THE INSULATED GATE BIPOLAR TRANSISTOR

IGBT

THEORY AND DESIGN

Vinod Kumar Khanna

IEEE

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To my daughter, Aloka, and my wife, Amita
My mother, Smt. Pushpa Khanna, and my father, Shri Amarnath Khanna

CONTENTS

PREFACE

The insulated gate bipolar transistor (IGBT) represents the most commercially advanced device of a new family of power semiconductor devices synergizing high-input impedance MOS-gate control with low forward-voltage drop bipolar current conduction. It reduces the size and complexity of controlling circuitry, thereby drastically reducing the system cost. Today, it is finding widespread applications in the medium-power and medium-frequency range in uninterruptible power supplies, industrial motor drives, and domestic and automotive electronics. During recent years, no other single device has been able to revolutionize the power device scenario and cast its impact on life of the common man as much as IGBT alone has done as a power conditioning device in domestic, consumer, and industrial sectors. Power is the *life blood* driving all electrical installations, machines, trains, computers, telecommunication networks, entertainment, and other household equipment, all over the world.

Despite the growing interest in this device since its conception, no book is currently available which is, to the best of my knowledge, completely devoted to the physics and technology of IGBT. There is a dearth of generalized treatises on physics and technology of semiconductor devices. Presently available books deal with semiconductor device physics, power semiconductor devices, thyristor physics, field-effect and bipolar transistor physics, MOS physics, and related device technologies. The overwhelming pervasion of IGBT in industrial and consumer electronics warranted publication of a new book that comprehensively treats the subject. The enormous interest in IGBT constituted my principal motivation in undertaking the project of writing this book.

As its title indicates, this book has a singularity of focus on IGBT. However, it goes without saying that IGBT represents an interesting combination of PIN diode, bipolar transistor, bipolar thyristor, and power DMOSFET properties. So this text on IGBT prepares the reader not only with regard to IGBT but also with regard to the aforesaid devices that work in harmony resulting in IGBT characteristics. The expansive topical coverage of this book therefore incorporates useful material from both MOS and bipolar aspects, greatly enhancing the utility of the book. To elaborate, the forward conduction characteristics of IGBT are controlled by conductivity modulation of the PIN diode as well as MOSFET channel length. The latching of the IGBT is governed by the current gain of the bipolar transistor and regenerative thyristor action. A smaller channel length yields low forward drop device but makes it vulnerable to latching of built-in parasitic bipolar thyristor. Controlling the forward blocking capability of the IGBT requires careful attention to planar floating field ring termination design. The reverse blocking voltage is dictated by beveling during chip dicing. Likewise, the turn-off time of IGBT is determined by the carrier lifetime and hence the reverse recovery waveform of the PIN diode. So, if we look with this broad perspective, learning about IGBT requires a good knowledge about these constituent devices. Thus although the focus is on a singular device, the remaining devices are automatically a part of the overall picture. The era of MOS-bipolar combination devices has already dawned, and the book seeks to introduce the reader to this new era of intermixed technologies.

This book is written at the tutorial level to fulfill the needs of power device courses in electrical and electronics engineering and microelectronics engineering. The targeted audience of this book also includes practicing engineers and scientists. The students of today are the professionals of tomorrow. A careful blending of a tutorial design for students and specialist design for the practitioners has been made. By providing a large number of examples sprinkled throughout the text, as well as appending both questions and problems at the end of each chapter, it is hoped that classroom adaptation of the book will be easy with proper selection of course material. Up-to-date end-of-chapter references will provide the researcher a useful guide to the literature on IGBT. Thus the book caters to the requirements of a wide cross section of readership embracing students, professionals, and researchers.

A comprehensive, in-depth, and state-of-the-art treatment of the subject has been provided, encompassing a wide range of topics. Chapter 1 introduces the reader to the power semiconductor device scenario, the need for MOS-bipolar combination devices, and the birth of the IGBT. The working principle of IGBT is described in a simple way. The IGBT equivalent circuit is introduced, and the SPICE model is discussed. Packaging and handling precautions of IGBTs, gate driving circuits, and protection techniques are briefly presented.

Chapter 2 summarizes the basic types of IGBTs, their operational features, performance characteristics, limitations, specifications, and applications. Lateral and vertical IGBT structures are discussed. Nonpunchthrough and punchthrough types of IGBTs are explained. Their doping profiles and operational differences are described. Different modes of operation of IGBTs, such as forward conduction and blocking modes, are dealt with. IGBT turn-on and turn-off with resistive and inductive loads are analyzed. Soft-switching concepts are outlined. Effects of temperature and nuclear irradiation on IGBT characteristics are pointed out. The working of trench-gate and self-clamped IGBTs is addressed.

Chapter 3 covers the fundamentals of MOS structure including thermal equilibrium energy-band diagram, flat-band voltage, threshold voltage, capacitance effects, power DMOSFET structures, ON-resistance components, safe operating area, radiation and thermal effects on device characteristics, DMOSFET geometrical topologies, and so on, which are essential for understanding the physical principles of operation of IGBT.

Chapter 4 presents the theory of bipolar devices such as the PN-junction diode, the PIN rectifier, the bipolar junction transistor, the thyristor, and the junction field-effect transistor. After perusal of this chapter, the reader will be able to understand the essential principles of bipolar device operation.

From Chapter 5 onwards, the study of IGBT models begins, including static, dynamic, and electrothermal behavior. Discussions of PIN rectifier–DMOSFET and bipolar transistor–DMOSFET models of IGBT are followed by analytical models of ON-state carrier distribution, two-dimensional effects, modeling of device–circuit interactions, transient analysis of IGBT circuits, and so forth.

Because latching is a serious problem with IGBTs, this issue is discussed in detail in Chapter 6, outlining the causes of latching and the techniques of providing latching immunization of IGBT structure. After explaining static and dynamic latchup, methods of latchup prevention are dealt with exhaustively.

Since the IGBT is a conglomeration of millions of elementary cells, Chapter 7 delves into the design techniques of IGBT unit cell using computer-aided design tools. The discussion begins with semiconductor selection and vertical structure design; followed by emitter and base doping profiles and channel length, transconductance and forward voltage drop, trade-off between conduction and switching losses, unit cell layout design, and intercell spacing; then N-buffer layer structural optimization; and concludes with field ring and field plate termination design, as well as other techniques of junction edge termination for surface electric field minimization and breakdown voltage enhancement.

Chapter 8 describes the enabling technologies for power IGBT fabrication. Each unit process step is discussed, and the various steps are integrated for IGBT realization. Main steps are starting silicon preparation, epitaxial growth, polySi deposition, gate oxide fabrication, diffusion and ion implantation, mask making and microlithography, dry etching, and plasma processes, trench excavation, metallization, encapsulation, and electron irradiation for lifetime tailoring. Process simulation is also reviewed.

Chapter 9 addresses the subject of power IGBT modules and the associated technologies. Discussion of logic circuits and power device integration is followed by a summary of isolation techniques. Different types of protection and other accessories in the module are described. Flat-pack modules and materials technology for modules are also examined.

Chapter 10 provides both a retrospective as well as a bird's-eye view of futuristic IGBT technologies. It surveys new design ideas and IGBT structures, giving projections on future trends in this rapidly expanding field. Structures considered include the non-self-aligned trench IGBT, dynamic N-buffer IGBT, lateral IGBTs with reverse blocking capability and high-temperature latch-up immunity, self-aligned sidewall-implanted N^+ emitter lateral IGBT with high latchup current capability, LIGBT structure for larger FBSOA, lateral IGBT with integrated current sensor, dielectrically isolated fast LIGBT, lateral IGBT in thin (SOI) substrate, lateral trench-gate bipolar transistor, trench planar IGBT, clustered IGBT in homogeneous base technology, trench-clustered IGBT, double-gate injection-enhanced gate transistor, and many others.

Finally, Chapter 11 gives a perspective of the proliferating applications of IGBTs in circuits such as motor drives, automotive ignition, power supplies, welding, induction heating, and so on. Different types of converters such as DC-to-DC converters, DC-to-AC converters and AC-to-DC converters are mathematically analyzed. Soft-switching converters are touched upon. SABER and SPICE circuit models and design methods are also discussed.

It is earnestly hoped that the above topical coverage of this book will be useful for graduate/postgraduate students and researchers in this field. The book will serve as a textbook cum reference book on the subject. If the book serves the purpose of those for whom it is intended, I will deem my endeavors amply rewarded.

Although utmost care has been taken to ensure accuracy in presentation and content, no work can claim to be error-free and complete. Suggestions for improvement are cordially welcomed from our readers.

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It gives me immense pleasure to thank the director, senior scientists, and my colleagues at CEERI, Pilani, for encouragement in my efforts. I wish to thank the group leader and members of the erstwhile power device group, with whom I shared many insights into the power device physics and technology over our years of working together. I am obliged to Prof. Dr. Arnold Kostka and Mr. B. Maj, Technical University, Darmstadt, for guiding me into the simulation field.

It was a great opportunity working with my editor, Ms. Christina Kuhnen. I appreciate her prompt response and quick action on my problems, without which it would not have been possible to adhere to the schedule. I am grateful to the reviewers of the manuscript for their constructive criticism and for pointing out many errors and omissions, thereby bringing the book to its present form and contents.

Any new book owes its origin to its predecessors as well as to research papers, reports, and review articles. I am indebted to the numerous authors of these works, many of whom are listed in the reference section at the end of each chapter. The interested reader is referred to the excellent works cited in the references to acquire an indepth knowledge of any specialized topic.

I am indebted to Dr. P. K. Khanna and Mr. Vijay Khanna for moral support.

Finally, I thank my daughter and wife for their love, patience, and understanding and for tolerating my long hours of work with grace, during the course of this project spanning over two years. Thanks from my heart to all of the above and also to anyone who may have directly or indirectly helped me in this work and whom I may have forgotten to mention.

VINOD KUMAR KHANNA

Pilani, India
June 2003

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1

POWER DEVICE EVOLUTION AND THE ADVENT OF IGBT

1.1 INTRODUCTORY BACKGROUND

Power semiconductor devices are the essential components determining the efficiency, size, and cost of electronic systems for energy conditioning. The proliferating demand of controllable power electronic systems has promoted research on novel device materials, structures, and circuit topologies [1–7]. Present-day power devices are invariably fabricated using silicon as the base material. Among the upcoming semiconductor materials, silicon carbide has attracted the most attention [8–10]. The higher breakdown field of SiC (2.2×10^6 V/cm for 4H-SiC, 2.5×10^5 V/cm for Si) enables it to offer a projected 200-fold reduction in specific ON resistance as compared to Si devices. SiC devices also promise superior high-temperature performance due to the large energy gap (4H-SiC: 3.26 eV; Si: 1.12 eV), high thermal conductivity (4H-SiC: 4.9 W/cm; Si: 1.5 W/cm), high chemical inertness, high pressure, and radiation resistance of this material.

Power device and process design engineers worldwide are relentlessly searching for the *perfect semiconductor switch* defined by the following characteristic features: (i) *Very low driving losses*: The switch has high input impedance so that the drive current is infinitesimally small. Furthermore, the drive circuit is simple and inexpensive. (ii) *Insignificant ON state or forward conduction losses*: The forward voltage drop at the operating current is zero. Additionally, the operational current density is large, making the chip small in size and cost-effective for a given current-carrying capability. (iii) *Minimal*

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OFF state or reverse blocking losses: Infinitely large reverse blocking voltage together with zero leakage current, even when exposed to elevated temperatures. (iv) *Extremely low switching losses*: Both the turn-on and turn-off times approach zero. In direct current (time period = ∞) and low-frequency (large but finite time period) applications, these losses are very small because the switching times are much less than the respective periodic times.

Advancements in power devices have revolutionized power electronics, and today's market offers a wide spectrum of devices intended for different applications. In applications where *gate turn-off capability is not necessary*, *thyristors or silicon-controlled rectifiers* (SCRs), the highest power density devices, have been the workhorse of power electronics [5–6], carrying high forward currents of ~ 3500 A with a forward drop < 2 V and withstanding ≥ 6000 V in the reverse direction. Thyristors have long been the solo devices catering to the megawatt power range, available in ratings like 12 kV/1.5 kA, 7.5 kV/1.65 kA, 6.5 kV/2.65 kA, and so on. They are classified as: *phase-control thyristors* used for a 50/60-Hz AC mains line and the *inverter thyristors* for higher frequencies of ~ 400 Hz. Typical turn-on and turn-off times are 1 and 200 μsec. Thyristors are widely used in high-voltage DC (HVDC) conversion, static var compensators, solid-state circuit breakers, large power supplies for electrochemical plants, industrial heating, lighting and welding control, DC motor drives, and so on.

As turn-off is accomplished by collector–emitter voltage reversal in conventional thyristors, in applications where the *load current is both turned on and turned off by the input signal*, *power bipolar junction transistors* (BJTs) have been extensively used. *Modular double or triple Darlington transistors* (1200 V, 800 A) are used in converters with switching frequencies up to several kilohertz. Although bipolar transistors have turn-off time < 1 μsec, they need very high base current drive both in the ON state and during turn-off. A competing device is the gate turn-off thyristor (GTO). It has forward current capability much higher than the BJT but requires excessively high gate drive current (750 A for 4000 V, 3000 A GTO). Its switching frequency is limited to 1–2 kHz with $t_{on} = 4$ μsec and $t_{off} = 10$ μsec. GTOs are used in DC and AC motor drives, uninterruptible power supply (UPS) systems, static var compensators, and photovoltaic and fuel cell converters from a few kilowatts to several megawatts of power. Improvements in the GTO structure, the gate drive, the packaging, and the inverse diode led to a new switching component, the *integrated gate commutated thyristor* (IGCT), a hard-switched GTO, which may be viewed as the hybridization of a modified GTO structure with very low inductive gate drive. Also, 4.5-kV and 5.5-kV IGCTs with currents up to 4 kA, as well as 6-kV/6-kA IGCTs [11–12], are commercially available, with further possibility of extension up to 10 kV, depending on market demand.

Another device accepted for *gate turn-off applications* is the *vertical double-diffused MOSFET* (VDMOSFET) [13]. Its gate drive current is very low, and 500-V/50-A VDMOSFET devices have switching frequencies of ~ 100 kHz with turn-on and turn-off times below 100 nsec. Fast switching speed, ease of drive, wide safe operating area (SOA), and capability to withstand high rates of rise of ON-state voltage (dV/dt) have made VD-MOSFETs the logical choice in power circuit designs. However, VDMOS-FETs operate by unipolar conduction. So, their ON resistance drastically increases with drain-source voltage capability, restricting their exploitation to voltages less than a few hundred volts. Moreover, as the voltage rating increases, the inherent reverse diode shows increasing reverse recovery

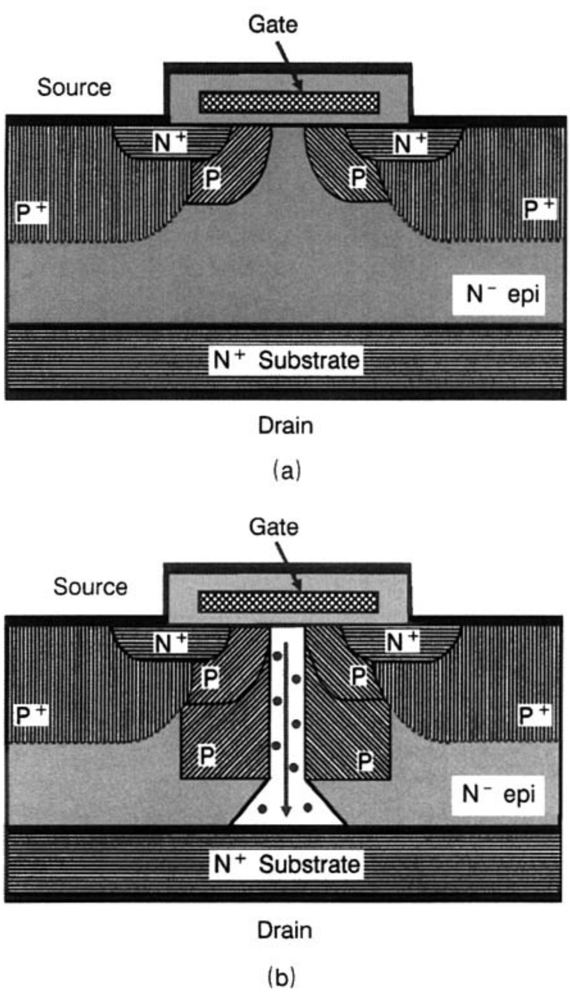

Figure 1.1 Structure of (a) conventional MOSFET and (b) Cool MOSFET.

charge (Q_{rr}) and reverse recovery time (t_{rr}), causing more switching losses. Power VDMOSFETs have gained a strong foothold in low-voltage, low-power, and high-frequency applications such as switch-mode power supplies (SMPS), brushless DC motor (BLDM) drives, solid-state DC relays, automobile power systems, and so on. A new approach to reduce the high-voltage-sustaining drift zone resistance is offered by the Cool-MOS concept [14–15], allowing

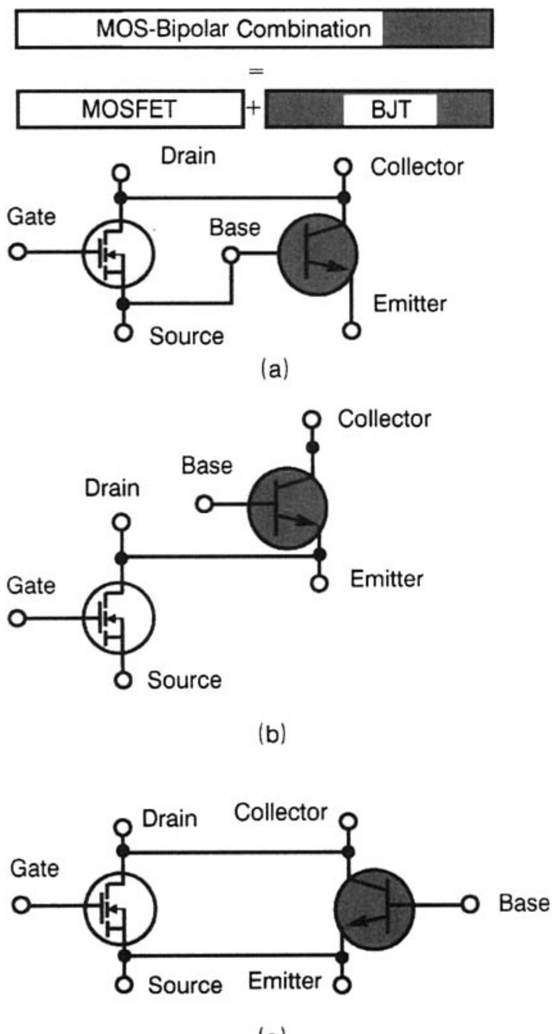

Figure 1.2 MOS–bipolar combinations. (a) Darlington configuration. (b) Series or cascade configuration. (c) Parallel or cascode configuration.

reduction of ON resistance by a factor of 5–10 compared to conventional MOSFETs having equal area, in the breakdown voltage range 600–1000 V. Here vertical P stripes are inserted into the N-drift zone (Fig. 1.1). Due to the finely structured sequence of opposite polarity layers, a marked increase in doping occurs in this zone. In the blocking state, with increasing drain–source voltages, the space-charge region at the border between P and N stripes expands, eventually leading to the depletion of the epilayer. The OFF-state voltage therefore comprises both horizontal and vertical components. Due to horizontal extension of the depletion region, drift region thickness need not be large, leading to lower conduction and switching losses and also requiring less gate drive power. For withstanding higher voltages, the area with P stripes is made larger. Reduction in doping is not necessary, as in conventional MOSFETs. Thus in Cool MOSFET, an extra P-doped region is introduced in the N-drift region. This allows a much higher breakdown voltage to be achieved using a much higher doping concentration for the N-drift region than in a conventional MOSFET. The use of a high doping concentration for the N-drift region reduces the ON resistance of the device.

Thus we find that amongst the presently available power switches, each offers distinct advantages in certain applications but suffer from shortcomings in other areas. Thus, it was considered worthwhile to blend the properties of MOSFET and bipolar devices. Indeed, the amelioration of device parameters toward the ideal switch was considerably accelerated by the idea of *MOS–bipolar combination.* In the beginning, many MOS–bipolar merger alternatives were explored. The performance characteristics and limitations of the chief combinations are pointed out below. The *Darlington configuration* (Fig. 1.2a) provides a high current gain at high output currents but gives a larger forward voltage drop than a single transistor and longer turn-off time because negative base drive cannot be applied to the BJT base during turn-off. Consequently, it exhibits high switching losses. In the *series or cascade configuration* (Fig. 1.2b) the drawbacks include the increase of forward drop and the need to drive one gate along with one base. In the *parallel or cascode Configuration* (Fig. 1.2c), the BJT must be driven in harmony with the MOSFET for turn-off loss minimisation, thus restricting the useful cut-off frequency. The breakthrough overcoming the above limitations was achieved with the success of the insulated gate bipolar transistor (IGBT).

1.2 INSULATED GATE BIPOLAR TRANSISTOR

Other names of this device include the insulated gate rectifier (acronym IGR), conductivity-modulated FET (COMFET), gain-enhanced MOSFET (GEMFET), BiFET (bipolar FET), and injector FET. It is a prime member of the family of MOS–bipolar combination devices. Other members of this family are the MOS-gated thyristor (MOS-SCR) and MOS-controlled thyristor (MCT).

The IGBT was first demonstrated by Baliga in 1979 [16] and then in 1980 by Plummer and Scharf [17], by Leipold et al. [18], and by Tihanyi [19]. Advantages of IGBT were comprehensively described by Becke and Wheatley [20] and by Baliga et al. in 1982 [21] and 1983 [22]. More work was carried out by Russell [23], Chang et al. [24], Goodman et al. [25], Baliga et al. [26], Yilmaz et al. [27] and Nikagawa et al. [28]. The IGBT was commercially introduced in the marketplace in 1983. Since then there has been a significant improvement in the device ratings and characteristics, from the initial 5 kW for discrete IGBTs to more than 200 kW for IGBT power modules. Presently, several large companies are manufacturing this device, notable among them being IXYS Corporation, International Rectifier, Powerex, Philips, Motorola, Fuji Electric, Mitshubishi Electric, Hitachi, Toshiba, Siemens, Eupec, and so on. Today, the IGBT is an established replacement of the power BJT, Darlington transistor, MOSFET, and GTO thyristor in the medium voltage (600–2500 V), medium power (10 kW), and medium frequency range up to 20 kHz. Also, 600-V/50-A IGBTs capable of hard switching at 150 kHz are commercially available. Just as the power MOSFET has replaced the BJT in low-voltage applications (< 200 V), the IGBT has replaced the BJT in the medium-voltage range 200–2000 V and is suitable for compact smart power modules. Modules with 6500-V blocking voltage capability and 200-, 400-, and 600-A current have been reported. High-voltage IGBTs are used for electric traction such as streetcars and locomotives. High-power IGBTs are challenging the dominance of GTOs in the megawatt range due to their high speed, large RBSOA, and easy controllability. However, the available power ratings of IGBTs are lower than those of GTOs, up to a rated switch power of 36 MVA (6 kV, 6 kA). MOS-SCR and MCT are alternative candidates for these applications. The injection-enhanced IGBT or IEGT [29] is a promising candidate as a next-generation high-power MOS-gated device, which can replace GTO. Basically, IGBTs operate like a bipolar transistor and have a smaller carrier accumulation in the N-type high resistance layer. So, IGBTs with forward blocking voltage > 1700 V suffer from a much larger ON-state voltage drop than do gate turn-off thyristors (GTOs). To reduce the ON-state voltage, a carrier profile similar to the GTO is adopted in the IEGT, retaining the easy gate drivability and turn-off capability of IGBT. The 4500-V IEGT has a forward drop V_F of 2.5 V at 100 A/cm^2. Current density of IEGT at $V_F = 2.5$ V is 10 times that of UMOS–IGBT (U-groove metal-oxide semiconductor–IGBT).

Today, minimum feature sizes in IGBT chips are shrinking down to 1 μm and submicron technologies using direct stepping on wafer. The IGBT is the most widely used power device in the medium power and medium frequency range, finding widespread applications in AC motor drives, traction control, inductive heating systems, radiological systems (X-ray tubes), uninterruptible power supplies (UPS), switch-mode power supplies (SMPS), static var and

Table 1.1 Applications of Different Power Electronic Sectors

Sector No.	Power Electronics Sector	Applications
1	Low-power sector (< 10 kW)	Switching power supplies for computers, printers, facsimile machines, and consumer electronics; automotive electronics, heating and lighting circuits, small motor drives, and UPS.
2	Mid-power sector (between 10 kW and 1 MW)	Solid-state drives for multi-horsepower induction motors, UPS, and machines for factory automation (using smart power ICs and modules); heating, ventilation, and air-conditioning equipment.
3	High-power or megawatt-power sector	Solid-state motor drives for heavy motors, HVDC, UPS, etc.

harmonic compensators, and so on. Table 1.1 shows that major marketing opportunities for power electronics reside in the low- and medium-power sectors. As the IGBT pervades these sectors, the utility of this device escalates.

A close look at the power electronics scenario reveals that the area between 100 V and 1000 V has vastly benefited from IGBT development and modular packaging concepts. IGBTs have gained immense importance since their introduction in the market in 1983. The IGBT is readily interconnected with control circuitry in low-cost plastic modules that are used for driving small machines for factory automation. The high output impedance of IGBTs allows parallel connection of many IGBTs. No device draws more current than its neighbors, resulting in better current sharing. So for higher load current applications, current up-scaling is accomplished by paralleling several devices. Today, 600-V, 1200-V, 2500-V, and 3300-V IGBTs/IGBT modules are commercially available up to current ratings of 2400 A. Also, 4.5- and 6.5-kV IGBT modules have been reported.

High-current and high-voltage IGBTs (> 1700 V, 1000 A) are used for traction and industrial applications. Both IGBTs and IGCTs have the potential to decrease the cost and increase the power density of pulse-width modulation voltage-source converters (VSCs), because of snubberless operation. The high voltage requirement of electrical power transmission and distribution (HVDC) systems is handled by series stacking of IGBTs. As traction systems use parallel connection of devices and HVDC employs series connection, the nature of these applications differs [30]. Consequently, the failure modes of devices in these systems are of opposite nature: *open-circuit failure* for traction and *short-circuit failure* for HVDC. These counter requirements have led to two different packaging concepts: the die-soldered, nonhermetic, wire-bonded module, mounted by bolting to heat sink and single-side cooled; and the dry contact, hermetic, presspack, mounted by pressure stacks and double-side cooled, as adapted from thyristor technology.

1.3 ADVANTAGES AND SHORTCOMINGS OF IGBT

IGBT is created by the functional integration of MOS and bipolar device technologies in monolithic form. It combines the best attributes of the existing families of MOS and bipolar devices (Table 1.2) to achieve optimal device characteristics, approximately fulfilling the criteria of the ideal power switch. Moreover, it has no integral diode like the MOSFET. In an IGBT, absence of the diode provides the user an opportunity to choose an external fast recovery diode suitable for a particular application or to purchase a "co-pak" having the IGBT and the diode in the same package. So, problems associated with the integral diode across the P-base/N-drift region in the power MOSFET are absent in the IGBT.

The major difficulty with the MOSFET is the reverse recovery characteristic of the diode. High carrier lifetime in the N-drift region of as-fabricated MOSFETs makes reverse recovery of diode slow accompanied by a large recovery charge. With increasing voltage ratings, the integral diode exhibits higher reverse recovery charge and reverse recovery time, and thereby high losses. Furthermore, this charge produces a high reverse recovery current, which increases with di/dt. The high current flowing through the transistors in the circuit causes excessive power dissipation and thermal stresses on them. To improve the reverse recovery characteristic, electron irradiation is performed with subsequent annealing of positive oxide charge around 200°C. But still the integral diode in the MOSFET creates problems due to the existence of a bipolar transistor in the structure (Fig.1.3). The voltage drop across the base resistance of this bipolar transistor due to current flowing during reverse recovery forward biases the emitter-base junction of the transistor. The high voltage developed across the transistor often leads to second breakdown. Thus actuation of the bipolar transistor during diode reverse recovery causes serious problems in power MOSFETs.

The IGBT provides high input impedance MOS gating, together with large bipolar current-carrying capability, while designed to support high voltages. A circuit designer views the IGBT as a device with MOS input characteristics and bipolar output characteristics—that is, a voltage-controlled BJT device. This feature simplifies, to a large extent, the driving circuit. This, combined with IGBT ruggedness, eliminates the complexity of protective snubber circuits, allowing simple, lightweight, and economic power electronic systems to be constructed with IGBTs. Over and above, integration of MOS control with bipolar conduction is a way of building intelligence in the chip because "electronic intelligence" is intimately related to the controlling strategy for

Table 1. 2 Features, Pros and Cons of MOSFETs and Bipolars

Serial No.	MOSFETs	Bipolars
	Features:	**Features:**
1	Single-carrier device	Two-carrier device
2	Works by majority carrier drift	Operates by minority-carrier diffusion
3	Voltage driven	Current driven
4	Drain current α channel width	Collector current α emitter length and area
5	Higher breakdown voltage is achieved using lightly doped drain region	Higher breakdown voltage requires lightly doped collector region
6	Current density for given voltage drop is high at low voltages and low at high voltages	Current density for given voltage drop is medium, and severe trade-off exists with switching speed
7	Square-law current–voltage characteristics at low current and linear I–V at high current	Exponential I–V characteristics
8	Negative temperature coefficient of drain current	Positive temperature coefficient of collector current
9	No charge storage	Charge stored in base and collector
	Pros:	**Cons:**
1	High input impedance $Z \sim 10^9$–10^{11} Ω	Low input impedance $Z \sim 10^3$–10^5 Ω
2	Minimal drive power. No DC current required at gate	Large drive power. DC current needed at base continuously
3	Simple drive circuit	Complex drive circuit as large positive and negative currents are required
4	More linear operation and less harmonics	More intermodulation and cross-modulation products
5	Devices can be easily paralleled	Devices cannot be easily paralleled
6	No thermal runaway	Prone to thermal runaway
7	Less susceptible to second breakdown	Vulnerable to second breakdown
8	Maximum operating temperature = 200°C	Maximum operating temperature = 150°C
9	Very low switching losses	Medium to high switching losses depending on trade-off with conduction losses
10	High switching speed, which is less temperature-sensitive	Lower switching speed, which is more sensitive to temperature
	Cons:	**Pros:**
1	High ON resistance	Low ON resistance
2	Low transconductance	High transconductance