ADVANCED POWER RECTIFIER CONCEPTS

B. Jayant Baliga

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Dedication

The author would like to dedicate this book to his wife, Pratima, for her unwavering support throughout his career devoted to the enhancement of the performance and understanding of power semiconductor devices.

Preface

Today the semiconductor business exceeds $200 billion with about 10 percent of the revenue derived from power semiconductor devices and smart power integrated circuits. Power semiconductor devices are recognized as a key component of all power electronic systems. It is estimated that at least 50 percent of the electricity used in the world is controlled by power devices. With the wide spread use of electronics in the consumer, industrial, medical, and transportation sectors, power devices have a major impact on the economy because they determine the cost and efficiency of systems. After the initial replacement of vacuum tubes by solid state devices in the 1950s, semiconductor power devices have taken a dominant role with silicon serving as the base material. These developments have been referred to as the *Second Electronic Revolution*.

Bipolar power devices, such as bipolar transistors and thyristors, were first developed in the 1950s. Due to the many advantages of semiconductor devices when compared with vacuum tubes, there was a constant demand for increasing the power ratings of these devices. Their power ratings and switching frequency increased with advancements in the understanding of the operating physics, the availability of larger diameter, high resistivity silicon wafers, and the introduction of more advanced lithography capability. During the next 20 years, the technology for the bipolar devices reached a high degree of maturity. By the 1970s, bipolar power transistors with current handling capability of hundreds of amperes and voltage blocking capability of over 500 volts became available. More remarkably, technology was developed capable of manufacturing an individual power thyristor from an entire 4-inch diameter silicon wafer with voltage ratings over 5000 volts.

In the 1970s, the power MOSFET product was first introduced by International Rectifier Corporation. Although initially hailed as a replacement for all bipolar power devices due to its high input impedance and fast switching speed, the power MOSFET has successfully cornered the market for low voltage (< 100 V) and high switching speed (> 100 kHz) applications but failed to make serious inroads in the high voltage arena. This is because the on-state resistance of power MOSFETs increases very rapidly with increase in the breakdown voltage. The resulting high conduction loss, even when using larger more expensive die, degrades the overall system efficiency.

The large on-state voltage drop for high voltage silicon power MOSFETs and the large drive current needed for silicon power bipolar transistors encouraged the development of the insulated gate bipolar transistor (IGBT)[1]. First commercialized in the early 1980s, the IGBT has become the dominant device used in all medium and high power electronic systems in the consumer, industrial, transportation, and military systems, and even found applications in the medical sector.

In conjunction with the development of improved power switches, there has been a need to improve the performance of power rectifiers. The ability to operate power systems at higher frequencies was limited by the poor switching performance of power rectifiers in the 1980s[2]. The advanced rectifier concepts discussed in this monograph evolved during this time to enable significant improvements in their switching characteristics. These advanced rectifier concepts targeted both low voltage applications where silicon unipolar devices can be utilized and high voltage applications where silicon bipolar devices are required. The advanced concepts proposed for silicon bipolar rectifiers can be effectively utilized for devices with reverse blocking voltages up to 5000 volts. For recently proposed microgrids, power rectifiers with even larger reverse blocking voltages of up to 15-20 kV are needed for the development of high frequency solid-state-transformers. This application can be served with the advanced concepts described in this book with silicon carbide as the base semiconductor material.

Due to these developments, it is anticipated that there will be an increasing need for technologists trained in the discipline of designing and manufacturing power semiconductor devices. This monograph complements my recently published textbook which dealt with only the basic power rectifier structures due to space limitations[3]. For the convenience of readers, some portions of the chapters on 'Schottky Rectifiers' and 'P-i-N Rectifiers' from the textbook have been reproduced in this monograph. As in the case of the textbook, analytical expressions that describe the behavior of the advanced power rectifier concepts have been rigorously derived using the fundamental semiconductor Poisson's, continuity, and conduction equations in this monograph. The electrical characteristics of all the power rectifiers discussed in this book can be computed using these analytical solutions as shown by typical examples provided in each section. In order to corroborate the validity of these analytical formulations, I have included the results of two-dimensional numerical simulations in each section of the book. The simulation results are also used to further elucidate the physics and point out two-dimensional effects whenever relevant. Due to increasing interest in the utilization of wide band-gap semiconductors for power devices, the book includes the analysis of silicon carbide structures.

In the first chapter, a broad introduction to potential applications for power devices is provided. The electrical characteristics for ideal power rectifiers are then defined and compared with those for typical devices. The second chapter provides a detailed analysis of the Schottky rectifier structure which is borrowed from the textbook. On-state current flow via thermionic emission is described followed by the impact of image force barrier lowering on the reverse leakage current. These phenomena influence the selection of the barrier height to optimize the power losses as described in the chapter. The influence of the tunneling current component is also included in this chapter due to its importance for silicon carbide Schottky rectifiers.

The subsequent chapters are devoted to various advanced power rectifier structures. The unipolar device structures are first covered in the chapters on the 'Junction Barrier controlled Schottky (JBS) Rectifier', the 'Trench Schottky Barrier controlled Schottky (TSBS) Rectifier', and the 'Trench MOS Barrier controlled Schottky (TMBS) Rectifier'. The JBS rectifier concept is attractive for reducing the reverse leakage current in Schottky power rectifiers while retaining a low on-state voltage drop. This concept is also suitable for integration of the Schottky rectifier with the power MOSFET structure[4]. The TSBS concept is particularly suitable for reducing the leakage current in silicon carbide Schottky rectifiers. The TMBS concept provides yet another alternative to reducing the leakage current in silicon Schottky rectifiers. This concept is not suitable for application to silicon carbide structures due to the high electric field generated in the oxide.

The above concepts are applicable to the development of unipolar devices. When the reverse blocking voltage becomes large (more than 200 volts for silicon devices and 5000 volts for silicon carbide devices), it is advantageous to utilize bipolar current flow in power rectifiers to reduce the on-state voltage drop. Chapter 6, which is based upon portions borrowed from the textbook, describes the physics of operation of high voltage P-i-N rectifiers. The theory for both low-level and high-level injection conditions during on-state current flow is described here. The impact of this on the reverse recovery phenomenon during turn-off is then analyzed. The influence of end region recombination is included in the analysis.

For the development of high voltage silicon power rectifiers with reduced reverse recovery charge, the concept of merging the P-i-N and Schottky diodes was proposed in the 1980s[5]. Although first met with skepticism as having the worst attributes of both the P-i-N and Schottky rectifiers, the concept has now been embraced by the semiconductor industry as having the best characteristics of both devices with products available in the marketplace for motor control applications. Chapter 7 provides a detailed analysis of the MPS concept with analytical formulations developed for the on-state carrier distribution, the on-state voltage drop, and the reverse recovery characteristics. In this monograph, it is also demonstrated that the MPS concept can be extended to silicon carbide power rectifiers with judicious choice of the Schottky contact width and barrier height.

An alternate approach to improving the reverse recovery characteristics in power rectifiers is by utilizing the SSD structure[6]. In this concept, the highly doped

P^+ region of the P-i-N rectifier structure is confined to a portion of the cell structure with a shallower lightly doped P- region used for the rest of the anode region. The low injection efficiency of the P- region suppresses the injection of minority carriers (holes) resulting in a reduced hole concentration near the anode. When the doping concentration in the P- region is made small, the characteristics of the SSD structure approach those of the MPS rectifier structure. As the doping concentration of this region is increased, the characteristics of the SSD structure approach those of the P-i-N rectifier structure[7]. The operation of silicon and silicon carbide rectifiers with the SSD structure is described in Chapter 8.

Several other power rectifier structures have also been proposed in the literature. It has been demonstrated that the stored charge in the P-i-N rectifier structure can be reduced by decreasing the doping concentration in the P^+ anode region[8]. However, this produces a large increase in the on-state voltage drop especially at surge current levels. A power rectifier called SPEED has been proposed that is similar to the SSD structure with a deep lightly doped P region[9]. The reverse recovery characteristic of this structure is not as good as that for the SSD and MPS rectifier structures. For the reasons cited in this paragraph, these alternate power rectifier structures have not been included in this monograph.

I am hopeful that this monograph will be useful for researchers in academia and to product designers in the industry. It can also be used for the teaching of courses on solid state devices as a supplement to my textbook[3].

Prof. B. Jayant Baliga
December 2008

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Contents

Chapter 1

Introduction

Solid state devices began to displace vacuum tubes in the 1950s for various power control applications. Power devices are required for applications 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. Today, all of these applications are served by silicon devices.

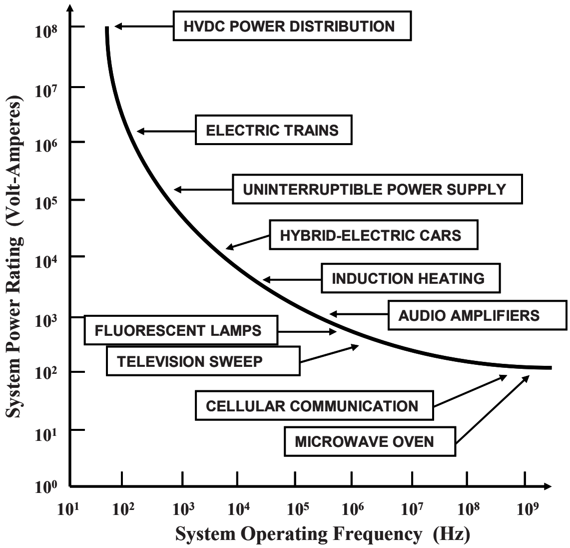

Fig. 1.1 Applications for Power Devices.

B.J. Baliga, *Advanced Power Rectifier Concepts*, DOI: 10.1007/978-0-387-75589-2_1,

When the operating voltage of the power circuit is relatively small (< 100 volts), silicon unipolar devices offer the best performance[1]. Bipolar silicon devices have better characteristics for applications where the circuit operating voltage is relatively large (> 100 volts). The development of power devices from wide band gap semiconductors, such as silicon carbide, allows extending the operating voltage of unipolar structures to at least 5000 volts[2]. In modern power circuits, it is common-place to utilize power transistors as switches to regulate the power flow to the load while using power rectifiers to control the direction of current flow. With the advent of high performance power switches (power MOSFETs and IGBTs), the performance of power rectifiers often limits the operation of power circuits. This book focuses on advanced concepts for power rectifiers that allow reducing power losses in circuits enabling an increase in system efficiency.

1.1 Ideal Power Switching Waveforms

An ideal power device must be capable of controlling the flow of power to loads with zero power dissipation. The loads encountered in systems may be inductive in nature (such as motors and solenoids), resistive in nature (such as heaters and lamp filaments), or capacitive in nature (such as transducers and LCD displays). Most often, the power delivered to a load is controlled by turning-on a power switch on a periodic basis to generate pulses of current that can be regulated by a control circuit. The ideal waveforms for the power delivered through a power switch are shown in Fig. 1.2. During each switching cycle, the switch remains on for a time

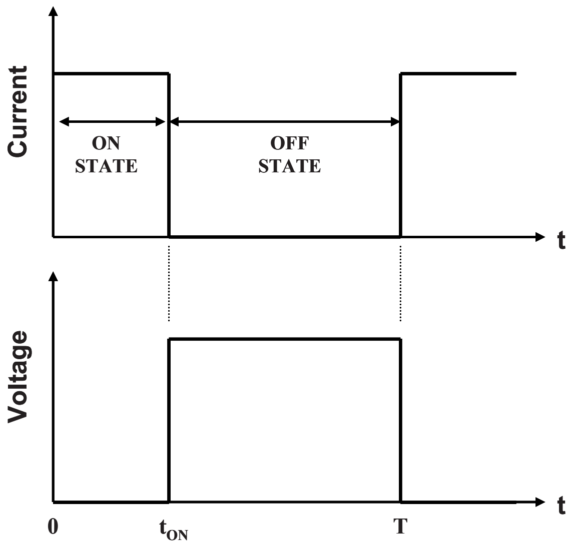

Fig. 1.2 Ideal Switching Waveforms for Power Delivery.

upto t_{ON} and maintains an off-state for the remainder of the period T. This produces pulses of current that flow through the circuit including the power rectifiers. For an ideal power rectifier, the voltage drop during the on-state is zero resulting in no power dissipation. Similarly, during the off-state, the (leakage) current in the ideal power rectifier is zero resulting in no power dissipation. In addition, it is assumed that the ideal power rectifier makes the transition between the on-state and off-state instantaneously resulting in no power loss as well.

Typical power rectifiers exhibit a finite voltage drop in the on-state and leakage current flow in the off-state. In addition, bipolar power rectifiers exhibit a large reverse recovery current when switching from the on-state to the off-state. This produces considerable power dissipation not only in the rectifier but also the power transistor used to control the current flow. After the invention and development of the insulated gate bipolar transistor in the 1980s[3], it became apparent that the performance of power rectifiers is limiting the performance of high voltage power circuits for motor control[4]. This led to the innovations in power rectifiers that are discussed in this book.

1.2 Ideal and Typical Power Rectifier Characteristics

Silicon power rectifiers have served the industry for well over five decades but cannot be considered to have ideal device characteristics. An ideal power rectifier should exhibit the current-voltage (*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.

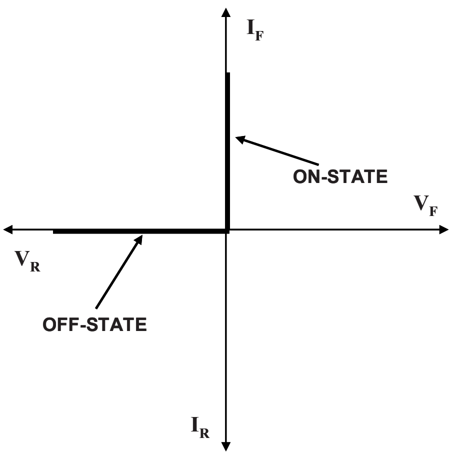

Fig. 1.3 Characteristics of an Ideal Power Rectifier.

Actual 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 off-state power loss. In addition, bipolar power rectifiers exhibit a large reverse current flow for a short duration to remove the stored charge created within the structure by the on-state current flow. The doping concentration and thickness of the drift region of the device must be carefully chosen with a design target for the breakdown voltage (BV). Moreover, the power dissipation in power rectifiers increases when their voltage rating is increased due to an increase in the on-state voltage drop.

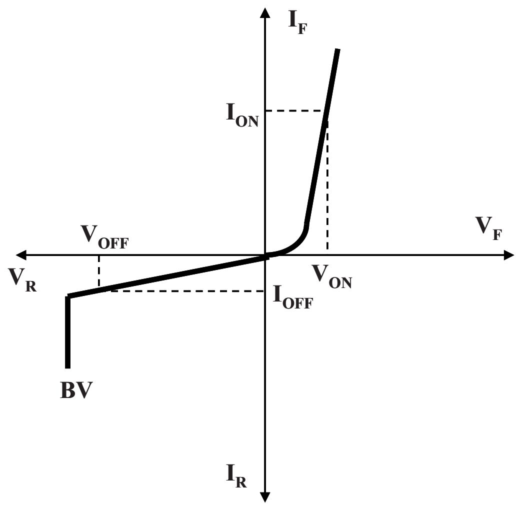

Fig. 1.4 Characteristics of a Typical Power Rectifier.

1.3 Unipolar Power Rectifiers

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 introducing 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 contains a metal-semiconductor barrier to produce current rectification. The power Schottky rectifier structure also contains a drift region, as show in Fig. 1.5, 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. Silicon P-i-N rectifiers are favored for designs with larger breakdown voltages due to their low on-state voltage drop despite slower switching properties.

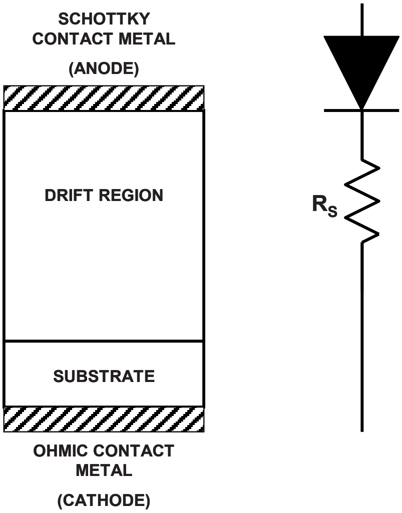

Fig. 1.5 The Power Schottky Rectifier Structure and its Equivalent Circuit.

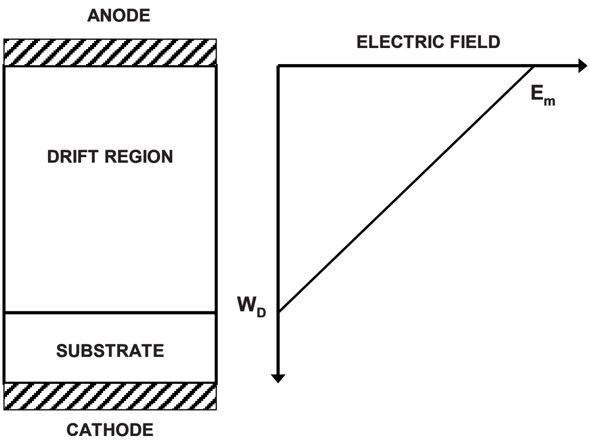

Fig. 1.6 The Ideal Drift Region and its Electric Field Distribution.

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[5]. The solution of Poisson's equation leads to a triangular electric field distribution, as shown in Fig. 1.6, within a uniformly doped drift region 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:

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

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*. The depletion width under breakdown conditions is given by:

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

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

$$N_D = \frac{\varepsilon_S E_C^2}{2qBV} \quad \textbf{[1.3]}$$

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

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

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[2].

One of the fundamental problems encountered with silicon Schottky rectifiers is the large reverse leakage current flow when the device is designed with small on-state voltage drop. This is associated with the Schottky barrier lowering and pre-breakdown avalanche multiplication phenomena which produce an increase in the leakage current by on order of magnitude when the reverse voltage increases from zero to typical operating levels. This increase in the leakage current can be suppressed by shielding the Schottky contact from the high electric field generated within the semiconductor.

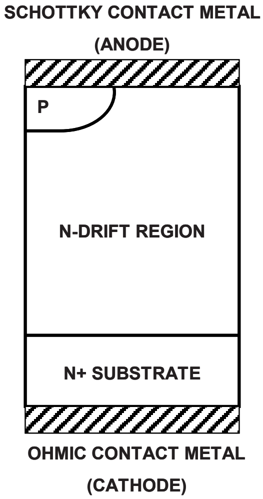

Fig. 1.7 The Junction Barrier controlled Schottky (JBS) Rectifier Structure.

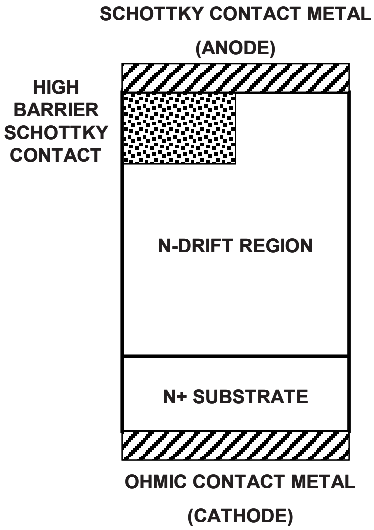

Fig. 1.8 The Trench Schottky Barrier controlled Schottky (TSBS) Rectifier Structure.

One approach to reducing the leakage current in power Schottky rectifiers is by incorporation of a P-N junction as illustrated in Fig. 1.7. This concept, called the Junction Barrier controlled Schottky (JBS) rectifier[6,7], has been effectively utilized for improving the performance of low voltage silicon devices and high voltage silicon carbide devices. In the case of the silicon carbide structures, the shielding of the Schottky contact reduces the leakage current by many orders of magnitude by mitigating the tunneling phenomenon at the Schottky contact[2].

An alternate method for shielding the anode Schottky contact from the high electric fields in the semiconductor is by using a second Schottky contact with larger barrier height. It is preferable to locate the Schottky contact with the larger barrier height within a trench, as shown in Fig. 1.8, to enhance the shielding effect. This structure is consequently called the Trench Schottky Barrier controlled Schottky (TSBS) rectifier. Although first proposed[8] for the improvement of silicon devices, this idea has found greater interest for silicon carbide structures due to the larger barrier heights available in wide band gap semiconductors.

In principle, it is also possible to shield the anode Schottky contact by incorporating an MOS region as illustrated in Fig. 1.9. It is preferable to form the MOS structure within a trench to enhance the shielding phenomenon[9]. This approach is feasible for silicon devices with a mature MOS technology. In the case of silicon carbide, this approach is not advisable because very high electric field is generated in the oxide that can lead to its destructive failure. In the case of silicon devices, this idea has been combined with the charge-coupling phenomenon to allow a significant reduction in the resistance of the drift region. Such structures will be discussed in a subsequent monograph on the topic of charge coupled power devices.

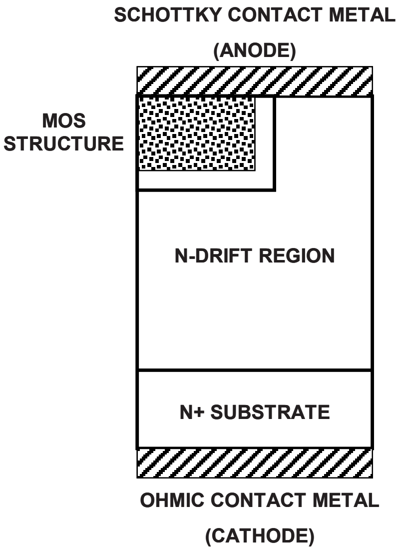

Fig. 1.9 The MOS Barrier controlled Schottky (MBS) Rectifier Structure.

1.4 Bipolar Power Rectifiers

The resistance of the drift region becomes very large for silicon unipolar Schottky rectifiers when the blocking voltage is increased beyond 100 volts. In contrast, very high voltage bipolar devices are feasible in silicon because of conductivity modulation of the drift region by the carriers injected during on-state current flow. The P-i-N rectifier structure that has been widely utilized by the industry for the last 50 decades is shown in Fig. 1.10. In the on-state, the P-N junction becomes forward biased allowing the injection of minority carriers whose concentration far exceeds the doping concentration of the drift region. An equal concentration of majority carriers is also prevalent in the drift region under these conditions to satisfy charge neutrality. Typical silicon P-i-N rectifiers have on-state voltage drops in the range of 1 to 2 volts even when designed to support large voltage in the reverse blocking mode. Commercial devices with blocking voltage capability of up to 10 kV have been developed.

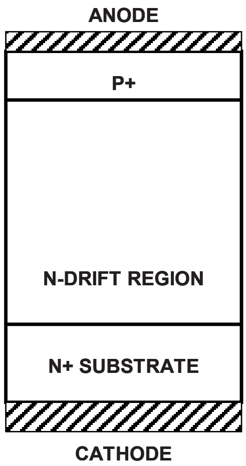

Fig. 1.10 The P-i-N Rectifier Structure.

The main drawback of the silicon P-i-N rectifier structure is its slow switching speed with a large reverse recovery current. This transient produces large power dissipation in the rectifier and the power switch controlling the transient. One approach to reducing the reverse recovery current is by reducing the lifetime using deep level impurities[1]. Another approach is to combine a Schottky contact and the P-N junction as illustrated in Fig. 1.11. Although this structure is identical in appearance to the JBS rectifier structure, it operates in the bipolar mode in the case of high voltage devices. This structure should not be considered as a simple parallel combination of a Schottky rectifier and a P-i-N rectifier because this would result in the worst performance attributed of both structures. In contrast, by merging the physics of current flow in the Schottky rectifier and the P-i-N rectifier, it is possible to realize the best attributes of both structures[10].

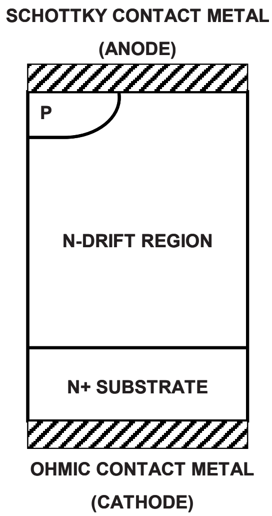

Fig. 1.11 The Merged P-i-N Schottky (MPS) Rectifier Structure.

1.5 Typical Power Rectifier Applications

Power rectifiers are used to control the direction of current flow in circuits. Most often, they are used in conjunction with power transistors, such as MOSFETs and IGBTs. Two typical examples for the application of high performance power rectifiers are provided in this section to emphasize the characteristics of importance from an application standpoint. The first example is in the 'Buck' converter used to reduce the voltage from one DC level to a smaller value. This circuit is popular for distributing power within a computer. The second example is in variable speed motor drives. This application is popular for operating induction motors with variable loads leading to large gains in efficiency.

1.5.1 DC-DC Buck Converter

The buck converter can be regarded as a DC-to-DC transformer because of its ability to reduce a DC input voltage to a smaller DC output voltage. As mentioned above, one popular application of the Buck-converter is to provide power to various loads inside a computer from the back-plane DC power supply. The back-plane power supply has a typical voltage range of 17-20 volts depending on the type of computer. Loads, such as disk drives require a DC voltage of 5-12 volts. In contrast, integrated circuits in the computer, such as the microprocessor and graphics chips, require a lower DC voltage in the range of 1-2 volts.

The commonly used Buck-converter circuit used for the DC-to-DC voltage conversion in computers is shown in Fig. 1.12. Due to the relatively low operating voltage in this circuit, a power MOSFET is typically used as the switch. When the transistor is turned on by the control circuit, current flows from the DC input source through the inductor to the load connected at the output terminals. When the transistor is switched off by the control circuit, the load current circulates through the rectifier and the inductor. The regulation of the DC output voltage can be achieved by adjusting the on-time of the transistor[11]. The switching waveforms for the transistor are similar to those shown in Fig. 1.2. The waveforms for the rectifier are a complement of those for the transistor.

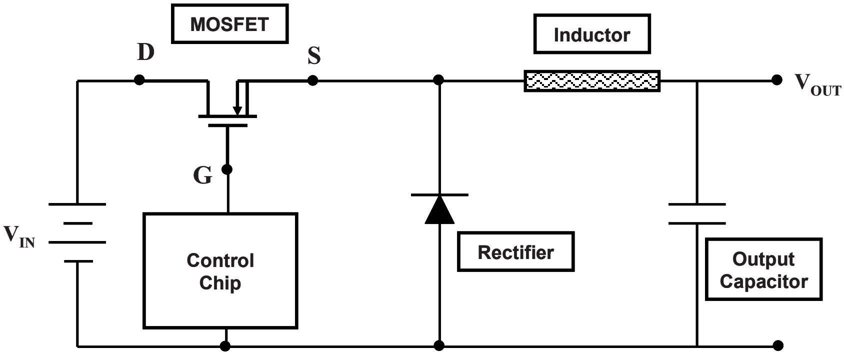

Fig. 1.12 The Buck DC-DC Converter Circuit.

There is a trend towards increasing the operating frequency of the DC-DC converter in an effort to reduce the size of the inductor. The power MOSFETs used as switches have inherent high frequency operating capability because of unipolar current flow. It is advantageous to also use unipolar current flow in the power rectifier to enable operation at high frequencies with low switching losses. It is also desirable to reduce the on-state voltage drop for the rectifier to reduce conduction losses when current is flowing through this path. These features are inherent in the silicon power Schottky rectifier structure. However, care must be taken to retain a sufficiently low leakage current at the maximum operating temperature to prevent thermal runaway.

1.5.2 Variable-Frequency Motor Drive

A significant increase in the efficiency for running motors can be achieved by used variable-frequency motor drives in place of constant speed drives with dampers to regulate the output. The most commonly used topology converts the constant frequency input AC power to a DC bus voltage and then use an inverter stage to produce the variable frequency output power[12]. The circuit diagram for a three-phase motor drive system is shown in Fig. 1.13. Six IGBTs are used with six fly-back rectifiers in the inverter stage to deliver the variable frequency power to the motor windings. A pulse-width-modulation (PWM) scheme is used to generate the variable frequency AC voltage waveform that is fed to the motor windings[13].

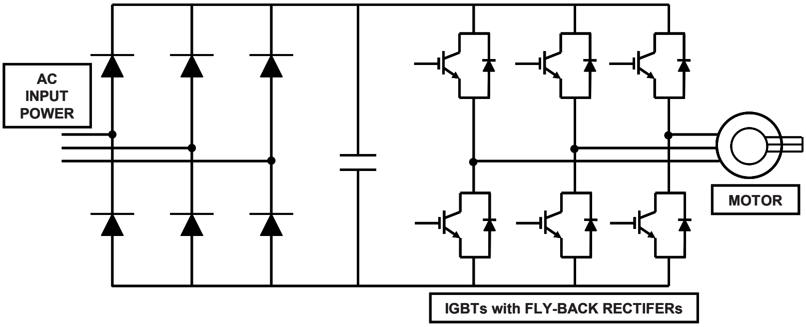

Fig. 1.13 Variable Frequency Motor Drive Circuit.

During each cycle of the PWM period, the current in the motor winding can be considered to remain approximately constant. This allows linearlization of the waveforms for the current and voltage experienced by the IGBTs and the rectifiers. Typical waveforms for the transistor and the fly-back diode are illustrated in Fig. 1.14. The large reverse recovery current typically observed in silicon P-i-N rectifiers during the time interval from t_1 to t_3 produces high power dissipation not only in the diodes but also in the transistors[1,4]. This power loss can be eliminated by replacing the silicon P-i-N rectifiers with silicon carbide Schottky rectifiers.

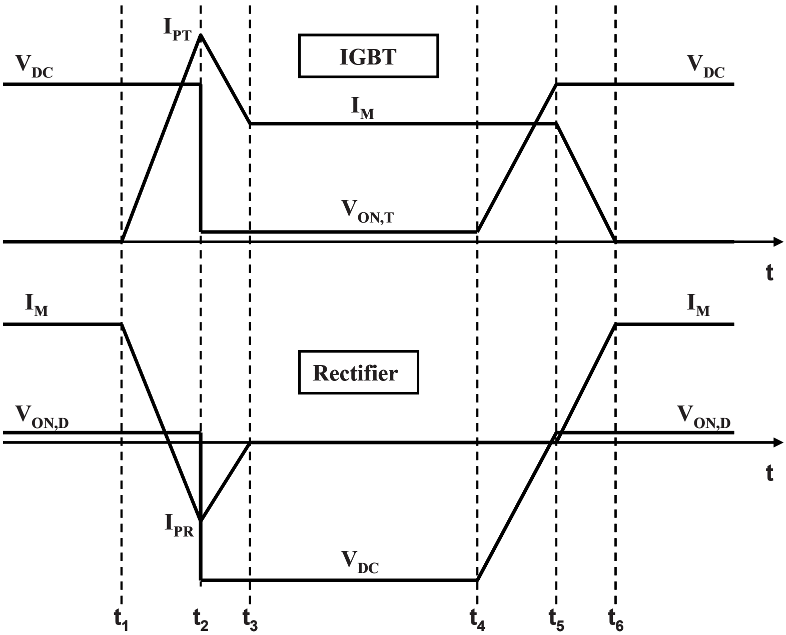

Fig. 1.14 Linearized Waveforms for the PWM Motor Drive Circuit.

1.6 Summary

The desired characteristics for power semiconductor rectifiers have been reviewed in this chapter. The characteristics of typical devices have been compared with those for the ideal case. Two high volume applications for the rectifiers have been briefly described. Various unipolar and bipolar power device structures that are suitable for these applications have been introduced here. These structures are discussed in detail in subsequent chapters of this book.

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Chapter 2

Schottky Rectifiers

A Schottky rectifier is formed by making an electrically non-linear contact between a metal and the semiconductor drift region. The Schottky rectifier is an attractive unipolar device for power electronics applications due to its relatively low on-state voltage drop and its fast switching behavior. It has been widely used in power supply circuits with low operating voltages due to the availability of excellent devices based upon silicon technology. In the case of silicon, the maximum breakdown voltage of Schottky rectifiers has been limited by the increase in the resistance of the drift region. Commercially available devices are generally rated at breakdown voltages of less than 100 volts.

Many applications described in chapter 1 require fast switching rectifiers with low on-state voltage drop that can also support over 500 volts. The much lower resistance of the drift region for silicon carbide enables development of such Schottky rectifiers with very high breakdown voltages[1]. These devices not only offer fast switching speed but also eliminate the large reverse recovery current observed in high voltage silicon P-i-N rectifiers. This reduces switching losses not only in the rectifier but also in the IGBTs used within the power circuits[2].

In this chapter, the basic structure of the power Schottky rectifier is first introduced to define its constituent elements. The current transport mechanisms that are pertinent to power devices are elucidated for both the forward and reverse mode of operation. In the first quadrant of operation, the thermionic emission process is dominant for power Schottky rectifiers. In the third quadrant of operation, the influence of Schottky barrier lowering has a strong impact on the leakage current for silicon devices. In the case of silicon carbide devices, the influence of tunneling current must also be taken into account when performing the analysis of the reverse leakage current.

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The information in this chapter is intended to provide the context and perspective for the discussion of advanced device concepts in subsequent chapters. A more detailed discussion of the fundamental concepts relevant to power Schottky rectifiers is provided in a recently published textbook[3]. This includes optimization of the Schottky barrier height depending upon the duty cycle and the maximum junction temperature.

2.1 Power Schottky Rectifier Structure

The basic one-dimensional structure of the metal-semiconductor or Schottky rectifier structure is shown in Fig. 2.1 together with electric field profile under reverse bias operation. The applied voltage is supported by the drift region with a triangular electric field distribution if the drift region doping is uniform. The maximum electric field occurs at the metal contact. The device undergoes breakdown when this field becomes equal to the critical electric field for the semiconductor.

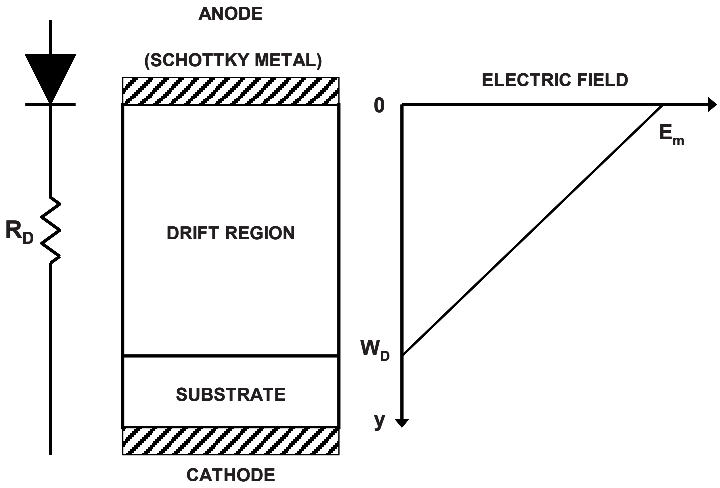

Fig. 2.1 Electric Field Distribution in a Schottky Rectifier.

When a negative bias is applied to the cathode, current flow occurs in the Schottky rectifier by the transport of electrons over the metal-semiconductor contact and through the drift region as well as the substrate. The on-state voltage drop is determined by the voltage drop across the metal-semiconductor interface and the ohmic voltage drop in the resistance of the drift region, the substrate and its ohmic contact.

At typical on-state operating current density levels, the current transport is dominated by majority carriers. Consequently, there is insignificant minority carrier stored charge within the drift region in the power Schottky rectifier. This enables switching the Schottky rectifier from the on-state to the reverse blocking off-state in a rapid manner by establishing a depletion region within the drift region. The fast switching capability of the Schottky rectifier enables operation at high frequencies with low power losses making this device popular for high frequency switch mode power supply applications. With the advent of commercially available high voltage Schottky rectifiers based upon silicon carbide, they are expected to be utilized in motor control applications as well.

A useful relationship for obtaining the Schottky barrier height is:

$$\Phi_{BN} = \Phi_M - \chi_S \quad \textbf{[2.1]}$$

where ϕ_M is the metal work function and χ_S is the electron affinity of the semiconductor. The potential difference between the Fermi level in the semiconductor (E_{FS}) and the Fermi level in the metal (E_{FM}) is called the *contact potential* (V_C) which is given by:

$$qV_C = \left(E_{FS} - E_{FM}\right) = \Phi_M - \Phi_S = \Phi_M - \left(\chi_S + E_C - E_{FS}\right) \quad \textbf{[2.2]}$$

where ϕ_S is the semiconductor work function and E_C is the conduction band edge. The built-in potential (V_{bi}) at the Schottky contact (equal to the contact potential) creates a depletion region within the semiconductor at zero bias given by:

$$W_0 = \sqrt{\frac{2\varepsilon_S V_{bi}}{qN_D}} \quad \textbf{[2.3]}$$

2.2 Forward Conduction

Current flow across the metal-semiconductor junction can be produced by the application of a negative bias to the N-type semiconductor region. Current flow across the interface then occurs mainly due to majority carriers – electrons for the case of an N-type semiconductor. The current flow via the thermionic emission process is the dominant current transport mechanism in silicon and silicon carbide Schottky power rectifiers. In the case of high mobility semiconductors, such as silicon, gallium arsenide and silicon carbide, the thermionic emission theory can be used to describe the current flow across the Schottky barrier interface[4]:

$$J = AT^2 e^{-(q\Phi_{BN}/kT)}\left[e^{(qV/kT)} - 1\right] \quad \textbf{[2.4]}$$

where A is the effective Richardson's constant, T is the absolute temperature, k is Boltzmann's constant, and V is the applied bias. An effective Richardson's constant of 110, 140, and 146 A/cm^2-^{o}K^2 can be used for n-type silicon[6], gallium arsenide[6], and 4H silicon carbide[3], respectively. This expression, based upon the superimposition of the current flux from the metal and the semiconductor[5] which balance out at zero bias, holds true for both positive and negative voltages applied to the metal contact.

When a forward bias is applied (positive values for V in Eq. [2.4]), the first term in the square brackets of the equation becomes dominant allowing calculation of the forward current density:

$$J_F = AT^2 e^{-(q\Phi_{BN}/kT)} e^{(qV_{FS}/kT)} \qquad \textbf{[2.5]}$$

where V_{FS} is the forward voltage drop across the Schottky contact. In the case of power Schottky rectifiers, a thick lightly doped drift region must be placed below the Schottky contact as illustrated in Fig. 2.1 to allow supporting the reverse blocking voltage. A resistive voltage drop (V_R) occurs across this drift region which increases the on-state voltage drop of the power Schottky rectifier beyond V_{FS}. In case of current transport by the thermionic emission process, there is no modulation of the resistance of the drift region because minority carrier injection is neglected. Due to the small thickness (typically less than 50 microns) of the drift region for power Schottky diodes, it is grown on top of a heavily doped N^+ substrate as a handle during processing and packaging of the devices. The resistance contributed by the substrate (R_{SUB}) must be included in the analysis because it can be comparable to that of the drift region especially for silicon carbide devices. In addition, the resistance of the ohmic contact (R_{CONT}) to the cathode may make a substantial contribution to the on-state voltage drop.

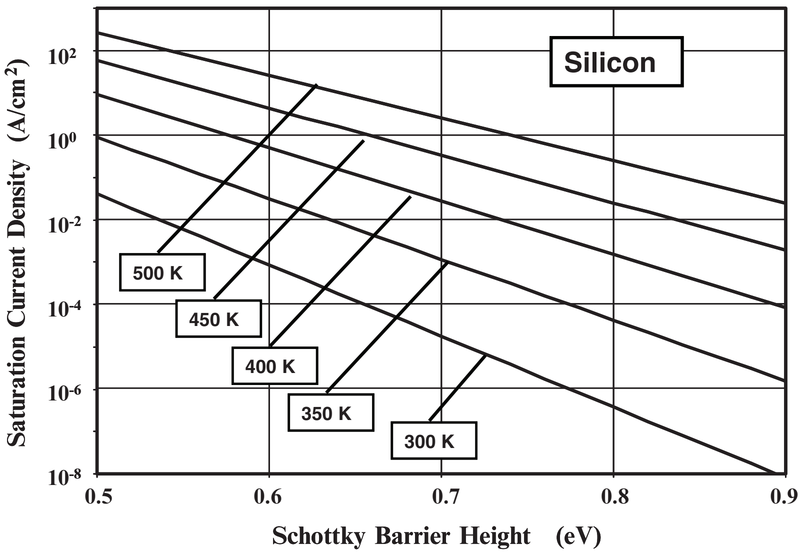

Fig. 2.2 Saturation Current Density for Silicon Schottky Barrier Rectifiers.

The on-state voltage drop (V_F) for the power Schottky rectifier, after including the resistive voltage drop, is given by:

$$V_F = V_{FS} + V_R = \frac{kT}{q}\ln\left(\frac{J_F}{J_S}\right) + R_{S,SP}J_F \qquad \textbf{[2.6]}$$