Chapter 1

Introduction

The increasing dependence of modern society on electrical appliances for comfort, transportation, and healthcare has motivated great advances in power generation, power distribution and power management technologies. These advancements owe their allegiance to enhancements in the performance of power devices that regulate the flow of electricity. After the displacement of vacuum tubes by solid state devices in the 1950s, the industry relied upon silicon bipolar devices, such as bipolar power transistors and thyristors. Although the ratings of these devices grew rapidly to serve an ever broader system need, their fundamental limitations in terms of the cumbersome control and protection circuitry led to bulky and costly solutions. The advent of MOS technology for digital electronics enabled the creation of a new class of devices in the 1970s for power switching applications as well. These silicon power MOSFETs have found extensive use in high frequency applications with relatively low operating voltages (under 100 volts). The merger of MOS and bipolar physics enabled creation of yet another class of devices in the 1980s. The most successful innovation in this class of devices has been the Insulated Gate Bipolar transistor (IGBT). The high power density, simple interface, and ruggedness of the IGBT have made it the technology of choice for all medium and high power applications with perhaps the exception of high voltage DC transmission systems.

Power devices are required for systems that operate over a broad spectrum of power levels and frequencies. In Fig. 1.1, the applications for power devices are shown as a function of operating frequency. High power systems, such as HVDC power distribution and locomotive drives, requiring the control of megawatts of power operate at relatively low frequencies. As the operating frequency increases, the power ratings decrease for the devices with typical microwave devices handling about 100 watts. All of these applications are served by silicon devices. Thyristors are favored for the low frequency, high power applications, IGBTs for the medium frequency and power applications, and power MOSFETs for the high frequency applications.

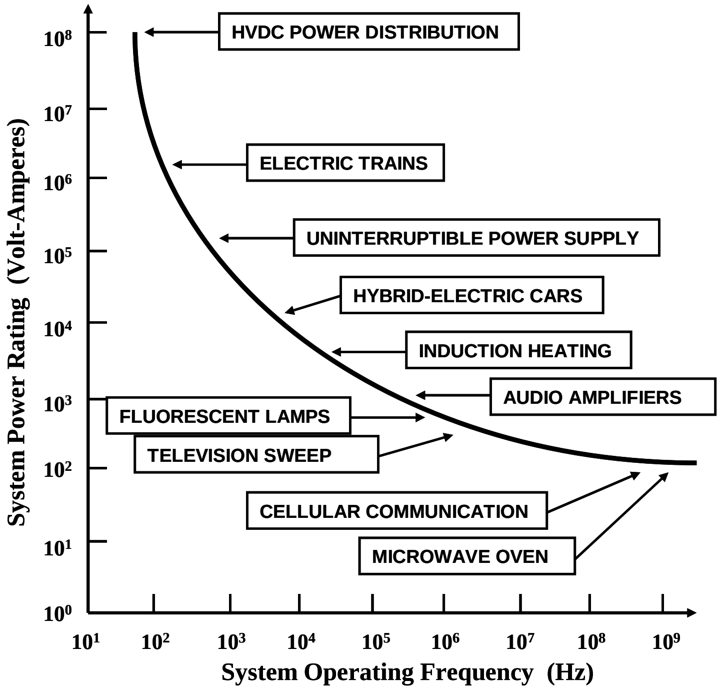

Fig. 1.1 Applications for Power Devices.

Another approach to classification of applications for power devices is in terms of their current and voltage handling requirements as shown in Fig. 1.2. On the high power end of the chart, thyristors are available that can individually handle over 6000 volts and 2000 amperes enabling the control of over 10 megawatts of power by a single monolithic device. These devices are suitable for the HVDC power transmission and locomotive drive (traction) applications. For the broad range of systems that require operating voltages between 300 volts and 3000 volts with significant current handling capability, the IGBT has been found to be the optimum solution. When the current requirements fall below 1 ampere, it is feasible to integrate multiple devices on a single monolithic chip to provide greater functionality for systems such as telecommunications and display drives. However, when the current exceeds a few amperes, it is more cost effective to use discrete power

MOSFETs with appropriate control ICs to serve applications such as automotive electronics and switch mode power supplies.

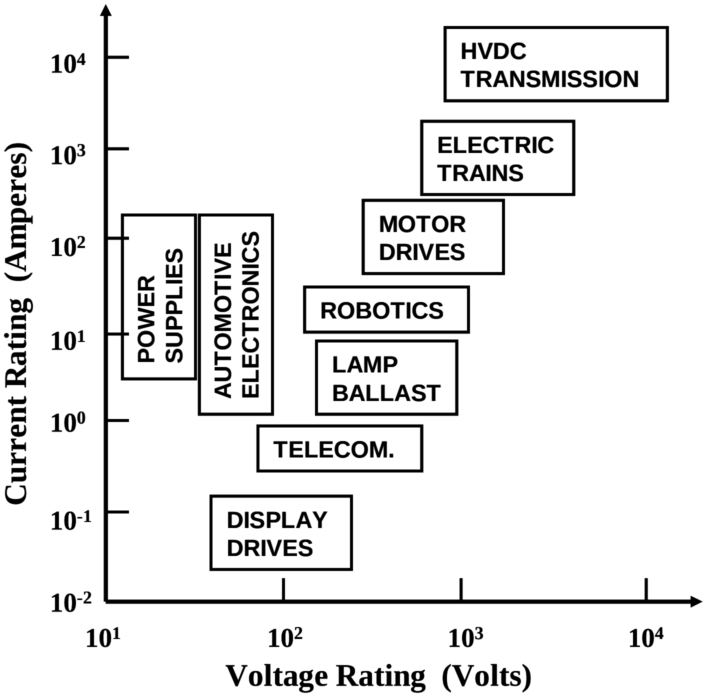

Fig. 1.2 System Ratings for Power Devices.

1.1 Ideal and Typical Power Device Characteristics

Although silicon power devices have served the industry for well over five decades, they cannot be considered to have ideal device characteristics. An ideal power rectifier should exhibit the *i*-*v* characteristics shown in Fig. 1.3. In the forward conduction mode, the first quadrant of operation the figure, it should be able to carry any amount of current with zero on-state voltage drop. In the reverse blocking mode, the third quadrant of operation in the figure, it should be able to hold off any value of voltage with zero leakage current. Further, the ideal rectifier should be able to switch between the on-state and the off-state with zero switching time. Actual silicon power rectifiers exhibit the *i*-*v* characteristics illustrated in Fig. 1.4. They have a finite voltage drop (V_{ON}) when carrying current on the on-state leading to ‘conduction’ power loss. They also have a finite leakage current (I_{OFF}) when blocking voltage in the off-state creating power loss. In addition, the doping concentration and thickness of the drift region of the silicon device must be carefully chosen with a design target for the breakdown voltage (BV)[1]. The power dissipation in power devices increases when their voltage rating is increased due to an increase in the on-state voltage drop.

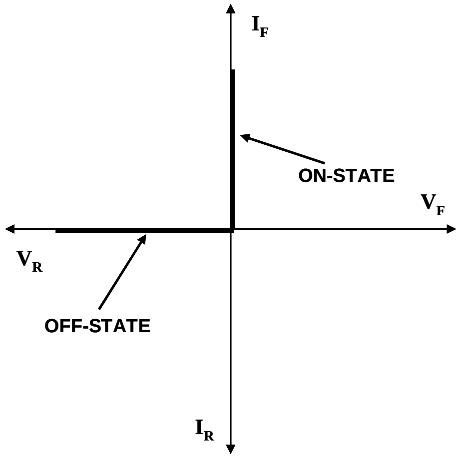

Fig. 1.3 Characteristics of an Ideal Power Rectifier.

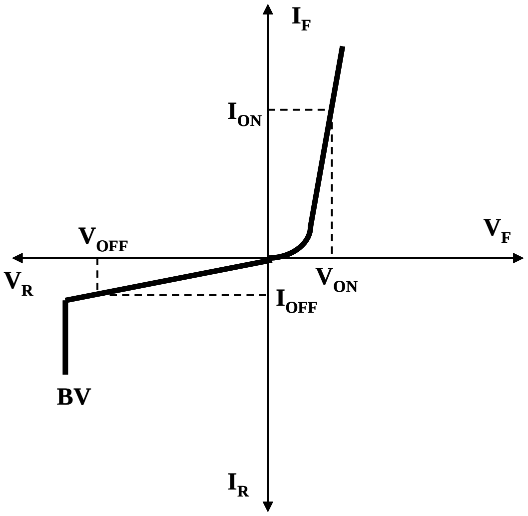

Fig. 1.4 Characteristics of a Typical Power Rectifier.

The *i*-*v* characteristics of an ideal power switch are illustrated in Fig. 1.5. As in the case of the ideal rectifier, the ideal transistor conducts current in the on-state with zero voltage drop and blocks voltage in the off-state with zero leakage current. In addition, the ideal device can operate with a high current and voltage in the active region with the forward current in this mode controlled by the applied gate bias. The spacing between the characteristics in the active region is uniform for an ideal transistor indicating a gain that is independent of the forward current and voltage.

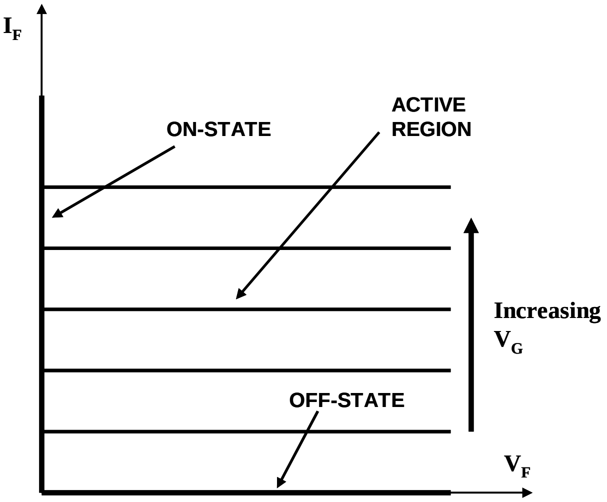

Fig. 1.5 Characteristics of an Ideal Transistor.

The *i*-*v* characteristics of a typical power switch are illustrated in Fig. 1.6. This device exhibits a finite resistance when carrying current in the on-state as well as a finite leakage current while operating in the off-state (not shown in the figure because its value is much lower than the on-state current levels). The breakdown voltage of a typical transistor is also finite as indicated in the figure with 'BV'. The typical transistor can operate with a high current and voltage in the active region. This current is controlled by the base current for a bipolar transistor while it is determined by a gate voltage for a MOSFET or IGBT (as indicated in the figure). It is preferable to have gate voltage controlled characteristics because the drive circuit can be integrated to reduce its cost. The spacing between the characteristics in the active region is non-uniform for a typical transistor with a square-law behavior for devices operating with channel pinch-off in the current saturation mode[1]. Recently, devices operating under a new super-linear mode have been proposed and demonstrated for wireless base-station applications[2].

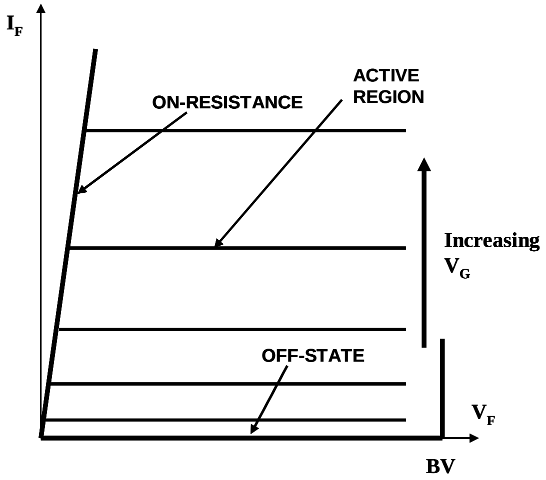

Fig. 1.6 Characteristics of a Typical Transistor.

1.2 Unipolar Power Devices

Bipolar power devices operate with the injection of minority carriers during on-state current flow. These carriers must be removed when the switching the device from the on-state to the off-state. This is accomplished by either charge removal via the gate drive current or via the electron-hole recombination process. These processes introduce significant power losses that degrade the power management efficiency. It is therefore preferable to utilize unipolar current conduction in a power device. The commonly used unipolar power diode structure is the Schottky rectifier that utilizes a metal-semiconductor barrier to produce current rectification. The high voltage Schottky rectifier structure also contains a drift region, as show in Fig. 1.7, which is designed to support the reverse blocking voltage. The resistance of the drift region increases rapidly with increasing blocking voltage capability as discussed later in this chapter. Silicon Schottky rectifiers are commercially available with blocking voltages of up to 100 volts. Beyond this value, the on-state voltage drop of silicon Schottky rectifiers becomes too large for practical applications[1]. Silicon P-i-N rectifiers are favored for designs with larger breakdown voltages due to their lower on-state voltage drop despite their slower switching properties. As shown later in the book, silicon carbide Schottky rectifiers have much lower drift region resistance enabling design of very high voltage devices with low on-state voltage drop.

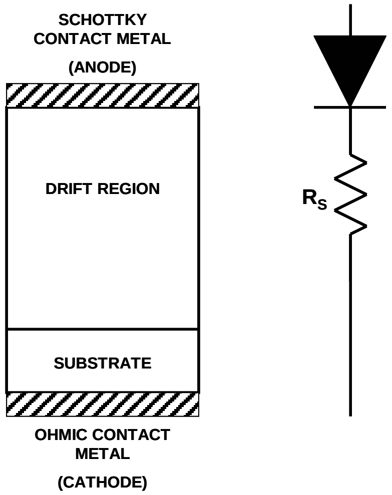

Fig. 1.7 The Power Schottky Rectifier Structure and its Equivalent Circuit.

The most commonly used unipolar power transistor is the silicon power Metal-Oxide-Semiconductor Field-Effect-Transistor or MOSFET. Although other structures, such as JFETs or SITs have been explored[3], they have not been popular for power electronic applications because of their normally-on behavior. The commercially available silicon power MOSFETs are based upon the structures shown in Fig. 1.8. The D-MOSFET was first commercially introduced in the 1970's and contains a 'planar-gate' structure. The P-base region and the N^+ source regions are self-aligned to the edge of the Polysilicon gate electrode by using ion-implantation of boron and phosphorus with their respective drive-in thermal cycles. The n-type channel is defined by the difference in the lateral extension of the junctions under the gate electrode. The device supports positive voltage applied to the drain across the P-base/N-drift region junction. The voltage blocking capability is determined by the doping and thickness of the drift region. Although low voltage (< 100 V) silicon power MOSFET have low on-resistances, the drift region resistance increases rapidly with increasing blocking voltage limiting the performance of silicon power MOSFETs to below 200 volts. It is common-place to use the Insulated Gate Bipolar Transistors (IGBT) for higher voltage designs.

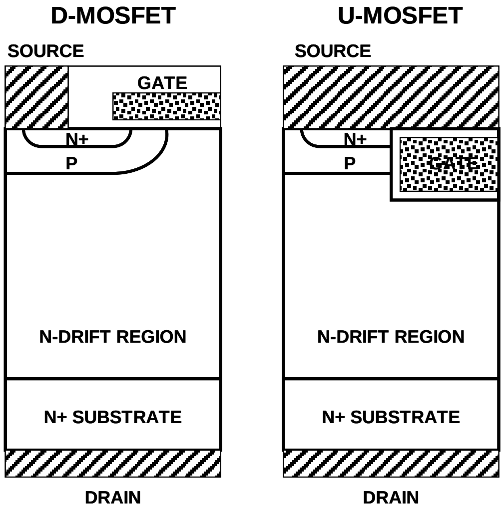

Fig. 1.8 Silicon Power MOSFET Structures.

The silicon U-MOSFET structure became commercially available in the 1990s. It has a gate structure embedded within a trench etched into the silicon surface. The N-type channel is formed on the side-wall of the trench at the surface of the P-base region. The channel length is determined by the difference in vertical extension of the P-base and N^+ source regions as controlled by the ion-implant energies and drive times for the dopants. The silicon U-MOSFET structure was developed to reduce the on-state resistance by elimination of the JFET component within the D-MOSFET structure[1].

1.3 Bipolar Power Devices

The commonly available silicon power bipolar devices are the bipolar transistor and the gate turn-off thyristor or GTO. These devices were originally developed in the 1950's and widely used for power switching applications until the 1970s when the availability of silicon power

MOSFETs and IGBTs supplanted them. The structures of the bipolar transistor and GTO are shown in Fig. 1.9. In both devices, injection of minority carriers into the drift region modulates its conductivity reducing the on-state voltage drop. However, this charge must be subsequently removed during switching resulting in high turn-off power losses. These devices require a large control (base or gate) current which must be implemented with discrete components leading to an expensive bulky system design.

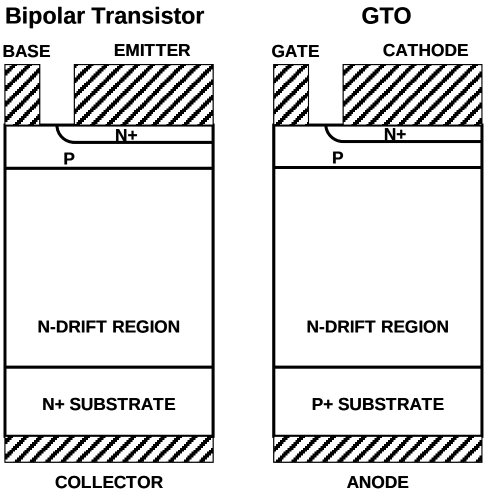

Fig. 1.9 Silicon Bipolar Device Structures.

Several groups have worked on the development of bipolar transistors[4,5,6,7] and GTOs[8,9] using silicon carbide. The large junction potential for silicon carbide results in a relatively high on-state voltage drop for these devices when compared with commercially available silicon devices. For this reason, the focus of this book is on unipolar silicon carbide structures.

1.4 MOS-Bipolar Power Devices

The most widely used silicon high voltage (>300 volt) device for power switching applications is the *Insulated Gate Bipolar Transistor* (IGBT) which was developed in the 1980s by combining the physics of operation of bipolar transistors and MOSFETs[10]. The structure of the IGBT is deceptively similar to that for the power MOSFET as shown in Fig. 1.10 if viewed as a mere replacement of the N^+ substrate with a P^+ substrate. This substitution creates a four-layer parasitic thyristor which can latch up resulting in destructive failure due to loss of gate control. Fortunately the parasitic thyristor can be defeated by the addition of the P^+ region within the cell[1]. The benefit of the P^+ substrate is the injection of minority carriers into the N-drift region resulting in greatly reducing its resistance. This has enabled the development of high voltage IGBT products with high current carrying capability.

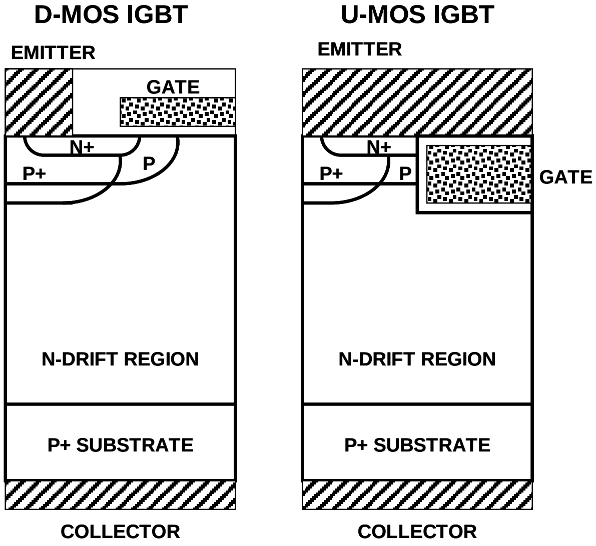

Fig. 1.10 IGBT Device Structures.

The development of the IGBT in silicon carbide has been analyzed and attempted by a few research groups[11,12,13]. The large junction potential and high resistance of the P^+ substrate for silicon carbide results in a relatively high on-state voltage drop for these devices when compared with commercially available silicon devices. Their switching speed is also compromised by the injected stored charge in the on-state. For these reasons, silicon carbide based IGBTs are not discussed in this book.

1.5 Ideal Drift Region for Unipolar Power Devices

The unipolar power devices discussed above all contain a drift region which is designed to support the blocking voltage. The properties (doping concentration and thickness) of the *ideal drift region* can be analyzed by assuming an abrupt junction profile with high doping concentration on one side and a low uniform doping concentration on the other side, while neglecting any junction curvature effects by assuming a parallel-plane configuration. The resistance of the ideal drift region can then be related to the basic properties of the semiconductor material[14].

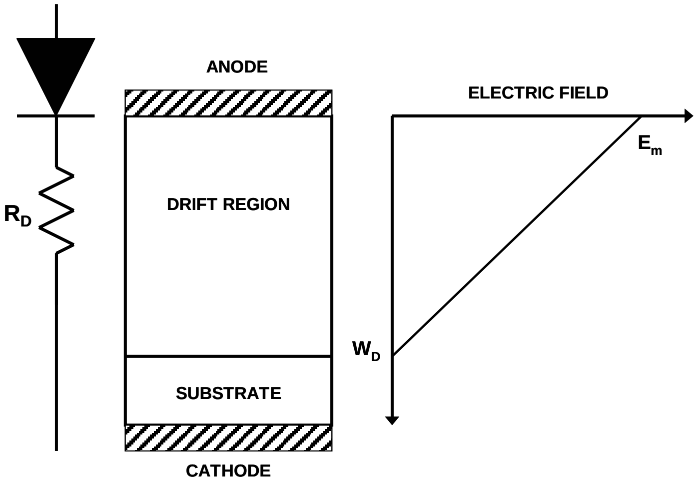

Fig. 1.11 The *Ideal Drift Region* and its Electric Field Distribution.

The solution of Poisson’s equation leads to a triangular electric field distribution within a uniformly doped drift region[1] with the slope of the field profile being determined by the doping concentration. The maximum voltage that can be supported by the drift region is determined by the maximum electric field (E_m) reaching the critical electric field (E_c) for breakdown for the semiconductor material. The critical electric field for breakdown and the doping concentration then determine the maximum depletion width (W_D).

The specific resistance (resistance per unit area) of the ideal drift region is given by:

$$R_{on.sp} = \left(\frac{W_D}{q\mu_n N_D} \right) \qquad \textbf{[1.1]}$$

Since this resistance was initially considered to be the lowest value achievable with silicon devices, it has historically been referred to as the *ideal specific on-resistance of the drift region*. More recent introduction of the charge-coupling concept, described later in this chapter, has enabled reducing the drift region resistance of silicon devices to below the values predicted by this equation. The depletion width under breakdown conditions is given by:

$$W_D = \frac{2BV}{E_C} \qquad \textbf{[1.2]}$$

where BV is the desired breakdown voltage. The doping concentration in the drift region required to obtain this breakdown voltage is given by:

$$N_D = \frac{\varepsilon_S . E_C^2}{2.q.BV} \qquad \textbf{[1.3]}$$

Combining these relationships, the specific resistance of the ideal drift region is obtained:

$$R_{on-ideal} = \frac{4BV^2}{\varepsilon_S \mu_n E_C^3} \qquad \textbf{[1.4]}$$

The denominator of this equation ($\varepsilon_S.\mu_n.E_C^3$) is commonly referred to as *Baliga's Figure of Merit for Power Devices*. It is an indicator of the impact of the semiconductor material properties on the resistance of the drift region. The dependence of the drift region resistance on the mobility (assumed to be for electrons here because in general they have higher mobility values than for holes) of the carriers favors semiconductors such as Gallium Arsenide. However, the much stronger (cubic) dependence of the on-resistance on the critical electric field for breakdown favors wide band gap semiconductors such as silicon carbide. The critical electric field for breakdown is determined by the impact ionization coefficients for holes and electrons in semiconductors as discussed in the next chapter.

The change in the specific on-resistance for the drift region with critical electric field and mobility is shown in Fig. 1.12 for the case of a breakdown voltage of 1000 volts. The location of the properties for silicon, gallium arsenide, and silicon carbide are shown in the figure by the points. The improvement in drift region resistance for GaAs in comparison with silicon is largely due to its much greater mobility for electrons. The improvement in drift region resistance for SiC in comparison with silicon is largely due to its much larger critical electric field for breakdown. Based upon these considerations, excellent high voltage Schottky rectifiers were developed from GaAs in the 1980s[15]. Much greater improvement in performance is clearly indicated for silicon carbide devices which is the subject of this book.

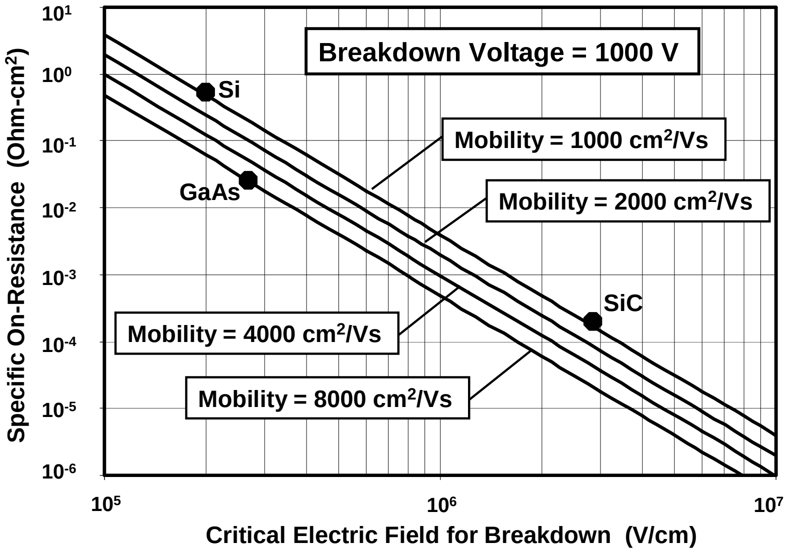

Fig. 1.12 Specific On-Resistance of the *Ideal Drift Region*.

1.6 Summary

The motivation for the development of silicon carbide unipolar devices has been reviewed in this chapter. Although excellent unipolar silicon Schottky rectifiers and power MOSFETs are commercially available with breakdown voltages below 200 volts, the resistance of their drift region increases rapidly at higher breakdown voltages producing significant power losses in applications. This problem can be overcome using silicon carbide based unipolar devices.

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