Preface

Power semiconductor devices are 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.

Bipolar power devices, such as bipolar transistors and thyristors, were first developed in the 1950s. Their power ratings and switching frequency increased with advancements in the understanding of the operating physics and availability of more advanced lithography capability. The physics underlying the current conduction and switching speed of these devices has been described in several textbooks[1,2]. Since the thyristors were developed for high voltage DC transmission and electric locomotive drives, the emphasis was on increasing the voltage rating and current handling capability. The ability to use neutron transmutation doping to produce high resistivity n-type silicon with improved uniformity across large diameter wafers enabled increasing the blocking voltage of thyristors to over 5000 volts while being able to handle over 2000 amperes of current in a single device. Meanwhile, bipolar power transistors were developed with the goal of increasing the switching frequency in medium power systems. Unfortunately, the current gain of bipolar transistors becomes low when it is designed for high voltage operation at high current density. The popular solution to this problem, using the Darlington configuration, had the disadvantage of increasing the on-state voltage drop resulting in an increase in the power dissipation. In addition to the large control currents required for bipolar transistors, they suffered from second breakdown failure modes. These issues produced a cumbersome design with snubber networks, which raised the cost and degraded the efficiency of the power control system.

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 losses, even when using larger more expensive die, degrade the overall system efficiency.

In recognition of these issues, I proposed two new thrusts in 1979 for the power device field. The first was based upon the merging of MOS and bipolar device physics to create a new category of power devices[3]. My most successful innovation among MOS-Bipolar devices has been the *Insulated Gate Bipolar Transistor (IGBT)*. Soon after commercial introduction in the early 1980s, the IGBT was adopted for all medium power electronics applications. Today, it is manufactured by more than a dozen companies around the world for consumer, industrial, medical, and other applications that benefit society. The triumph of the IGBT is associated with its huge power gain, high input impedance, wide safe operating area, and a switching speed that can be tailored for applications depending upon their operating frequency.

The second approach that I suggested in the early 1980s for enhancing the performance of power devices was to replace silicon with wide band gap semiconductors. The basis for this approach was an equation that I derived relating the on-resistance of the drift region in unipolar power devices to the basic properties of the semiconductor material. This equation has since been referred to as *Baliga's Figure of Merit (BFOM)*. In addition to the expected reduction in the on-state resistance with higher carrier mobility, the equation predicts a reduction in on-resistance as the inverse of the cube of the breakdown electric field strength of the semiconductor material.

In the 1970s, there was a dearth of knowledge of the impact ionization coefficients of semiconductors. Consequently, an association of the breakdown electric field strength was made with the energy band gap of the semiconductor[4]. This led to the conclusion that wide band gap semiconductors offer the opportunity to greatly reduce the on-state resistance of the drift region in power devices. With a sufficiently low on-state resistance, it became possible to postulate that unipolar power devices could be constructed from wide band gap semiconductors with lower on-state voltage drop than bipolar devices made out of silicon. Since unipolar devices exhibit much faster switching speed than bipolar devices because of the absence of minority carrier stored charge, wide band gap based power devices offered a much superior alternative to silicon bipolar devices for medium and high power applications. Device structures that were particularly suitable for development were identified as Schottky rectifiers to replace silicon P-i-N rectifiers, and power Field Effect Transistors to replace the bipolar transistors and thyristors prevalent in the 1970s.

The first attempt to develop wide band gap based power devices was undertaken at the General Electric Corporate Research and Development Center, Schenectady, NY, under my direction. The goal was to leverage a 13-fold reduction in specific on-resistance for the drift region predicted by the BFOM for Gallium Arsenide. A team of 10 scientists was assembled to tackle the difficult problems of the growth of high resistivity epitaxial layers, the fabrication of low resistivity ohmic contacts, low leakage Schottky contacts, and the passivation of the GaAs surface. This led to an enhanced understanding of the breakdown strength[5] for GaAs and the successful fabrication of high performance Schottky rectifiers[6] and MESFETs[7]. Experimental verification of the basic thesis of the analysis represented by BFOM was therefore demonstrated during this period. Commercial GaAs based Schottky rectifier products were subsequently introduced in the market by several companies.

In the later half of the 1980s, the technology for the growth of silicon carbide was developed with the culmination of commercial availability of wafers from CREE Research Corporation. Although data on the impact ionization coefficients of SiC was not available, early reports on the breakdown voltage of diodes enabled estimation of the breakdown electric field strength. Using these numbers in the BFOM predicted an impressive 100-200 fold reduction in the specific on-resistance of the drift region for SiC based unipolar devices. In 1988, I joined North Carolina State University and subsequently founded the *Power Semiconductor Research Center (PSRC)* - an industrial consortium – with the objective of exploring ideas to enhance power device performance. Within the first year of the inception of the program, SiC Schottky barrier rectifiers with breakdown voltage of 400 volts were successfully fabricated with on-state voltage drop of about 1 volt and no reverse recovery transients[8]. By improving the edge termination of these diodes, the breakdown voltage was found to increase to 1000 volts. With the availability of epitaxial SiC material with lower doping concentrations, SiC Schottky rectifiers with breakdown voltages over 2.5 kV have been fabricated at PSRC[9]. These results have motivated many other groups around the world to develop SiC based power rectifiers. In this regard, it has been my privilege to assist in the establishment of national programs to fund research on silicon carbide technology in the United States, Japan, and Switzerland-Sweden. Meanwhile, accurate measurements of the impact ionization coefficients for 6H-SiC and 4H-SiC in defect free regions were performed at PSRC using an electron beam excitation method[10]. Using these coefficients, a BFOM of over 1000 is predicted for SiC providing even greater motivation to develop power devices from this material.

Although the fabrication of high performance, high voltage Schottky rectifiers has been relatively straight-forward, the development of a suitable silicon carbide MOSFET structure has been more problematic. The existing silicon power D-MOSFET and U-MOSFET structures do not directly translate to suitable structures in silicon carbide. The interface between SiC and silicon dioxide, as a gate dielectric, needed extensive investigation due to the large density of traps that prevent the formation of high conductivity inversion layers. Even after overcoming this hurdle, the much higher electric field in the silicon dioxide when compared with silicon devices, resulting from the much larger electric field in the underlying SiC, leads to reliability problems. Fortunately, a structural innovation, called the ACCUFET, to overcome both problems was proposed and demonstrated at PSRC[11]. In this structure, a buried P^+ region is used to shield the gate region from the high electric field within the SiC drift region. This concept is applicable to devices that utilize either accumulation channels or inversion channels. Devices with low specific on-resistance have been demonstrated at PSRC using both 6H-SiC and 4H-SiC with epitaxial material capable of supporting over 5000 volts[12]. This device structure has been subsequently emulated by several groups around the world.

Although many papers have been published on silicon carbide device structures and process technology, no comprehensive book written by a single author is available that provides a unified treatment of silicon carbide power device structures. This book has been prepared to fill this gap. The emphasis in the book is on the physics of operation of the devices elucidated by extensive two-dimensional numerical analysis.

The simulations were done for 4H-SiC, rather than 6H-SiC, because its larger breakdown strength results in superior device performance. This analysis provides general guidelines for understanding the design and operation of the various device structures. For designs that may be pertinent to specific applications, the reader should refer to the papers published in the literature, the theses of my M.S. and Ph.D. students, as well as the work reported by other research groups. Comparison with silicon devices is provided to enable the reader to understand the benefits of silicon carbide devices.

In the introduction chapter, the desired characteristics of power devices are described with a broad introduction to potential applications. The second chapter provides the properties of silicon carbide that have relevance to the analysis and performance of power device structures. Issues pertinent to the fabrication of silicon carbide devices are reviewed here because the structures analyzed in the book have been constructed with these process limitations in mind. The third chapter discusses breakdown voltage, which is the most unique distinguishing characteristic for power devices, together with edge termination structures. This analysis is pertinent to all the device structures discussed in subsequent chapters of the book.

The fourth chapter provides a brief analysis of P-i-N rectifiers followed by a detailed analysis of the Schottky rectifier structure in chapter five. The sixth chapter introduces the concept and explains the benefits of shielding the Schottky contact. This approach is essential for mitigating the generation of high leakage current in silicon carbide Schottky rectifiers arising from Schottky barrier lowering and tunneling currents. The next chapter describes power JFET and MESFET structures with planar and trench gate regions. These normally-on structures can be used to construct the *Baliga-Pair* circuit[13], described in chapter eight, which has been shown to be ideally suitable for motor control applications. This represents a near term solution to taking advantage of the low specific on-resistance of the silicon carbide drift region while awaiting resolution of reliability issues with the gate oxide in silicon carbide power MOSFET structures.

Chapter nine provides a description of silicon carbide power MOSFET structures with emphasis on problems associated with simply replicating structures originally developed in silicon technology. Innovative approaches to prevent high electric field in the gate oxide of silicon carbide power MOSFETs are then discussed in chapter ten. In this chapter, accumulation-mode structures are shown to provide the advantages of larger channel mobility and lower threshold voltage leading to a reduction in the specific on-resistance. In chapter eleven, issues with adopting the silicon UMOSFET structure to silicon carbide are enunciated followed by analysis of solutions to these problems in chapter twelve. Once again, methods for shielding the gate oxide are shown to enable reduction of the electric field in the gate oxide to acceptable levels. The shielding is also demonstrates to ameliorate the base reach-through problem allowing a reduction of the base width and hence the channel resistance contribution.

The application of the charge-coupling concept to silicon carbide is explored in chapter thirteen to reduce the resistance of the drift region. This approach is applicable to very high voltage structures with blocking voltage capability exceeding 3000 volts. In chapter fourteen, the operation of the integral diode within the silicon carbide power MOSFET structures is analyzed for utilization as a fly-back rectifier in motor control applications. A unique mode of current conduction in the silicon carbide power MOSFET in the third quadrant of operation is identified here which allows for a reduction of the on-state voltage drop of the integral diode.

Although the emphasis in this book has been on discrete vertical silicon carbide structures, for the sake of completeness, the fifteenth chapter describes high voltage lateral silicon carbide structures that are suitable for integration with CMOS circuits. In the concluding sixteenth chapter, the performance of silicon carbide devices is compared with that of silicon devices using a typical motor control application as an example to provide the reader with a perspective on the benefits of using silicon carbide devices. From an applications perspective, it is demonstrated that the replacement of the silicon P-i-N rectifier with the silicon carbide JBS rectifier provides a significant reduction in the power losses for the system as well as the stress experienced by the silicon IGBT. This approach is already becoming a commercially viable option due to the availability of silicon carbide Schottky rectifier products from several companies.

Throughout the book, experimental results are included whenever pertinent to each chapter. This provides a historical context and a brief summary of the state of the art for silicon carbide devices. Issues that must be addressed before commercialization of silicon carbide structures becomes viable are pointed out in these sections of the book.

I am hopeful that this book will be used for the teaching of courses on solid state devices and that it will make an essential reference for the power device industry. To facilitate this, analytical solutions are provided throughout the book that can be utilized to understand the underlying physics and model the structures. Comparison of the silicon carbide structures with their silicon counterparts is also included whenever pertinent to the discussion.

Ever since my identification of the benefits of utilizing wide band gap semiconductors for the development of superior power devices twenty-five years ago, it has been my mission to resolve issues that would impede their commercialization. I wish to thank the sponsors of the Power Semiconductor Research Center and the Office of Naval Research for supporting this mission during the last fifteen years. This has been essential to providing the resources required to create many breakthroughs in the silicon carbide technology which I hope will enable commercialization of the technology in the near future. I look forward to observing the benefits accrued to society by adopting the silicon carbide technology for conservation of fossil fuel usage resulting in reduced environmental pollution.

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