Preface

The adverse impact on the environment resulting from carbon emissions into the atmosphere is widely accepted worldwide. The carbon emission can be reduced by taking two approaches. The first approach is based upon energy conservation. Energy conservation can be achieved without compromising the standard of life in our society by improving the efficiency for the management and distribution of power. Power semiconductor devices are recognized as a key component for achieving this goal [1]. It is estimated that at least 50% of the electricity used in the world is controlled by power devices. With the wide spread use of electronics in the consumer, industrial, lighting, and transportation sectors, power devices have a major impact on the economy because they determine the cost and efficiency of systems. The second approach to mitigating carbon emissions is by the development of renewable energy sources such as wind power and solar power. These installations require power electronic inverters to convert the generated power to a well-regulated 60 Hz AC power that can be distributed to consumers and the industry. Due to the relatively high power levels involved, the power semiconductor devices used in these applications must have high voltage and current handling capability.

In the 1950s, the power rectifiers and thyristors were introduced to replace the existing vacuum tubes. The solid state devices offered much smaller size, improved ruggedness, and greater efficiency. Over the last six decades, the power ratings of thyristors have steadily grown. The current handling capability has been increased from 100 A to over 4,000 A by using larger diameter silicon wafers while the blocking voltage capability has simultaneously been increased from 200 V to more than 8,000 V by using higher resistivity silicon produced with the neutron transmutation doping process. These devices have been primarily used in HVDC power transmission and distribution systems.

The complexity and power losses in the commutation circuits required with thyristors motivated the development of Gate Turn-Off (GTO) thyristors in the 1960s. These devices found favor in large motor drive applications such as in steel mills and electric trains (traction). The power ratings of GTOs grew steadily in the last five decades to reach a current handling capability of 4,000 A with a blocking voltage capability of 6,000 V [1].

The large drive current needed for silicon GTOs encouraged the development of the insulated gate bipolar transistor (IGBT) [2] in the 1980s. During the last three decades, 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. The U.S. Department of Energy has estimated that the implementation of IGBT-based variable speed drives for controlling motors is producing an energy savings of over 2 quadrillion btus per year, which is equivalent to 70 GW of power. This energy savings eliminates the need for generating electricity from 70 coal-fired power plants resulting in reducing carbon dioxide emissions by over one trillion pounds each year. The power ratings of IGBTs have been increased to a current handling capability of over 1,000 A with blocking voltages of 6,000 V. They are now being applied to not only high power motor drives for traction [3] (Shinkansen bullet train) but also for HVDC power distribution [4].

With on-going investments in renewable energy sources such as wind and solar power that utilize power semiconductor device in inverters, it is anticipated that there will be an increasing need for technologists trained in the discipline of designing and manufacturing power semiconductor devices. My recently published textbook [5] provides a comprehensive analysis of the basic power rectifier, transistor, and thyristor structures. In 2009, the textbook was complemented with a monograph on *Advanced Power Rectifier Concepts* to familiarize students and engineering professionals with diodes that exhibit improved performance attributes. In 2010, the textbook was complemented with a monograph on 'Advanced Power MOSFET Concepts' to familiarize students and engineering professionals with switches that exhibit improved performance attributes.

This monograph introduces the reader to advanced MOS-gated power thyristor concepts that enable improvement of performance of these high voltage structures. The voltage ratings for the devices discussed here range from 5,000 V to 20,000 V. For the convenience of readers, analysis of the basic thyristor structures, with the same voltage ratings as the novel device structures, has been included in the monograph to enable comparison of the performance. As in the case of the textbook, analytical expressions that describe the behavior of the advanced power thyristor structures have been rigorously derived using the fundamental semiconductor Poisson's, continuity, and conduction equations in this monograph. The characteristics of IGBTs have also been included in this book because they have displaced thyristors in many high power motor drive and power transmission systems. The electrical characteristics of all the power devices 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 high voltage power devices is provided. The electrical characteristics for ideal power switches are then defined and compared with those for typical devices. The second and third chapters provide analyses of the silicon and silicon carbide power thyristors. The analysis includes the blocking characteristics, the on-state voltage drop, and switching behavior. The silicon Gate Turn-Off thyristor structure is then discussed in Chap. 4. The fifth chapter is devoted to silicon IGBT structures to provide a benchmark. Any alternate silicon or silicon carbide device technology must outperform the commonly used silicon IGBT systems today.

The analysis of silicon carbide MOSFETs and IGBTs is provided in Chaps. 6 and 7. The much larger breakdown field strength for 4H-SiC allows increasing the doping concentration in the drift region by a factor of 200 times while shrinking the thickness of the drift region by one-order of magnitude. This makes 5 kV and 10 kV silicon carbide MOSFETs with low on-resistance feasible. For even higher blocking voltages, the silicon carbide IGBT structure needs to be developed. However, the silicon carbide MOSFET and IGBT structures must be designed to shield the gate oxide from the much larger electric fields prevalent in silicon carbide to avoid rupture. In addition, the base region must be shielded to avoid reach-through breakdown. The on-state voltage drop of these devices becomes limited by the channel resistance and buffer layer design.

The eighth and ninth chapters discuss the MOS-Controlled Thyristor (MCT) structure and the Base-Resistance Controlled Thyristor (BRT) structure, which utilize MOS-gate control of the turn-on and turn-off of the thyristor. The tenth chapter describes the Emitter Switched Thyristor (EST) which also utilizes an MOS-gate structure to control the turn-on and turn-off of the thyristor while allowing construction with the IGBT process. This device has the added feature of a good safe operating area.

The final chapter provides a comparison of all the high voltage power device structures discussed in this book. The performance of all the devices is compared over a wide range of blocking voltages to provide a broader view.

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 [5].

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