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功率半导体器件基础

Fundamentals of Power Semiconductor Devices

（英文版）

〔美〕B. Jayant Baliga　著

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内容简介

本书作者是功率半导体器件领域的著名专家，IGBT 器件发明人之一。本书结合作者多年的实践经验，深入讨论了半导体功率器件的物理模型、工作原理、设计原则和应用特性，不仅详细介绍了硅基器件，还讨论了碳化硅器件的特性与设计要求。主要内容包括材料特性与输运物理、击穿电压、肖特基整流器、P-i-N 整流器、功率 MOSFET 器件、双极型晶体管、晶闸管、IGBT 器件等。

本书可作为微电子、电力电子等相关领域科研人员、工程技术人员的参考书，也可作为相关专业高年级本科生、研究生的教材。

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推 荐 序

本书作者 Baliga 教授任教于美国北卡罗莱纳州立大学（North Carolina State University，NCSU），是世界著名的功率半导体器件专家，曾撰写和编辑过多本有关功率半导体器件的著作。自 1974 年在通用电气公司从事高压晶闸管器件制造至今，他已开展了近 40 年半导体功率器件方面的研究工作。尤其在 20 世纪 70 年代金属-氧化物-半导体场效应晶体管，简称 MOS 场效应晶体管（Metal-Oxide-Semiconductor Field-Effect Transistor, MOSFET）问世后，他做出了一系列重大的贡献：发明了绝缘栅双极型晶体管（Insulated Gate Bipolar Transistor，IGBT）；于 1988 年在 NCSU 创建了包括工业界在内的“功率半导体研究中心”，该中心在碳化硅（SiC）功率整流器和 SiC-MOSFET 方面做出了开创性的贡献。另外，Baliga 教授在智能功率技术（smart power technique）方面也做出了很多贡献，他的研究领域包括新型器件的模型建立、功率器件制造技术（如砷化镓与碳化硅等新材料用于功率器件）。

本书与作者之前在同一领域中出版的著作不同，该书更强调功率器件的工作原理，可供从事功率半导体器件设计与制造的工程技术人员参考，也可用做高年级本科生与研究生的教材。

全书共分 10 章。第 1 章对功率器件的广泛应用做了简要介绍，并对理想的功率整流器和晶体管的电气特性做了定义；第 2 章介绍了用于功率器件的半导体材料的特性（碰撞电离系数与载流子寿命等）及输运物理；第 3 章介绍了击穿电压，包括雪崩击穿、器件掺杂分布对击穿电压的影响，以及采用边缘终断电极来改进器件耐击穿特性的方法；第 4 章介绍了肖特基整流器，包括结构、反向击穿机理分析及器件电容、散热考虑等；第 5 章介绍了 P-i-N 整流器结构与开关性能分析，包括基于碳化硅的 P-i-N 整流器；第 6 章介绍了功率场效应管，这是全书最主要的一章，讨论了包括 V-/VD-/U-MOSFET 在内的器件单元的结构与工作原理、基本的器件特性、改进击穿电压的方法、器件的导通电阻、开关/高频工作特性、高温下工作特性与单元设计优化、SiC-MOSFET 等；第

7 章介绍了双极型晶体管作为功率器件的基本结构与工作原理、电流增益、发射极电流拥挤现象讨论及输出特性、导通电阻等；第 8 章介绍了晶闸管（或称为可控硅）作为功率器件的结构与工作原理、耐压特性、导通电阻、开关特性等，以及其他各种结构，包括光激励、栅控可关断及三端双向结构；第 9 章介绍了绝缘栅双极型晶体管的器件结构与工作原理、器件建模等效电路、输出特性与耐压特性、导通态特性、电流饱和模型、开关特性、功耗最小化及这种结构所特有的闩锁（latch-up）效应抑制技术。

本书采用了计算机器件模拟来验证基于解析表达式的器件特性模型，同时可以对实际结构复杂的器件进行分析与优化设计。各章都附有习题，便于读者深入掌握书中所阐述的基本概念。

余志平　张莉
2012 年 4 月
于清华大学

Preface

Today the semiconductor business exceeds $200 billion with about 10% of the revenue derived from power semiconductor devices and smart power integrated circuits. Power semiconductor devices are recognized as a key component for all power electronic systems. It is estimated that at least 50% of the electricity used in the world is controlled by power devices. With the widespread 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. Because of the many advantages of semiconductor devices compared with vacuum tubes, there was a constant demand for increasing the power ratings of these devices. Their power rating 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 V became available. More remarkably, technology was developed capable of manufacturing an individual power thyristor from an entire 4-inch diameter silicon wafer with voltage rating over 5,000 V.

My involvement with power semiconductor devices began in 1974 when I was hired by the General Electric Company at their corporate research and development center to start a new group to work on this technology. At that time, I had just completed my Ph.D. degree at Rensselaer Polytechnic Institute by performing research on a novel method for the growth of epitaxial layers of compound semiconductors.[1–4] Although I wanted to explore this approach after joining the semiconductor industry, I was unable to secure a position at any of the major research laboratories due to a lack of interest in this unproven growth technology. Ironically, the OMCVD epitaxial growth process that I pioneered with Professor Ghandhi has now become the most commonly used method for the growth of high quality compound semiconductor layers for applications such as lasers, LEDs, and microwave transistors.

My first assignment at GE was to develop improved processes for the fabrication of high voltage thyristors used in their power distribution business. Since the thyristors were used 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 became of interest at this time. I was fortunate in making some of the critical contributions to annealing the damage caused to the silicon lattice during neutron irradiation making this process commercially viable.[5] This enabled increasing the blocking voltage of thyristors to over 5,000 V while being able to handle over 2,000 A of current in a single device.

Meanwhile, bipolar power transistors were being developed with the goal of increasing the switching frequency in medium power systems. Unfortunately, the current gain of bipolar transistors was found to be low when it was 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 poor safe-operating-area due to second breakdown failure modes. These issues produced a cumbersome design, with snubber networks, that 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.[6] 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 electronic 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 1979 for enhancing the performance of power devices was to replace silicon with wide bandgap 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.

The first attempt to develop wide-bandgap-semiconductor-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 ten 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[7] for GaAs and the successful fabrication of high performance Schottky rectifiers[8] and MESFETs.[9] 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 at North Carolina State University (NCSU) with the culmination of commercial availability of wafers from CREE Research Corporation. Although data on the impact ionization coefficients of SiC were 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 NCSU 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 V were successfully fabricated with on-state voltage drop of about 1 V and no reverse recovery transients.[10] By improving the edge termination of these diodes, the breakdown voltage was found to increase to 1,000 V. 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.[11] 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.[12] Using these coefficients, a BFOM of over 1,000 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 straightforward, the development of a suitable silicon carbide MOSFET structure has been 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 of these problems, was proposed and demonstrated at PSRC.[13] 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 5,000 V.[14] This device structure has been subsequently emulated by several groups around the world.

The availability of power semiconductor devices with high input impedance has encouraged the development of integrated control circuits. In general, the integration of the control circuit is preferred over the discrete counterpart due to reduced manufacturing costs at high volumes and improved reliability from a reduction of the interconnects. Since the complexity of including additional circuitry to an IC is relatively small, the incorporation of protective features such as over-temperature, over-current, and over-voltage has become cost effective. In addition, the chips can contain encode/decode CMOS circuitry to interface with a central microprocessor or computer in the system for control and diagnostic purposes. This technology is commonly referred to as *Smart Power Technology*.[15]

The advent of smart power technology portends a *Second Electronic Revolution*. In contrast to the integrated circuits for information processing, this technology enables efficient control of power and energy. These technologies can therefore be regarded as complementary, similar to the brain and muscles in the human body. Smart power technology is having an enormous impact on society. The widespread use of power semiconductor devices in consumer, industrial, transportation, and medical applications brings greater mobility and comfort to billions of people around the world. Our ability to improve the efficiency for the control of electric power results in the conservation of fossil fuels, which in turn provides reduction of environmental pollution.

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 textbook provides the knowledge in a tutorial format suitable for self-study or in a graduate/senior level university course. In comparison with my previous textbooks[16,17] (which have gone out of print), this book provides a more detailed description of the operating physics of power devices. Analytical expressions have been rigorously derived using the fundamental semiconductor Poisson's, continuity, and conduction equations. 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. Due to increasing interest in the utilization of wide bandgap semiconductors for power devices, the book includes the analysis of silicon carbide structures. To corroborate the validity of the analytical formulations, I have included the results of two-dimensional numerical simulations using MEDICI[18] in each section of the book. The simulation results are also used to elucidate further the physics and point out two-dimensional effects whenever relevant.

In Chap. 1, a broad introduction to potential applications for power devices is provided. The electrical characteristics for ideal power rectifiers and transistors are then defined and compared with those for typical devices. Chapter 2 provides the transport properties of silicon and silicon carbide that have relevance to the analysis and performance of power device structures. Chapter 3 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.

Chapter 4 provides a detailed analysis of the Schottky rectifier structure. 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.

Chapter 5 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 developed in detail. The impact of this on the reverse recovery phenomenon during turn-off is then analyzed. The influence of end region recombination, carrier–carrier scattering, and auger recombination are included in the analysis.

In Chap. 6, an extensive discussion of the operating principles and design considerations is provided for the power metal–oxide–semiconductor field effect transistor (MOSFET) structure. The influence of the parasitic bipolar transistor on the blocking voltage is described together with methods for its suppression. The basic physics of creating channels in the MOSFET structure is then developed. The concepts of threshold voltage, transconductance, and specific on-resistance are described. Various components of the on-state resistance are analyzed and optimization procedures are provided. Both the commercially available DMOS and UMOS structures are analyzed here. The modification of the physics required to produce a superlinear transfer characteristic is included due to its relevance for RF and audio applications. A detailed analysis of the device capacitances is then provided for use in the analysis of the switching behavior. Analysis of the gate charge is included here because of its common use in comparing device designs. The switching characteristics of the power MOSFET are then related to its capacitance, including the impact of the Miller effect. This is followed by discussion of the safe-operating-area, the integral body diode, high temperature characteristics, and complementary (p-channel) devices. A brief description of the process flow for the D-MOSFET and U-MOSFET structures is given in the chapter for completeness. The last portion of the chapter focuses on silicon carbide technology with the options of the Baliga–Pair configuration, the shielded planar structure, and the shielded trench-gate structure described in detail.

Chapter 7 is devoted to bipolar power transistors. The basic theory for current transport and gain in an N–P–N transistor is first developed followed by a discussion of issues relevant to power transistors. The various breakdown modes of the bipolar transistors are then explained. The physics governing the current gain of the bipolar transistor is extensively analyzed including high-level injection effects, the current-induced base, and emitter current crowding. The output characteristics for the bipolar transistor are then described with analysis of the saturation region, the quasisaturation mode, and the output resistance. This is followed by analysis of the switching characteristics. The influence of stored charge on the switching behavior of the bipolar transistor is described in detail during both the turn-on and turn-off transients. Issues dealing with second breakdown are then considered followed by ways to improve the current gain by using the Darlington configuration.

The physics of operation of the power thyristor is considered in Chap. 8. The impact of the four layer structure on the forward and reverse blocking capability is first analyzed including the use of cathode shorts. The on-state characteristics for the thyristor are then shown to approach those for a P–i–N rectifier. The gate triggering and holding currents are related to the cathode short design. Under switching characteristics, the turn-on physics is discussed with description of the involute design, the amplifying gate, and light-activated gate structures. The commutated switching behavior is also analyzed together with a discussion of voltage transients. The basic principles of the gate turn-off (GTO) thyristor are then described with analytical models for the storage, voltage-rise and current-fall times. The chapter concludes with the description of triacs, which are commonly used for AC power control.

The insulated gate bipolar transistor (IGBT) is discussed in depth in Chap. 9. The benefits of controlling bipolar current transport in a wide base P–N–P transistor using a MOS channel are explained. The design of both reverse blocking (symmetric) and unidirectional blocking (asymmetric) structures is considered here. The on-state characteristics of the IGBT are then extensively analyzed including the impact of high-level injection in the wide-base region and the finite injection efficiency of the collector junction. The discussion includes not only the basic symmetric IGBT structure but also the asymmetric structure and the transparent emitter structure. The utilization of lifetime control is compared with changes to the N-buffer-layer and P^+ collector doping concentrations. After developing the current saturation model for the IGBT structure, the output characteristics for the three types of IGBT structure are derived. The impact of the stored charge on the switching behavior of the device is then analyzed for the case of no-load, resistive-load, and inductive-load conditions for each of the three types of structures. The optimization of the power losses in the IGBT structure is then performed, allowing comparison of the three types of structures. The next section of the chapter describes the complementary (p-channel) IGBT structure. This is followed by an extensive discussion of methods for suppression of the parasitic thyristor in the IGBT due to its importance for designing stable devices. The next section on the safe-operating-area includes analysis of the FBSOA, RBSOA, and SCSOA. The trench-gate IGBT structure is then demonstrated to produce lower on-state voltage drop. This is followed by discussion of scaling up the voltage rating for the IGBT and its excellent characteristics for high ambient temperatures. Various methods for improving the switching speed of the IGBT structure and optimizing its cell structure are then discussed. The chapter concludes with the description of the reverse conducting IGBT structure.

The final chapter (Chap. 10) provides the basis for the comparison of various power devices from an applications viewpoint. A typical motor drive case is selected to demonstrate the reduction of power losses by optimization of the on-state and switching characteristics of the devices. The importance of reducing the reverse recovery current in power rectifiers is highlighted here.

Throughout the book, emphasis is placed on deriving simple analytical expressions that describe the underlying physics and enable representation of the device electrical characteristics. This treatment is invaluable for teaching a course on power devices because it allows the operating principles and concepts to be conveyed with quantitative analysis. The analytical approach used in the book based on physical insight will provide a good foundation for the reader. The results of two-dimensional numerical simulations have been included to supplement and reinforce the concepts. Due to space limitations, only the basic power device structures have been included in this book. Advanced structures will be covered in monographs to be subsequently published. I am hopeful that this book will be widely used for the teaching of courses on solid-state devices and that it will become an essential reference for the power device industry well into the future.

Raleigh, NC B. Jayant Baliga

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