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].

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December 2008

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http://www.springer.com/978-0-387-75588-5

Advanced Power Rectifier Concepts
Baliga, B.J.
2009, XVI, 352 p. 310 illus., Hardcover
ISBN: 978-0-387-75588-5