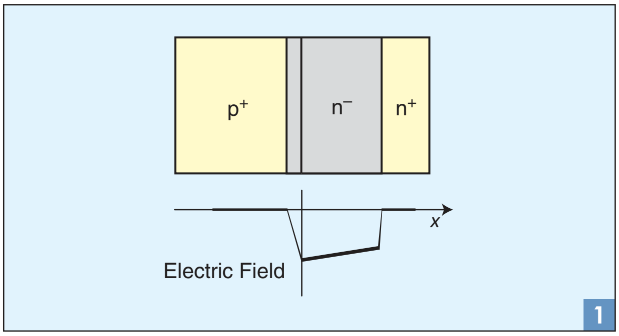
$$V_{\text{Blk}} \propto N_{\text{base}}^{-0.75}. \tag{1}$$

Therefore, as the impurity concentration in the base is reduced, the breakdown voltage capability of the device is improved. However, in doing so, the maximum allowable electrostatic field strength may be exceeded. Thereafter, the device designer can only improve the voltage-blocking capability by increasing the width of the base region. Unfortunately, this increase (and, hence, volume of the base region) will increase the forward voltage drop as the charge that has been injected from the highly doped regions (a phenomenon called conductivity modulation) has to move across a wider region during the forward-conduction state. A larger base volume also contains more stored charge during conduction, which must be removed to drive the device back to its off state (blocking mode), hence, requiring more time for the turn-off process to be completed. Therefore, devices rated for higher power operation, particularly devices rated for high blocking voltage (and high conduction current ratings), are necessarily slower to turn on and off than lower-rated devices. This physical behavior also sets up a tradeoff for improving conduction and switching performance at the expense of blocking capability (power rating). The desire to increase the power capability without sacrificing too much of the conduction properties in a device has led to the proliferation of device types and differing optimizations within device families to meet the specific design needs for converters and machine drives.

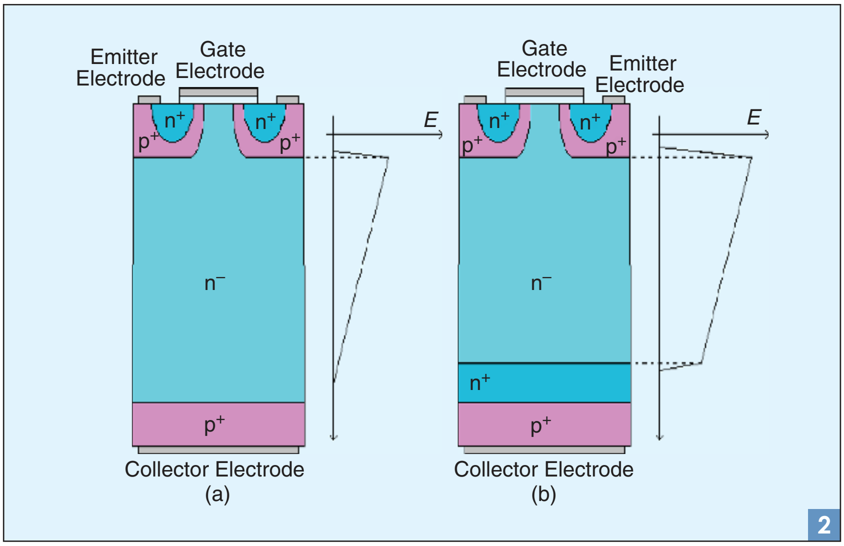
IGBT Devices

IGBTs are a wide-base pnp power transistor structure with an integrated MOS gate that replaces the conventional base electrode of a transistor. The original non-punch through (NPT) structure, illustrated in Figure 2(a), has been replaced with the punch through (PT) design by incorporating a highly doped n^+ region, referred to as a buffer layer or field-stop (FS) region, as shown in Figure 2(b). The buffer layer modifies the electric field present during forward blocking (i.e., positive collector voltage with respect to the emitter gives a similar electric field profile as shown in Figure 1) and allows a reduction in the n^- base width, thus improving overall conduction losses and switching times of the IGBT. Typical IGBTs used for high-power applications are rated at 3.3–6.5 kV blocking capability. A further improvement in performance for low- and medium-power devices can be made by replacing the planar-gate arrangement with a vertical or buried (trench) gate electrode shown in Figure 3. The buried gate reduces the current path during conduction, thus potentially reducing the forward-conduction drop. Modern sixth generation trench-gate IGBTs also have a lower input capacitance than earlier generations of both trench- and planar-gate devices.

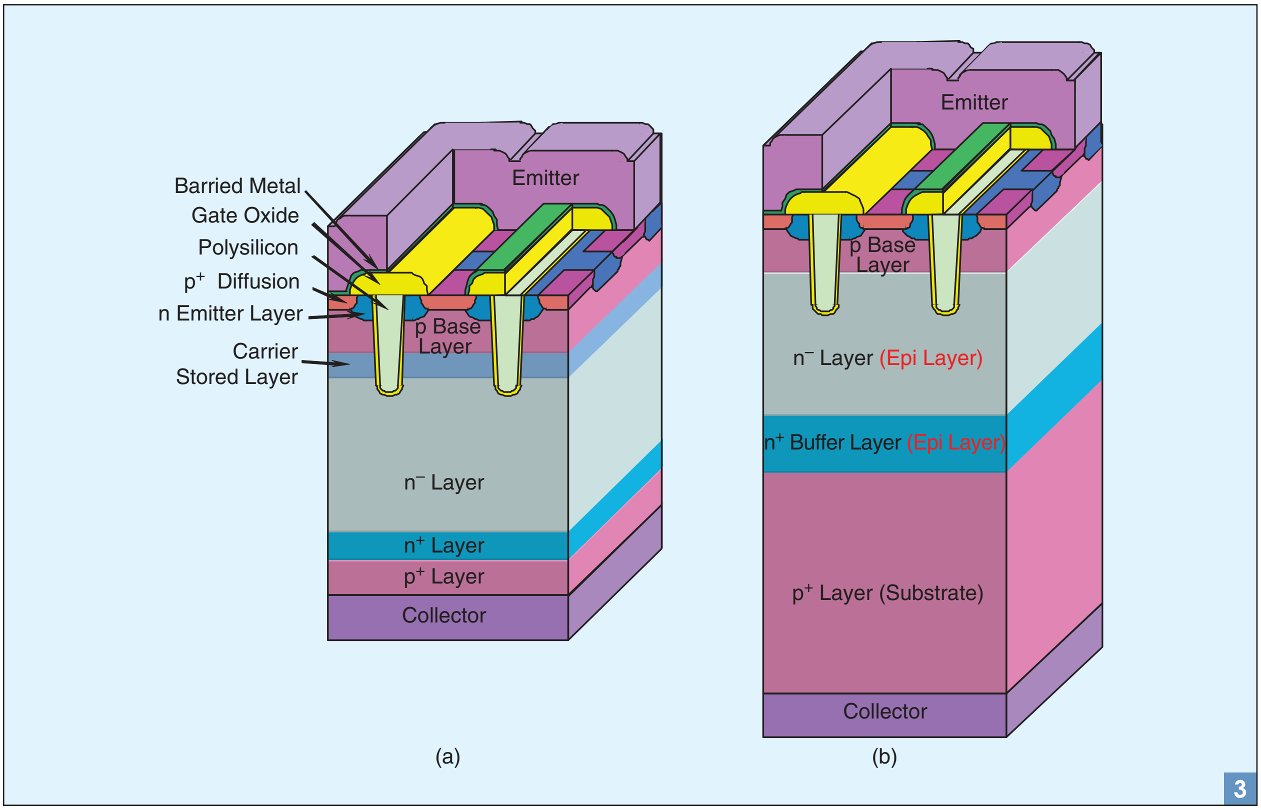
In both planar- and trench-gate designs, the charge-carrier concentration in the on state of the device near the emitter is very low compared with the concentration at the collector end of the device (curve B in Figure 4). The on-state voltage is proportional to the inverse of charge



p^+-n^--n^+ power device core structure. During the blocking state, the peak electric field occurs at the p^+-n^- junction.



Structure of NPT and PT with buffer layer IGBTs and their associated electric-field profiles.



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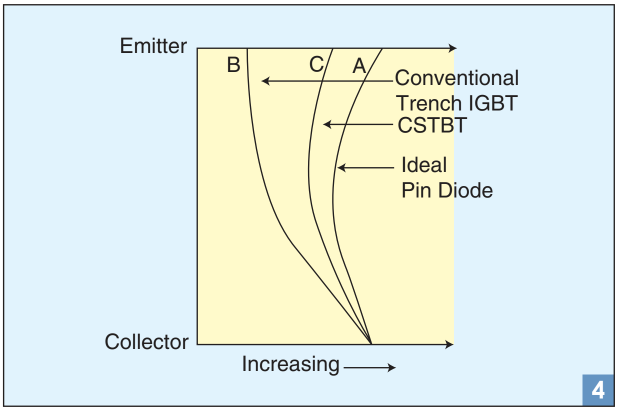
Comparison of IGBT cell structure. (a) Carrier-stored trench bipolar transistor (CSTBT) and (b) conventional PT trench IGBT. (Image courtesy of Powerex, Inc.)

concentration and is thus dominated by the low value near the emitter [3]. The excess stored charge, near the collector, dominates the switching behavior/losses. The introduction of a buried charge storage n-region between the p-emitter and n^--base regions improves the charge-carrier distribution closer to the ideal diode distribution (curve C of Figure 4), thereby enhancing the tradeoff between the on-state and switching losses, resulting in lower total losses [4].

The high-conductivity IGBT (HiGT) is similar to the device shown in Figure 3(a), except that the HiGT has a planar-gate structure [5]. This device has been shown to operate favorably when compared with a conventional IGBT, both rated for a 3.3-kV blocking capability.



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Comparison of charge-carrier profiles in various IGBT designs with that in an ideal power diode.

A modified soft PT (SPT) design, using a lightly doped buffer layer (similar to the FS region in a 6.5-kV IGBT), has allowed high-voltage devices to be fabricated with reduced on-state losses while keeping the processing advantages of a planar gate [6]. At typical operating voltages, the space-charge region during turn off and blocking does not reach the edge of this buffer layer. Therefore, despite a very thin base region, the dynamic electrical properties of the SPT-IGBT are almost comparable with those of a thicker NPT design. This technology has been demonstrated in IGBT devices with a blocking voltage capability in excess of 8 kV [7].

A variation of the trench-gate device with electron injection enhancement (IE) has been developed as IEGT [8]. The structure is similar to that shown in Figure 3(a). However, instead of a buried n-layer, only one of every five n^+-emitter regions is electrically connected to the contact metallization. This enhances electron injection from the connected emitters. The lifetime of the hole is also reduced at the p-collector (IEGT collector) to reduce hole-injection efficiency at the p^+-n^- junction. The net effect is to increase charge-carrier injection from the emitter side and reduce carrier injection from the collector side, causing the carrier profile to more closely approach the ideal pin-diode distribution.

Another proposed design by which the IGBT on-state charge-carrier profile is modified is by reducing the collector contact area and inserting a floating n^+ region there. The n^+ region is electrically isolated from the IGBT p-collector contact by a thin oxide layer. Electrons accumulate at the oxide interface near the p-collector, which enhances hole injection back from the collector region. This design is the injection-efficiency-controlled (IEC) IGBT [9].

IGBTs rated with blocking ratings above 5 kV are typically used in circuits with a dc-link voltage of 3 kV or in ac systems at 2.3 kV. By stacking devices in series, dc systems at 5.9 kV and higher, up to 150 kV [10], [11] or ac systems at 4.2 kV and higher can be realized. In addition, these type of devices, as do all NPT and modern SPT devices, have a positive temperature coefficient of the on-state voltage and can be configured in parallel for increased current capability in a system. Circuits requiring hundreds to thousands of amperes to be switched require multiple parallel dies to be used, as the maximum controllable current per die is limited to approximately 200 A/cm^2. Switching frequencies at these ultrahigh IGBT voltages and currents are of a few hundred hertz. Higher switching frequencies can be realized only with IGBTs typically rated for blocking voltages below 3 kV.

IGBT modules have also been developed, which integrate the usual IGBT device and clamp diode with a drive IC that can include sensing and protection functions [12]. These intelligent power modules (IPMs) are typically used for low-power converters, but their usage in high-power converters is expected to occur in the future.

Reliability for Devices

Power cycles endured during the operation of power electronic drives have a large effect on the lifetime and ultimate reliability of devices and their packages. For example, the power electronic devices in a drive for an urban tram may experience up to 10^8 power cycles with an associated device (Si junction temperature) temperature excursion of more than 80 °C [13], [14]. The failure rate [failure in time (FIT), where $1\ \text{FIT} = 1 \times 10^{-9}$ failures per device hour] in IGBT devices has decreased from 1,000 FIT in 1995 to the present rate of a few FIT [15]. The FIT of the gate driver and associated electronics is now higher than the IGBT device. IGBT package and device-related failures account for approximately 35% of the faults in drives.

Packaging

IGBT dies used in high-power converters are typically packaged in modules where multiple dies and associated diodes can be integrated into one package. However, several manufacturers offer disc-type packaging. Often modules house half-bridge, full-bridge, or three-phase bridge switch topologies. A typical module consists of three major parts: 1) an electrically insulating but thermally conductive substrate typically made of aluminum-nitride clad on both sides with copper (forms a direct bonded copper (DBC) substrate [16]), 2) a copper baseplate, and 3) a plastic housing. The Si die is soldered to the upper DBC surface with the bottom surface of the DBC soldered to the baseplate. Aluminum wire bonds connect the upper device electrodes and gate connections to the external package leads. A more recent packaging option for high-powered IGBTs, the press pack, is similar to that used for thyristors. Press packs have upper and lower copper pole pieces that connect (with a dry contact) directly to the IGBT collector and emitter [17]–[19]. Often a molybdenum or tungsten spacer is inserted between the upper pole piece and IGBT for a better match of the materials with respect to the coefficient of thermal expansion (CTE).

Typical package failures in modules occur due to crack growth at the wire-bond/silicon interface caused by temperature swings that create stress due to the different CTE values of Al and Si. The other major package-related failure in modules is solder fatigue. Again, different CTE values of Cu, Si, and solder combine to create shear stress that results in cracks and eventually voids that reduce the effective heat flow area between the Si die and the baseplate, further accelerating failure [20]. The mechanical stress associated with differing thermal expansion of package materials and the Si die also affects the electrical behavior of the devices through modification of the charge-carrier mobilities [21]. The press pack eliminates solder joints and wire bonds and has been shown to improve reliability over typical modules under accelerated life tests such as vibration, shock, and thermal cycling [22]. The failure mode of a device in a well-designed press pack is a short circuit and is desirable in a large series configuration of devices in a high-voltage application. Standard modules with wire bonds can have several failure modes that usually end up appearing as an open circuit. An open-circuit condition is desirable in parallel-connected device applications [23]. Of all commercial devices, only IGBTs are offered in press pack and plastic module package configurations. All other power device types are essentially offered only in press packs.

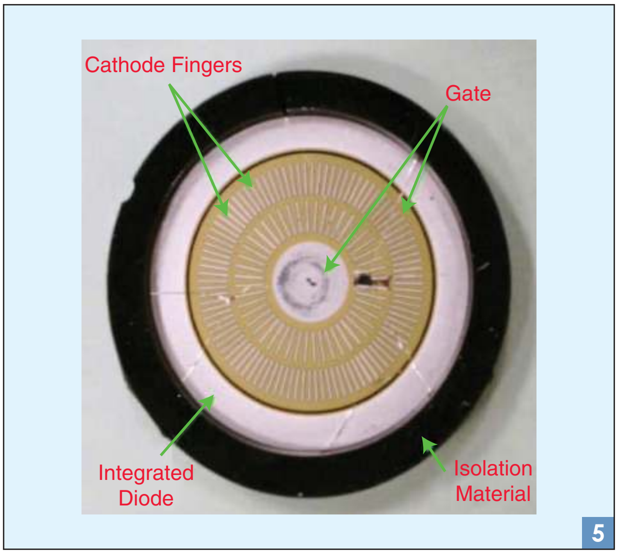
Devices

Overvoltage, particularly during turn off with an inductive load, can cause impact ionization leading to high currents and a corresponding excursion outside the so-called safe operating area (SOA), which causes thermal limits to be exceeded. This results in permanent damage to the device. Overcurrent conditions can also cause the thermal limit to be exceeded during the on or off state. Too high current densities during switching are a notable failure mode in thyristors and thus set a di/dt limit. Modern IGBTs can suffer from a latch-up or short-circuit phenomenon (generally thought to be related to the parasitic thyristor structure pnpn) only under excessive junction temperatures, though this latching effect has been greatly mitigated for the past few decades. Displacement current due to a high dv/dt, however, can inadvertently trigger thyristors.

The gate oxide in IGBTs can potentially be susceptible to electrostatic discharge damage and gate overvoltage, creating high local electric fields that puncture the oxide. Other device failure mechanisms can be traced to external radiation damage from cosmic rays. It has been shown that IGBTs can have an order of higher FIT magnitude than thyristors and power diodes resulting from cosmic ray damage [24]. The high electric field junction in an IGBT is close to the surface and thus is more susceptible to low-energy particles originating from packaging materials. This is unlike a thyristor or gate turn-off (GTO) device, where the high field junction is many microns below the silicon surface. For ultrahigh voltage devices, designing the n-base region is important to achieve an acceptable FIT rate.

Thyristor Devices

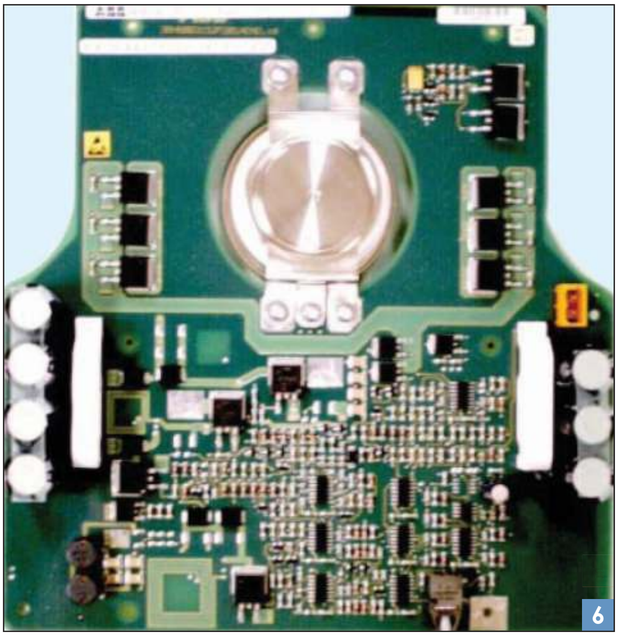
Thyristors can be produced as large-area power devices that are designed to block only in the forward direction (asymmetric) or in both forward and reverse directions



A typical GTO illustrating the gate region (golden hued) surrounding the cathode fingers (gray hued).

(symmetric). These devices have three pn junctions and as a result can latch in the forward-conduction mode (on state). This means that, after a short time of gate current injection, the device turns on and no longer requires the gate signal to remain in its on state. The speed of turn on in these large-area devices is greatly controlled by the amount of gate-cathode interdigitation [25], [26]. Conventional thyristors, such as SCRs, must have their current commutated to achieve turn off. When used to regulate real power in applications, such as electric grid transmission systems, the fundamental component of current always lags the voltage; therefore, the SCRs consume reactive power.

A controllable device that can turn off via the gate electrode requires an extreme amount of gate-cathode common periphery. This design became the GTO thyristor, and an example is shown in Figure 5. The device acts as a monolithic integrated set of parallel thyristors under each cathode region.



GTO with an integrated gate drive circuit known as an IGCT (ABB).

A nontrivial gate current is required for turn off to be achieved. Typically, 100% of the anode current must be commutated by the gate drive in approximately 1 μs. Because of the complexities of such a circuit, manufacturers now incorporate the gate-drive system as part of the switch module (Figure 6), creating the integrated gate commutated thyristor (IGCT) [27]. The close incorporation of the gate drive limits stray inductance in the control circuit and allows IGCTs to conduct thousands of amperes at turn on *di*/*dt* values of hundreds to a thousand amperes per microsecond. IGCTs are commercially available, rated from a few kilovolts to 6.5 kV, with a 10-kV device designed and previously reported [28]. For example, a 10-kV IGCT could be used without series connections of devices in a three-level neutral-point voltage-source converter rated at 7.2 kV rms line voltage.

The SOA of small area IGCTs exceeds 1 MW/cm^2, whereas large-area IGCTs have a reduced SOA at 200–300 kW/cm^2 [29]. This limit is determined to a great extent by the maximum controllable turn-off current. This limit is greatly influenced by the stray inductance in the gate turn-off driver circuit. Integrating this turn-off circuit in the package of the GCT wafer allows for much higher SOA. This integrated commutated thyristor concept is a promising innovation for next-generation high-power devices [30], [31] (Figure 7).

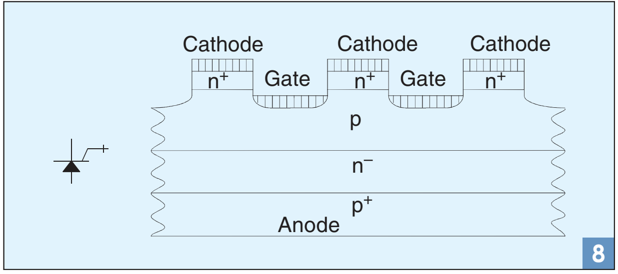
All IGBTs and most thyristors, including GTOs and IGCTs, are designed to give optimum performance during the on state with the maximum ability to block forward-applied voltage in the off state. Having the ability to block voltages in the forward and reverse directions (symmetric blocking) generally limits other performance metrics. However, a symmetric gate-commutated turn-off thyristor (SGCT) has been developed and commercialized for many years [32], [33]. For example, SGCT devices rated for 6.5 kV are incorporated into medium-voltage current source drives by several companies, providing better performance with fewer semiconductor devices (IGBT multilevel inverter design).

The SGCT device (represented in Figure 8) has no anode shorts, and no n$^+$-buffer layer between the n$^-$-base and p$^+$-anode (common in GTOs), making it an NPT structure. A modified edge bevel helps to improve the blocking capability by reducing the surface electric field. Further performance improvements are made using two energies of protons to irradiate the device during processing to create two distinct low carrier-recombination lifetime regions: one near the upper p-base/n$^-$-base junction and the second near the n$^-$-base/p$^+$-anode junction. The localized lifetime control lowers the turn-off energy losses and the associated anode turn-off tail current, as well as providing improvements in other parameters. In applications where the power switch must withstand reverse applied voltages, a diode is often used in series with a conventional asymmetric GCT. The total forward voltage drop of the diode and GCT (2.0 V plus 3.3 V, respectively) is higher than the SGCT (4.4 V) for a conduction current of 400 A. Thus, to achieve symmetric blocking capability, the SGCT can reduce the parts count, weight, and cost of a drive system compared with GCTs with diodes.

Other Thyristor Concepts

The devices described in this section are not currently available as commercial products but are undergoing advanced development and are included to be as comprehensive as possible in the discussion of power devices. A proposed design modification to the common anode-shorted GTO structure adds an oxide layer to electrically isolate the n^{+}-shorting region from the anode metallization. This is similar to the IEC IGBT device described earlier and is known as IEC-GTO [34]. This device effectively operates as a dual-anode GTO, where the oxide layer helps to increase the electron concentration near the anode during the on state. The performance enhancement provided by the IEC-GTO does not seem to be much better than GCT with a transparent (ultrathin) anode layer.

The MOS-gated turn-off (MTO) thyristor eliminates the need for a low-inductive gate turn-off power supply [35]. However, ultralow stray inductance between the cathode and the gate is required to maintain a large SOA. This was first realized by integrating the MOSFETs in the housing of the GCT wafer. Furthermore, using Si-Si bonding techniques to integrate the turn-off MOSFETs directly on the GCT wafer have shown promising results to make the MTO a viable concept. Meanwhile, the emitter turn-off (ETO) thyristor was proposed as an alternative to overcome the problems related to the high-inductive gate-cathode path. In the ETO concept, paralleled power MOSFETs (primary emitter switch) in series with the cathode of a GTO [36] is inserted (Figure 9). A second set of MOSFETs, attached between the GTO gate and source electrode of the primary MOS-switch array, is used to commutate the GTO cathode current when the primary MOS array is turned off. This allows stable turn off and an associated improved reverse bias safe operating area and is similar to the operation of the GCT, where the thyristor anode current is diverted from the cathode out the gate electrode and the p-base/n^{+}-emitter junction is turned off.



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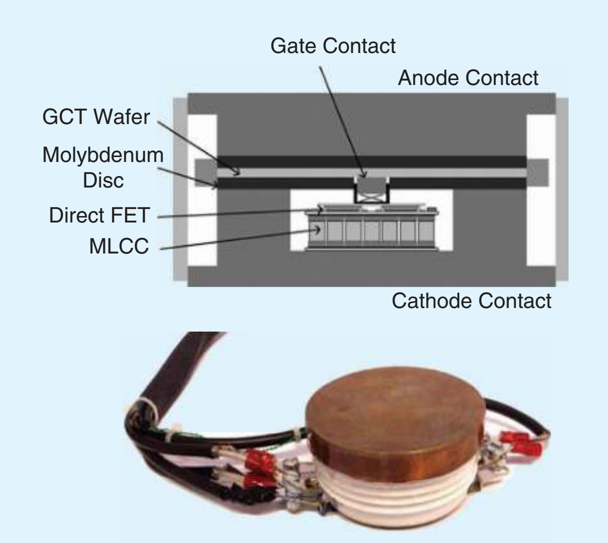
A cross section of SGCT cells (n^{-}-base not proportioned to other layers).



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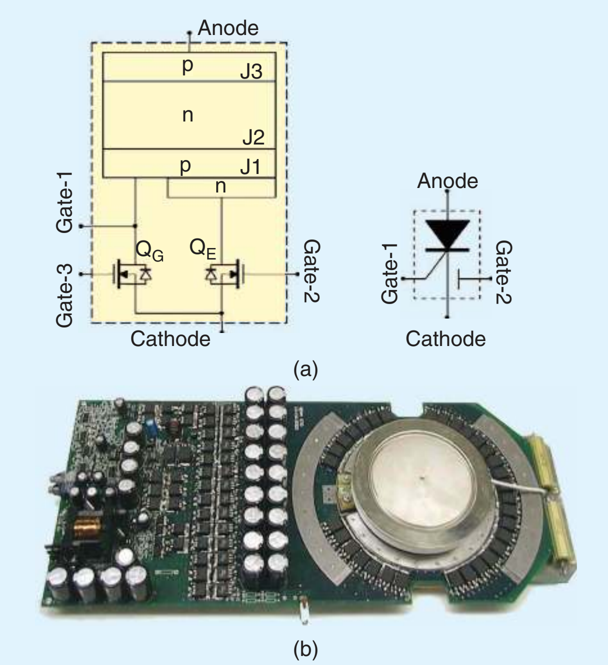
Integrated gate turn-off circuit with GCT wafer combined into one package.

Asymmetric blocking ETOs rated for 1 kA and 4.5 kV have been utilized in MW voltage source inverters but have been shown to fail from the poor reverse-recovery characteristics of the parasitic diode structure in the GCT portion of the ETO. This failure mode was addressed by using an external free-wheeling diode with a lower forward voltage drop than the parasitic diode. Recent work demonstrated that further reduction of the parasitic stray inductance in the gate-cathode path, for example, by integrating the MOSFETs in the housing of the GCT, also removed this problem. This integrated ETO (IETO) has been recently demonstrated and was tested repetitively at 2.5 times its nominal GCT turn-off capacity [37].

A variation of the ETO is one that self-powers the gate-drive and control circuitry [self-powered ETO (SPETO)] [38]. This eliminates the need for external gate power supplies. The turn-on and turn-off commands to the MOS gates are optically connected to the gate drive circuit. The power for the gate-drive systems is derived from a resistor capacitor (RC) snubber across the ETO, through an inductor capacitor



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(a) Circuit schematic and (b) photograph of an ETO device. (Photo courtesy of A. Huang.)

TABLE 1. QUALITATIVE SUMMARY COMPARISON OF COMMERCIAL DEVICES.

Devices	Switching Losses	Conduction Losses	Switching Frequency	Gating Mode	Failure Modes	Power Rating	Voltage Rating
IGBT	Low	High	10 kHz at medium voltage	Voltage	Open circuit in modules	Low to medium	Low to high
CSTBT and HiGT	Low	Medium	10 kHz	Voltage	Open circuit in modules	Low to medium	Low to medium
SPT-IGBT	Low	Medium	kHz	Voltage	Open circuit in modules	Low to medium	Low to high
IEGT	Low	Medium	kHz	Voltage	Open circuit in modules	Low to medium	Low to medium
IPM	Low	High	10 kHz	Voltage	Open circuit in modules	Low to medium	Low to medium
GTO	High	Low	100 Hz to few kHz	Current	Short circuit	Medium to high	Medium to high
IGCT	Medium	Low	100 Hz to few kHz	Current	Short circuit	Medium to high	Medium to high
SGCT	Medium	Low	100 Hz to few kHz	Current	Short circuit	Medium to high	Medium to high
SCR	Medium	Low	100 Hz to few kHz	Current (controllable on only)	Short circuit	Medium to high	Medium to high

(LC) filter, then processed by a small dc-dc converter to obtain the appropriate dc bias for the gate drive.

To further minimize conduction and switching losses, the dual GCT concept is being explored. The idea is to force the current during turn off from a low-forward drop GCT to a fast-switching GCT. Studies show that, in a soft-switching dc-to-dc converter, while switching at 50% duty cycle the combined switching and conduction losses could be reduced by 50% [39], [40].

Table 1 provides a summary of attributes for the commercially available technologies and gives a relative comparison between these thyristor- and transistor-type devices.

Future Trends

Superjunctions (SJs), also called charge-compensation structures, flatten the electric-field profile in the base region of a device, thus allowing thinner regions to achieve the same voltage rating. A thinner base region improves the switching frequency and conduction losses. SJ designs have been used in power MOSFETs and are being investigated for bipolar devices, such as transistors, with further extension in the future to thyristors [41].

Other device improvements may be made through the use of wide bandgap semiconductor materials such as SiC, GaN, and diamonds [42]. Material quality and the cost of manufacture limit adoption of these materials for high-power device fabrication, although a 4.5-kV rated IGCT built in SiC has been reported in the continuing push for multi-MW drives and converters [43].

Yet another trend that offers a great potential is the adaptation of device performance to specific converter topologies. A combined understanding of device and circuit design and the behavior of devices in these circuits often permit major cost reductions when SOA limits are well understood. In this sense, the use of soft-switching converters in medium-voltage applications offers great potential when the power devices are designed and specified for this type of operation.

The trend in IGBT technology of increasing power capability continues to encroach on applications where thyristors, such as IGCTs, are now used. The advantage of a comparatively simpler gate drive subsystem in IGBTs continues to provide this impetus. Finally, more functionality with respect to control, gate drive, current and voltage sensing, and overload limiting functions continue to be integrated into power device modules or onto the silicon itself as complexity is learned to be managed and fabricated. This general trend of increased power capability for IGBTs and more functionality should continue in the foreseeable future.

Maximum current and voltage ratings, new packaging and cooling for improved thermal performance, new functionality, and increased turn-off capability will continue to be improved and require redesign of high-powered drives [44].

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