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INSULATED GATE BIPOLAR TRANSISTORS

An insulated gate bipolar transistor (*IGBT*) is a semiconductor device that combines many of the good features of field-effect transistors (*FET*s) and bipolar junction transistors (*BJT*s). It is used most widely as a switch in power conversion circuits. The IGBT has a metal–oxide–semiconductor (*MOS*) gate that behaves as a capacitor. For an n -type device, when the gate terminal potential is raised above the threshold voltage with respect to the cathode, the device is turned on. If the gate–cathode voltage is high enough, the device can carry substantial current with a very low voltage drop from anode to cathode, typically less than 3 V. The current the device can carry varies with the area—more area means more current. In the 600 V to 1700 V blocking range, IGBTs typically operate at current densities around 75 A/cm^2 to 200 A/cm^2 . As is true with any power semiconductor, higher voltage devices operate at lower current densities. When the potential of the gate terminal is the same as, or lower than, the cathode, the device is in the off state. In the off state (also called the forward blocking state), the IGBT will conduct close to zero current with a large potential from anode to cathode. IGBTs have been designed with blocking voltages of over 2000 V.

Figure 1 shows two commonly used diagrams to represent the IGBT in circuit schematics. The device can be thought of and modeled as a pseudo-Darlington configuration of a MOSFET driving a BJT or a MOSFET with a diode in series with the drain (Fig. 2). Current flow through the MOSFET–BJT equivalent circuit during conduction is shown in Fig. 3. In this article, only the n -type IGBT is discussed. The “ n ” in n -type comes from the base region doping. A complementary p -type device is possible, but for a number of reasons the n -type is superior for switching applications. IGBT manufacturers and much of the literature refer to the terminals of the IGBT as collector, emitter, and gate, instead of anode, cathode, and gate, respectively. This can be misleading, since what is referred to as the IGBT collector is actually the *emitter* of the equivalent circuit *p–n–p* transistor, and similarly for the so-called emitter being the *collector* of the *p–n–p*. The left symbol in Fig. 1 illustrates the reason for this misleading terminology. This symbol, which is more convenient to draw than its counterpart on the right, makes it appear that the cathode is an emitter and the anode is a collector. This article will swim against the tide by holding to the anode, cathode, gate terminology to minimize confusion.

The MOSFET–BJT model is superior for a conceptual understanding of the IGBT. The MOSFET controls base current to the BJT while the BJT provides current gain. The forward blocking voltage (i.e., with the anode more positive than the cathode) is provided by the base–collector junction in the BJT. So, this is a model of a *low-voltage* MOSFET connected to a *high-voltage* BJT. This is important because the current density that a MOSFET can handle scales inversely with its voltage rating. If the MOSFET were a high voltage type, the current handling capacity of an IGBT would be restricted by the limited current capability, due to the high on-state resistance, of the FET. High-voltage BJTs suffer from low-current gain (the ratio of the collector current to the base current), but this combination of MOSFET and BJT nevertheless makes an excellent switch.

A perfect switch has the following characteristics: (1) zero voltage drop at any current when the switch is on, (2) zero current at any voltage when off, and (3) instantaneous transition between the on and off states. Items (1) and (2) are always desirable, but item (3) is only desirable where all other components are perfect. In reality, because of deficiencies in real devices and stray inductance in circuits, point (3) must be revised. A real switch should have a *controllable* transition between states. The reason for this will be demonstrated

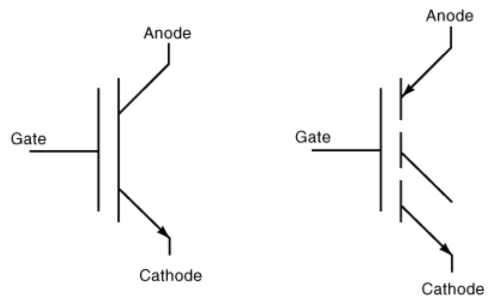

Fig. 1. Schematic diagrams of an IGBT.

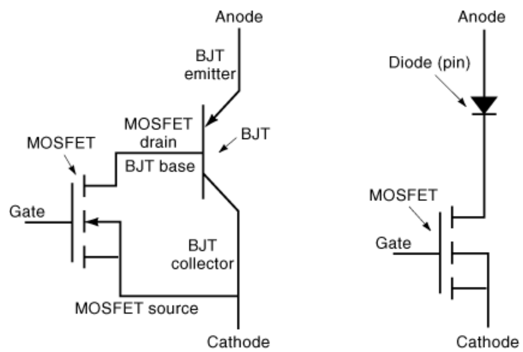

Fig. 2. Equivalent circuits of an IGBT. The MOSFET–BJT model on the left is more accurate.

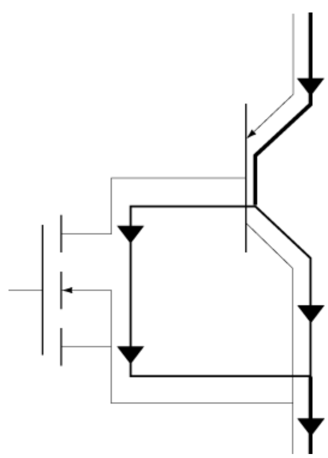

Fig. 3. Current flow through the IGBT equivalent circuit. The MOSFET regulates base current to the IGBT.

later. As mentioned previously, the IGBT has low forward voltage drop at high current densities. Among silicon devices, only thyristors can operate at higher current densities with lower forward drops. The IGBT can block reasonably high voltages, although thyristors can block more. Finally, the IGBT has a controllable transition between fully on and fully off. This is the downfall of thyristors—they are uncontrollable during the switching

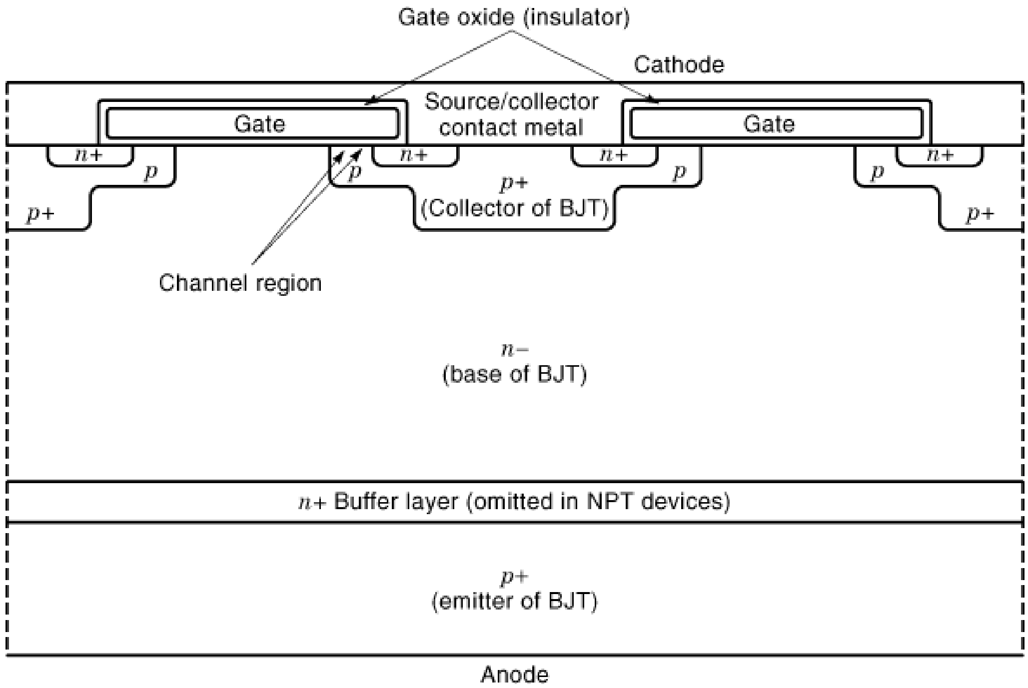

Fig. 4. Cross section of an IGBT. Figure is not to scale: approximate horizontal dimension, 40 μ m; approximate vertical dimension, 300 μ m.

transition. A separate issue is that an IGBT can operate at higher switching frequencies than a thyristor. We will take each of these in turn.

Forward Drop

The forward voltage drop of an IGBT is the voltage from the anode (+) to the cathode (−) of the device. The drop consists of the voltage drop across the emitter–base junction of the BJT added to the voltage drop from drain to source of the MOSFET (Fig. 2.). This is the same as the drop from emitter to collector of the BJT. Normally, a BJT that is fully on (i.e., saturated) has an emitter–collector voltage drop of 0.5 V or less. The voltage drop from emitter to base is around 1 V. It is impossible for the BJT in an IGBT to saturate because the MOSFET enforces the condition that the emitter–collector drop must be larger than the emitter-base drop. The base-collector junction, therefore, cannot go into forward bias, which is the necessary condition of saturation. Typical values for forward drop in fully on 600 V IGBTs today range from 1.9 V to 2.1 V, while the maximum values range from 2.5 V to 2.7 V. These values are for current densities of around 100 A/cm^2 .

Figure 4 shows a cross section of an IGBT cell. Figure 5 shows the areas of voltage drop in the cross section of the IGBT cell. The regions of voltage drop from the bottom of the figure are (1) the drop across the emitter–base junction, (2) the resistive drop in the base, (3) the resistive drop in the JFET region, and (4) the resistive drop in the channel. The base is conductivity modulated by holes injected from the emitter. The hole density decreases from emitter to collector due to recombination, so higher breakdown voltage devices (which necessarily have thicker base regions) have higher forward drops. The conductivity modulation of the base is what differentiates an IGBT from a MOSFET. A MOSFET has the same cross section as the IGBT except for

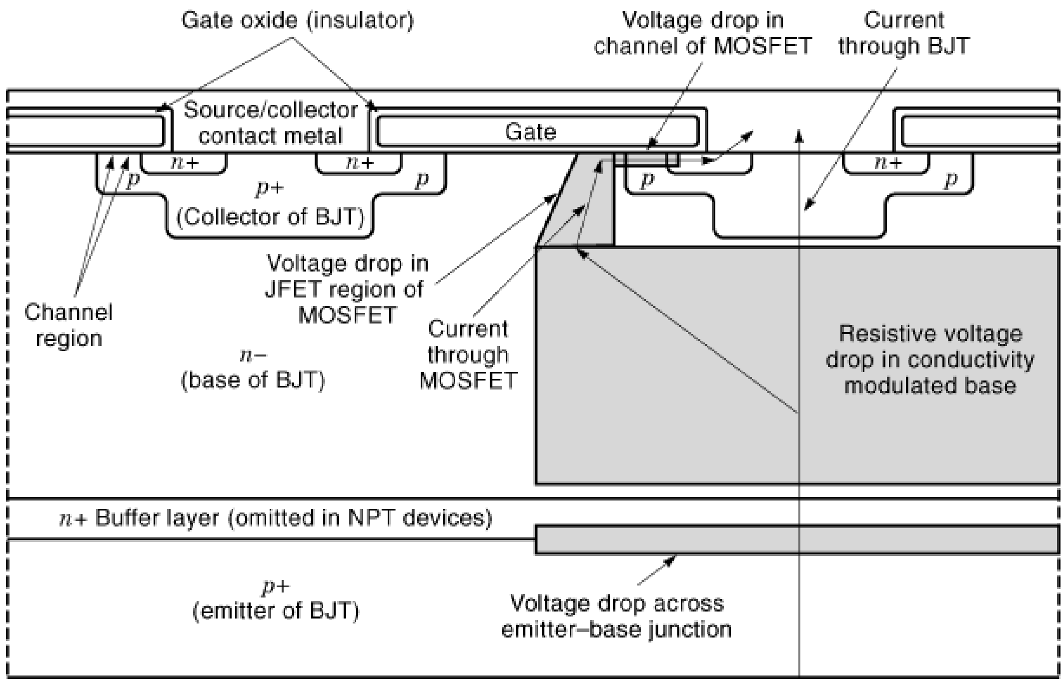

Fig. 5. Cross section of an IGBT with separate regions of voltage drop highlighted. Figure is not to scale.

the omission of the emitter region. Thus the base resistance in a MOSFET is much larger than in an IGBT with the same voltage rating because there are vastly fewer free carriers in the MOSFET than in the conductivity modulated IGBT base. A MOSFET does not have any *p*–*n* junction drops, so for low-voltage devices (below about 100 V), the power MOSFET is superior to the IGBT in terms of on-state voltage. The JFET region of the device is not conductivity modulated. Only the BJT base current flows in this region and the channel. The current through here might be around 35% of the total device current, but this number can vary significantly. The resistance of the JFET region is dependent on the geometry and doping of the device. The final voltage drop occurs in the channel. MOS physics dictate the resistance of this region, which, like the JFET region, carries only unipolar current.

One can improve the on-state drop of the IGBT by reducing the drop in the channel, the JFET region, and/or the base. The *p*–*n* junction drop is unavoidable. Manufacturers optimize the channel loss in the same fashion as in a MOSFET. The JFET region and its attendant loss can be eliminated completely by using a trench or buried gate. This is shown in Fig. 6. The trench gate is more difficult to fabricate than a surface gate, and such technology is only beginning to be employed in IGBTs on a broad scale.

Four methods of decreasing the voltage drop in the base are (1) reducing base resistivity, (2) reducing base width, (3) increasing the minority carrier lifetime in the base, and (4) increasing the emitter injection efficiency (γ). Reducing base resistivity is not possible because this would decrease the blocking voltage of the device. Low base doping (nearly intrinsic) is necessary to keep the electric field at the base–collector junction below the critical value where avalanche breakdown occurs. Reducing base width is possible and is commonly done by adding a buffer layer. The buffer layer is a highly doped region placed next to the emitter to pin the electric field when it “punches through” the low doped base to the buffer layer. Thus this is called punch through (PT) technology. The disadvantage of this method is that γ is substantially reduced. Manufacturers use the buffer

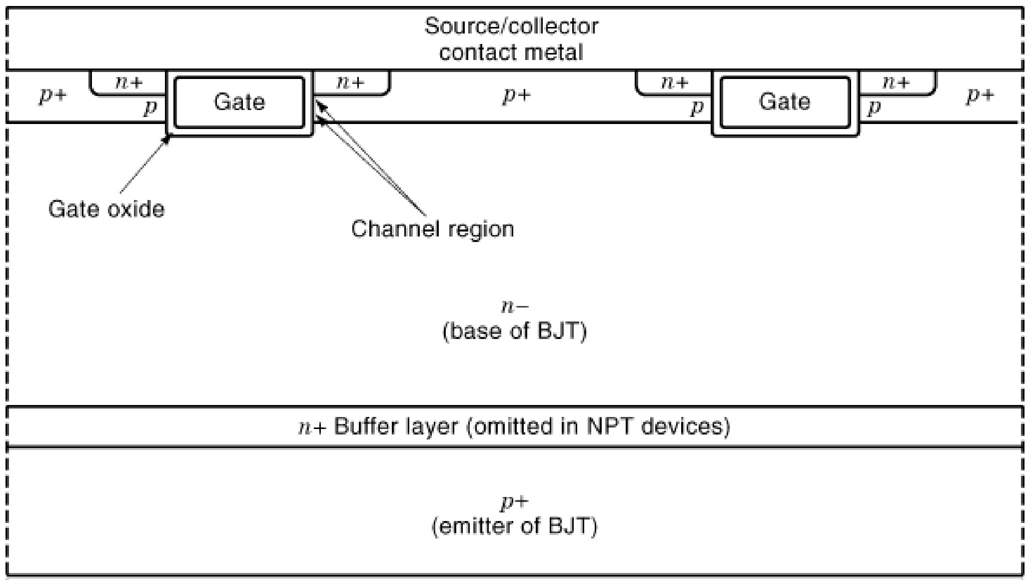

Fig. 6. Trench gate IGBT cross section. The gate is buried instead of mounted on the surface, eliminating the JFET region.

layer, nonetheless, because switching speed is improved with reduced γ, and the reduced base width translates into reduced cost. The base must be epitaxially grown on a $p+$ wafer, and epitaxial growth is expensive.

Manufacturers do not increase minority carrier lifetime in the base. In fact, they purposely *reduce* the lifetime to make the IGBT turn off more quickly. The same techniques used to reduce the lifetime in *pin* rectifiers and other bipolar devices are used here. Reducing carrier lifetime in the base boosts the on-state voltage, but this is a trade-off that is necessary for a device with a reasonable switching speed. A similar circumstance exists with the emitter injection efficiency. For the reasons stated above, IGBT designers often include a buffer layer, which has the side effect of reducing γ. However, a reduced γ means charge storage in the base is reduced and hence device switching speed improves. In NPT (non-punch through) technology, γ is high because the buffer layer is excluded. Of course, the width of the base in NPT devices is much larger than in PT devices. NPT technology has advantages (discussed below) but it is confined to higher voltage devices where the silicon wafer can be made entirely of low doped silicon. In such cases, the emitter is diffused into the wafer instead of being the substrate on which the rest of the device is grown. NPT technology can be used in lower voltage devices if processing techniques for handling thin wafers improve.

Optimizing forward voltage drop in the IGBT is difficult, because of the inherent trade-offs between low forward voltage drop and switching speed, specifically, turn-off time.

Switching Speed and Controllable Switching Trajectories

Turn-on of an IGBT is accomplished by increasing the gate–cathode voltage above the threshold voltage (typically 3 V to 7 V). For the IGBT to be fully on, the gate–cathode voltage must be around 15 V, although this, like the threshold voltage, varies from device to device. (One must always consult manufacturer data sheets for specific values or ranges of values.) The IGBT gate–cathode (not anode–cathode) turn-on characteristic is nearly identical to that of the MOSFET. The gate–cathode voltage is increased to the threshold voltage where it remains while the Miller capacitance discharges. Then the gate voltage can be increased to its final value. This charging time is dependent on both the circuit driving the gate and the circuit to which the anode and cathode are connected.

The anode–cathode voltage falls if the gate–cathode voltage exceeds threshold *and* if the external circuit allows it. When the gate voltage reaches threshold, the IGBT begins to conduct current. Until the base region is filled with carriers, the IGBT is in the state called *dynamic saturation*. In this state it has a higher voltage drop than normal because the base region has not been heavily conductivity modulated. This time that the device spends in this state depends primarily on the width of the base: it takes more time for carriers to flood a wider base region.

Just as with a MOSFET, turn-off of the IGBT is accomplished by discharging the gate–cathode capacitance. Bringing the gate–cathode voltage below the threshold voltage turns the IGBT off, but typically gate drive circuits are designed to bring the gate potential somewhat negative with respect to the source for noise immunity. Discharging the G-K capacitance is hindered by the Miller effect, and the IGBT exhibits a current tail caused by recombination of excess carriers in the base. It took time for the carriers to flood the base during dynamic saturation, and now it takes time for these carriers to be eliminated. Because this current tail typically occurs when the anode–cathode voltage is at a high value, this is a time of large power dissipation in the device. Minimizing the current tail is desirable but negatively impacts on-state voltage.

Turn-On. The IGBT can make the transition from the off state to the on state very quickly. In this it is limited by dynamic saturation (discussed above) and the Miller effect, which increases the apparent gate capacitance. Miller effect here is identical to that experienced in other transistors and can be overcome by drive circuits that rapidly charge the gate. However, in the most common power electronic circuit configuration, *rapid turn-on can destroy the circuit!* IGBTs are commonly used in bridge circuits, such as shown in Fig. 7, the basic building block of which is a phase leg. The loads these circuits drive are typically inductive because the load is typically a transformer, motor, or filter inductor. A typical situation is shown in Fig. 8. In circuit A in the figure, current from the load is flowing through the upper diode to the source. The lower IGBT is gated on in circuit B, and an ideal diode would instantly switch off, but real diodes have a reverse recovery time. During the first phase of this, the diode is a short circuit to current flowing in *either* direction, so if the IGBT were turned fully on, tremendous currents would flow in the reverse direction through the diode, destroying the on IGBT, the diode, or, due to Ldi/dt overshoot, the off IGBT, which is paired with the recovering diode. This condition is called transient shoot through. Instead, the IGBT is more slowly gated on in order to limit this current and its time rate of change, di/dt. The graph in Fig. 8 shows such a situation with a large current overshoot for the purpose of clarity. The diode leaves forward bias in the midst of its reverse recovery, at which point the IGBT voltage can collapse. Up to this point, the IGBT has been subjected to very large power dissipation. Finally, the diode fully recovers and the lower IGBT conducts the load current only.

The IGBT is very well suited to the task of gently commutating the current in the opposite diode. It has a linear region just as a BJT does, and this limits the current during shoot through. At large current densities, the device leaves saturation (or, more correctly, the closest an IGBT gets to saturation) and goes into the linear region, where current is limited. Figure 9 shows the general shape of output curves of an IGBT. This controllable turn-on characteristic is very important not only for circuit design but also for comparing the IGBT to other devices. Various flavors of thyristor are sometimes touted as superior to the IGBT, and in on-state voltage they typically are superior, but such thyristors almost always have uncontrollable turn-on. In order to avoid mayhem in the circuit (as described above), thyristors must have additional circuitry called snubbers. The IGBT holds a clear advantage here, and this explains why these devices, touted as replacements, will not replace the IGBT.

Turn-Off. Discharging the gate–cathode capacitance of the device shuts off the base current to the intrinsic BJT. At this point, the free carriers in the base must recombine or be extracted. There is no possibility of extracting carriers through the “base lead” as would be done in a power BJT because this base lead in the IGBT is not accessible. Hence the device exhibits behavior equivalent to open base turn-off in a BJT. The anode

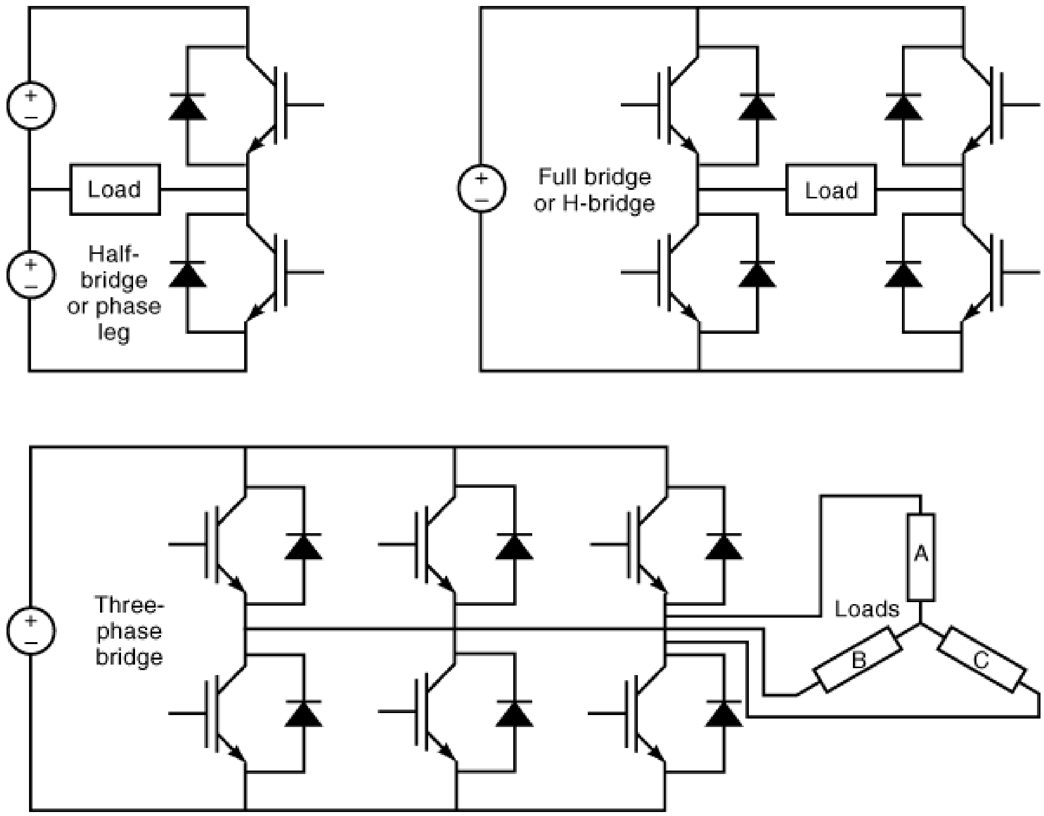

Fig. 7. Bridge circuits. The totem pole or half-bridge is the basic building block of the full and three-phase bridges. Note the diode coupled to each IGBT.

current shows an exponential tail while carriers either recombine or are swept out or diffuse out of the base to the collector or emitter. Because the intrinsic BJT cannot saturate (i.e., the base–collector junction cannot go into forward bias), there is not a delay time for turn-off as would be seen in a saturated BJT. A sample current tail is shown in Fig. 8. When the IGBT is rapidly gated off, the anode current quickly falls due to the shutoff of base current from the MOSFET (due to the low current gain of the intrinsic BJT, the base current is a significant fraction of total current); then the current tail is seen. Lifetime killing in the base is the recipe for decreasing tail current, but this reduces current gain of the BJT and increases the on-state voltage drop.

Reverse Blocking

The PT IGBT cannot block more than a few volts (or tens of volts) in the reverse direction. That is, the cathode cannot be brought more than a few volts positive with respect to the anode. This is due to the highly doped buffer layer abutting the emitter. A $p+/n+$ junction cannot withstand voltages as high as a $p+/n-$ junction such as the base–collector. An NPT device, on the other hand, can withstand equal voltage in both the forward and reverse directions if designed to do so. The NPT device must include proper edge termination at its anode to keep the reverse electric field from causing premature edge breakdown. In no case can the IGBT conduct

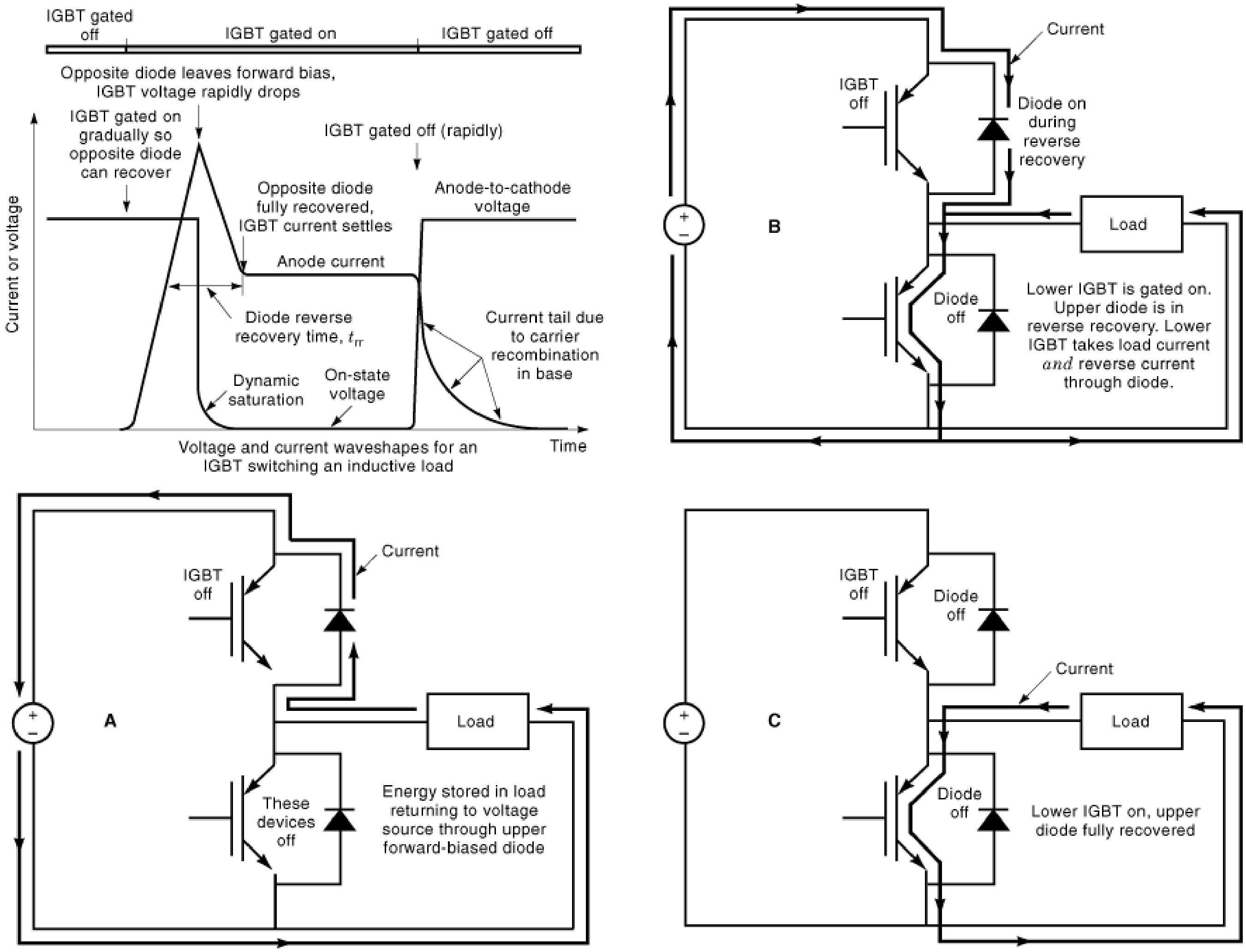

Fig. 8. Switching trajectory of an IGBT. The schematics illustrate the current path during reverse recovery of a free-wheeling diode.

current in the reverse direction, except as a transient phenomenon during reverse recovery of the base–emitter junction (if the MOSFET channel were conducting).

Device Failure

All failure in the IGBT is thermal failure. Whatever the failure mode, large power dissipation over time heats areas of the device past the point of recovery. All failure is recoverable, however, if these thermal limits are not exceeded. So, any abnormal condition can, in theory, be corrected before it causes catastrophe. This is easier said than done, because destruction typically occurs on a microsecond time scale.

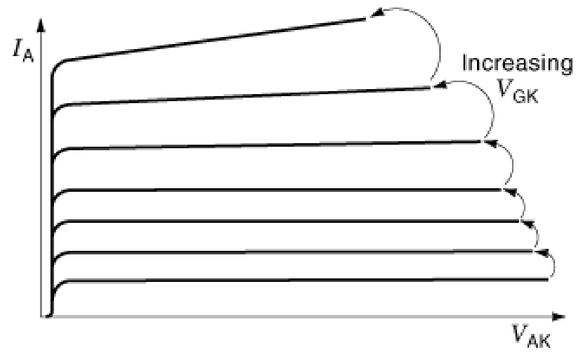

Fig. 9. Output characteristics of an IGBT: anode current versus anode–cathode voltage. Gate cathode voltage increases up the figure. Scales are arbitrary.

Parasitic Thyristor. The IGBT has a parasitic thyristor structure inherent to it (Fig. 4.). This device is the *p–n–p–n* structure of the emitter–base–collector of the *p–n–p* BJT with the $n+$ source of the MOSFET. The cathode metal shorts the source to the collector, but it is nonetheless possible for the source–collector junction to go into forward bias at very high temperatures or during large surge currents. Thyristor latchup takes the device outside the realm of gate control, and it typically results in device destruction unless the current is limited or interrupted externally. The $p+$ region of the collector (the channel area is just p) is used to decrease the resistance along the junction between source and collector. This reduces the chance of this junction going into forward bias. While thyristor latchup was a problem in first-generation devices, IGBT manufacturers now guarantee suppression of latchup below certain temperatures and current densities.

Safe Operating Area. The maximum current limit for the IGBT is dictated by the parasitic thyristor, and the maximum voltage limit is dictated by the width of the base and the edge terminations. Simultaneous application of high voltage and current, however, can cause avalanche breakdown even though the current and voltage are below the limits of thyristor and edge termination. Simultaneous application of high voltage and current occur during switching both at turn-on and turn-off. Under both conditions, the free carriers in the base enhance the electric field at the base–collector junction. If this exceeds a critical value (which value varies with temperature), avalanche breakdown occurs. This is not necessarily destructive, but the current rapidly increases under such conditions. If not limited, thermal failure of the device will occur. Manufacturers specify an *FBSOA* (forward biased safe operating area) for turn-on conditions and an *RBSOA* (reverse biased safe operating area) for turn-off conditions. The RBSOA is typically less than the FBSOA; however, due to the diode recovery problem outlined earlier, turn-on is more stressful in terms of simultaneous application of high voltage and current than is turn-off.

Short Circuit Withstand Capability. The IGBT should be able to withstand transient short circuits due to any sort of shoot through condition where the device is turned on into a stiff voltage source. Such shoot through conditions may be caused by diode reverse recovery, load faults, or control circuit malfunction. In order to survive such conditions of high power dissipation, the device must be able to self-limit the current to such a level that it can survive until some protection circuitry shuts the device off. Ten microseconds is a reasonable amount of time for protection circuitry to trigger. Increasing short circuit rating is accomplished by doing all the things that *negatively* impact forward drop. Short circuit rating also decreases with increasing gate–cathode voltage, so the gate voltage must be well regulated when the device is on.

Device Paralleling

Typically, IGBTs are fabricated in sizes up to about 1 cm^2 die area. To handle currents beyond those which one die can safely accommodate, multiple dies can be paralleled. Paralleling of bipolar devices is problematic because the device voltages exhibit a negative temperature coefficient (*NTC*). That is, as the temperature of the device increases, the anode–cathode voltage decreases. One device that gets hotter than its neighbor will conduct more current, thereby getting hotter, and so on. This is the phenomenon called thermal runaway. (Thermal runaway in linear amplifier biasing is a different effect but operates on the same principle.) To parallel such devices, ballast resistors with a positive temperature coefficient (*PTC*) that overcomes the NTC of the device are placed in series with the device. These resistors add circuit complexity, cost, and additional power dissipation; hence they are undesirable. The IGBT is a bipolar device, but its unipolar MOSFET part can give it an overall PTC. Non-punch through devices have a PTC from room temperature up, but punch through devices (currently the most prevalent kind below 1000 V blocking voltage) exhibit PTC only above 125°C.

Lifetime Killing

The most common procedure used to kill minority carrier lifetime in power devices is electron irradiation. This technique of bombarding the device *after processing* with high-energy electrons is inexpensive. Lattice defects from electron bombardment occur uniformly throughout the device and are permanent, barring high temperature annealing. Electron irradiation will reduce current tail time in an IGBT but will also increase the forward voltage drop. Other lifetime reduction methods include doping the device with metals such as gold or platinum, but these are expensive and the impurities will not necessarily sit still over time; instead, they can migrate to other regions of the device. They also trade current tail time for on-state voltage. A very promising technique to reduce tail time without as much impact on the forward drop is ion bombardment. Ions such as hydrogen or helium nuclei with a tight energy distribution are fired at the IGBT to create one or more thin low lifetime regions (Fig. 10). The depth of penetration is dependent on the energy. These localized regions provide centers for recombination without the large attendant reduction in carrier concentration typical of other techniques. The equipment to perform this is expensive, and the operation must take place before significant surface processing, so such a technique is more onerous than electron irradiation. The defects induced by ions are thought to be stable over time, and research level studies have borne this out.

Numerical Modeling of the IGBT

Large quantities of research go into modeling the IGBT. The classic SPICE programs have significant limitations when modeling power device behavior because they are based on an “integrated circuit emphasis.” High level lifetime, base current injected at the collector instead of the emitter, and power dissipation in the IGBT are three areas that SPICE does not handle properly. Other programs based on physical models or subcircuits have been proposed, and a very important topic of proper coupling of electrical and thermal behavior is extensively covered in the literature. The perfect model would be accurate, fast, and easy to set up and use. One might surmise that the large number of papers being written on modeling the IGBT is evidence that the perfect model does not yet exist.

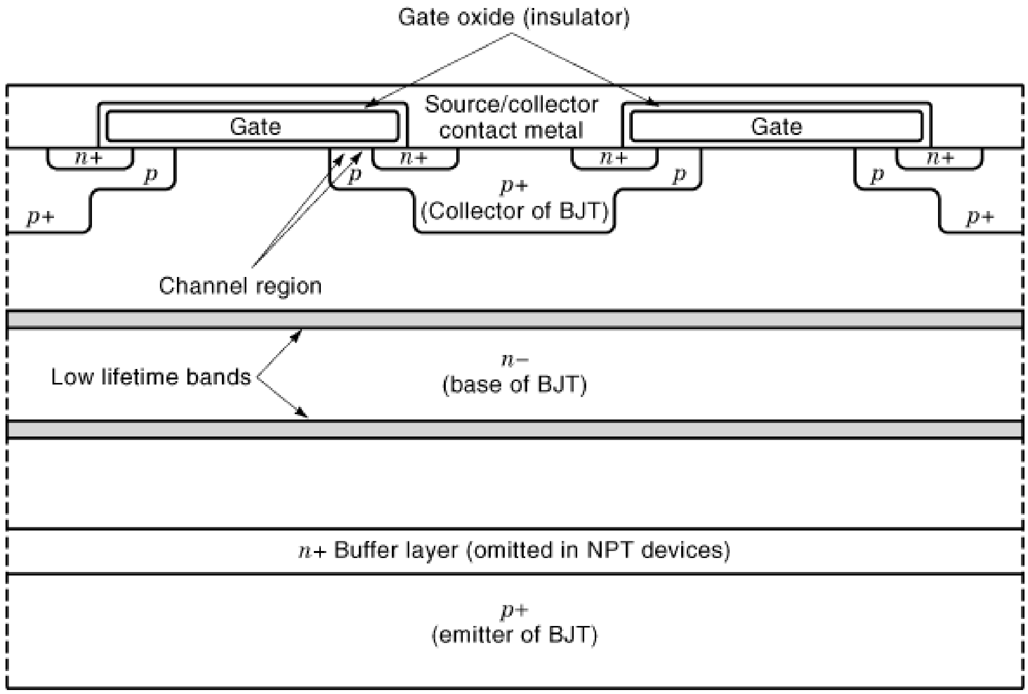

Fig. 10. Possible areas of lifetime reduction using ion implantation.

Further Research

Besides perfecting a numerical model of the IGBT, researchers in the field are working on perfecting the IGBT itself. The on-state voltage can be improved a few tenths of a volt more and the current tail time can simultaneously be reduced. Chip yields can increase and manufacturing costs can be lowered. Maximum blocking voltages well above 2000 V are obtained, but whether these are practical is another matter. The IGBT is immensely popular as a switching device above 100 V blocking (the MOSFET generally reigns below this level), and it is gradually being extended to cover applications currently handled by the gate turn-off thyristor (*GTO*). At some thousands of volts blocking rating, the IGBT will likely not be practical, but such an occurrence is yet in the future. Additional advances in processing such as trench gate, ion irradiation, and reliable thin wafer handling will make the IGBT even more widely used than it is today.

The current handling capability of IGBTs can be extended by paralleling devices. In theory, this can be done without limit. Practically, this is an area of significant research—getting the devices to equally share current under all conditions. The voltage capability can be extended by the series operation of IGBTs, and again, in theory, this can be done without limit. This is attractive because the impact of stray inductance is reduced at high voltage, and for a given power level, current can be reduced in the same proportion as voltage is increased. The difficulty with series operation is ensuring that the voltage is properly shared among devices at all times, even during switching.

Switching problems can be mitigated by using resonant topologies. These are circuits configured in such a way that the switching devices switch under conditions of zero, or near zero, voltage and/or current. Electromagnetic interference from resonant converters is typically less than from hard switch converters. The trade-off is that the circuits are more complicated and expensive, and the switching devices typically must withstand higher peak off-state voltages or on-state currents than devices in a hard switch topology. Many papers are written on this subject, but very few of these novel topologies are ever used in practice, except for niche applications.

We must briefly cover packaging. This area of research is not IGBT specific, but because the IGBT is the dominant power device, most research in this area is done with IGBTs in mind. Failures of IGBTs are often due to packaging failure. The IGBT is more rugged than the packages in which it is encapsulated, and the packaging technology must catch up to the device technology if we are to realize the full potential of the IGBT. Other nonspecific research that will benefit users of the IGBT includes on-chip or in-module current sensing and on-chip temperature sensing.

Finally, a very important area of research for the IGBT is research into improving *rectifiers*. As shown previously, the rectifier on the opposite switch of a totem pole is a major limiting factor in the performance of the IGBT. The IGBT has to be slowed to deal with poor rectifier behavior, and until this is fixed (rectified?) the IGBT cannot be used to its full potential.

For further information, the best place to start is Baliga's *Power Semiconductor Devices*. This covers the IGBT in detail with good mathematical development. In addition, this text covers much of the ancillary material necessary for an understanding of any power device, such as breakdown voltage, high level lifetime, MOS physics, and various rectifiers. Baliga presents the history of the IGBT in "Evolution of MOS–bipolar power semiconductor technology." A good fundamental modeling paper is Hefner and Blackburn's, "An analytical model for the steady-state and transient characteristics of the power insulated gate bipolar transistor." This covers a broad range of the dynamic and static behavior of IGBTs and is a good springboard for further investigation.

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