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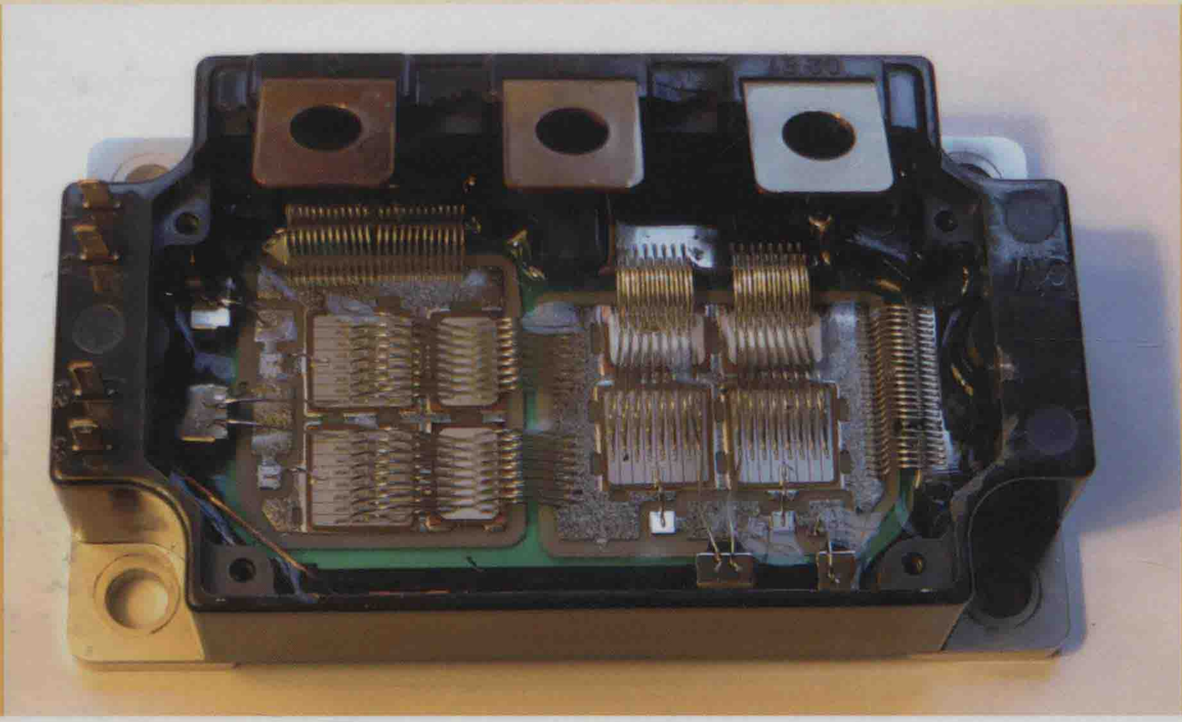

B. Jayant Baliga

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Physics, Design and Applications of the Insulated Gate Bipolar Transistor

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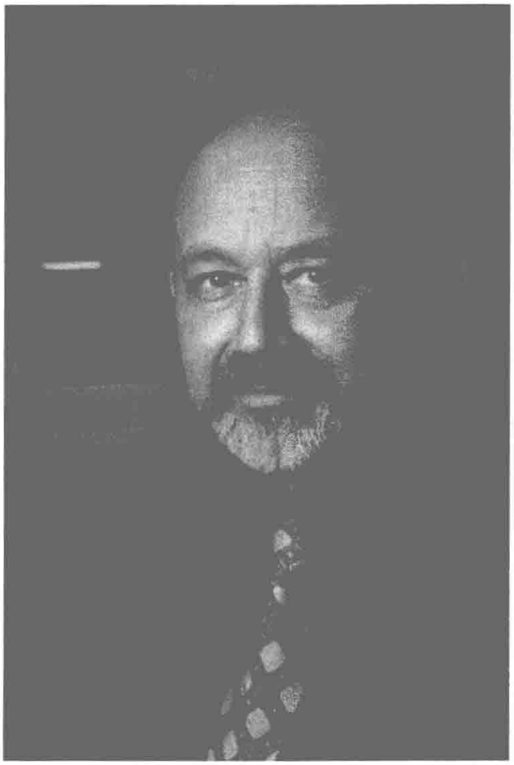
I dedicate this book to my wife, Pratima, for her support during my work on the development of the insulated gate bipolar transistor (IGBT) while working at the General Electric Company.

And the thousands of engineers from around the world who worked on improving the performance of the IGBT over the last 30 years and applying these devices to serve the needs of all the sectors of our worldwide economy.

About the Author



Prof. Baliga is internationally recognized for his leadership in the area of power semiconductor devices. In addition to over 550 publications in international journals and conference digests, he has authored and edited 18 books (*Power Transistors*, IEEE Press 1984; *Epitaxial Silicon Technology*, Academic Press 1986; *Modern Power Devices*, John Wiley 1987; *High Voltage Integrated Circuits*, IEEE Press 1988; *Solution Manual: Modern Power Devices*, John Wiley 1988; *Proceedings of the 3rd Int. Symposium on Power Devices and ICs*, IEEE Press 1991; *Modern Power Devices*, Krieger Publishing Co. 1992; *Proceedings of the 5th Int. Symposium on Power Devices and ICs*, IEEE Press 1993; *Power Semiconductor Devices*, PWS Publishing Company 1995; *Solution Manual: Power Semiconductor Devices*, PWS Publishing Company 1996; *Cryogenic Operation of Power Devices*, Kluwer Press 1998; *Silicon RF Power MOSFETs*, World Scientific Publishing Company 2005; *Silicon Carbide Power Devices*, World Scientific Publishing Company 2006; *Fundamentals of Power Semiconductor Devices*, Springer Science, 2008; *Solution Manual: Fundamentals of Power Semiconductor Devices*, Springer Science, 2008; *Advanced Power Rectifier Concepts*, Springer Science, 2009;

Advanced Power MOSFET Concepts, Springer Science, 2010; *Advanced High Voltage Power Device Concepts*, Springer Science, 2011. In addition, he has contributed chapters to another 20 books. He holds 120 US Patents in the solid-state area. In 1995, one of his inventions was selected for the *B.F. Goodrich Collegiate Inventors Award* presented at the *Inventors Hall of Fame.*

Prof. Baliga obtained his bachelor of technology degree in 1969 from the Indian Institute of Technology (IIT), Madras, India. He was the recipient of the *Philips India Medal* and the *Special Merit Medal (as Valedictorian)* at IIT, Madras. He obtained his Masters and PhD degrees from Rensselaer Polytechnic Institute (RPI), Troy NY, in 1971 and 1974, respectively. His thesis work involved gallium arsenide diffusion mechanisms and pioneering work on the growth of InAs and GaInAs layers using organometallic CVD techniques. At R.P.I., he was the recipient of the *IBM Fellowship* in 1972 and the *Allen B. Dumont Prize* in 1974.

From 1974 to 1988, Dr Baliga performed research and directed a group of 40 scientists at the General Electric Research and Development Center in Schenectady, NY, in the area of power semiconductor devices and high-voltage integrated circuits. During this time, he pioneered the concept of combining MOS and bipolar physics to create a new family of discrete devices. He is the *inventor of the IGBT* (insulated gate bipolar transistor) which is now in production by many international semiconductor companies. This invention is widely used around the globe for air-conditioning, home appliance (washing machines, refrigerators, mixers, etc.) control, factory automation (robotics), medical systems (CAT scanners, uninterruptible power supplies), and electric street-cars/bullet-trains, as well as for the drive-train in electric and hybrid-electric cars. IGBT-based motor control improves efficiency by over 40%. The IGBT is essential for deployment of compact fluorescent lamps (CFLs) to replace of incandescent lamps producing efficiency improvement by 75%. Since two-thirds of the electricity in the world is used to run motors and 20% of the electricity in the world is used for lighting, the availability of IGBTs has produced a cumulative electrical energy savings of more than 50,000 terawatt hours. In addition, the IGBT enabled the introduction of the electronic ignition system for running spark plugs in the internal combustion engine of gasoline powered cars and trucks. The resulting 10% improvement in fuel efficiency has saved consumers more than one trillion gallons of gasoline during the last 20 years. The cumulative impact of these electrical energy and gasoline savings is a cost savings of over $15 trillion for consumers, and a reduction in carbon dioxide emissions from coal-fired power plants by over 75 trillion pounds. For this achievement, he has been labeled the "man with the smallest carbon footprint on earth." Most recently, the IGBT has enabled creation of very compact, light-weight, and inexpensive defibrillators used to resuscitate cardiac arrest victims. Deployment of these portable defibrillators in fire-trucks, paramedic vans, in buildings, and on-board airlines, is projected by the American Medical Association (AMA) to save 100,000 lives per year in the US. For this work, *Scientific American Magazine* named him one of the *Eight heroes of the semiconductor revolution* in their 1997 special issue commemorating the solid-state century.

Dr Baliga is also the originator of the concept of merging Schottky and pn junction physics to create a new family of JBS power rectifiers that are commercially available from various companies. This concept originally implemented for silicon devices has become an essential concept for the commercialization of silicon carbide high-voltage Schottky rectifiers.

In 1979, Dr Baliga developed a theoretical analysis resulting in the Baliga's Figure of Merit (BFOM) which relates the resistance within power rectifiers and FETs to the basic semiconductor properties. He predicted that the performance of Schottky power rectifiers and power MOSFETs could be enhanced by several orders of magnitude by replacing silicon with other materials such as gallium arsenide and silicon carbide. This is forming the basis of a new generation of power devices in the twenty-first century.

In August 1988, Dr Baliga joined the faculty of the Department of Electrical and Computer Engineering at North Carolina State University, Raleigh, North Carolina, as a full professor. At NCSU, in 1991 he established an international center called the *Power Semiconductor Research Center (PSRC)* for research in the area of power semiconductor devices and high-voltage integrated circuits, and has served as its founding director. His research interests include the modeling of novel device concepts, device fabrication technology, and the investigation of the impact of new materials, such as GaAs and silicon carbide, on power devices. The first high-performance SiC Schottky rectifiers and power MOSFETs were demonstrated at PSRC in the 1990s resulting in the release of products by many companies during the last 10 years.

In 1997, in recognition of his contributions to NCSU, he was given the highest university faculty rank of *Distinguished University Professor of Electrical Engineering*. In 2008, Prof. Baliga was a key member of an NCSU team—partnered with four other universities—that was successful in being granted an Engineering Research Center from the National Science Foundation for the development of micro-grids that allow integration of renewable energy sources. Within this program, he is responsible for the fundamental sciences platform and the development of power devices from wide-band-gap semiconductors for utility applications.

Prof. Baliga has received numerous awards in recognition for his contributions to semiconductor devices. These include two *IR 100 awards* (1983, 1984), the *Dushman* and *Coolidge Awards* at GE (1983), and being selected among the *100 Brightest Young Scientists in America* by Science Digest Magazine (1984). He was elected *Fellow of the IEEE* in 1983 at the age of 35 for his contributions to power semiconductor devices. In 1984, he was given the *Applied Sciences Award* by the world famous sitar maestro Ravi Shankar at the Third Convention of Asians in North America. He received the 1991 IEEE William E. Newell Award, the highest honor given by the Power Electronics Society, followed by the 1993 IEEE Morris E. Liebman Award for his contributions to the emerging *Smart Power Technology*. In 1992, he was the first recipient of the BSS Society's *Pride of India Award*. At the age of 45, he was elected as Foreign Affiliate to the prestigious National Academy of Engineering, and was one of only four citizens of India to have the honor at that time (converted to regular Member in 2000 after taking US Citizenship). In 1998, the University of North Carolina system selected him for the *O. Max Gardner Award*, which recognizes the faculty member among the 16 constituent universities who has made the greatest contribution to the welfare of the human race. In December 1998, he received the IEEE J.J. Ebers Award, the highest recognition given by the IEEE Electron Devices Society for his technical contributions to the solid-state area. In June 1999, he was honored at the Whitehall Palace in London with the IEEE Lamme Medal, one of the highest forms of recognition given by the IEEE Board of Governors, for his contributions to development of an apparatus/technology of benefit to society. In April 2000, he was honored by his Alma Mater as a *Distinguished Alumnus*. In November 2000, he received the *R.J. Reynolds Tobacco Company Award for Excellence in Teaching, Research, and Extension* for his contributions to the College of Engineering at North Carolina State University. In 2011, Dr Baliga was selected to receive the *Alexander Quarles Holladay Medal for Excellence*, which recognizes members of the NCSU faculty who over their careers have made outstanding contributions to the University through their research, teaching, and extension services.

In 1999, Prof. Baliga founded a company, *Giant Semiconductor Corporation*, with seed investment from Centennial Venture Partners, to acquire an exclusive license for his patented technology from North Carolina State University with the goal of bringing his NCSU inventions to the marketplace. A company, *Micro-Ohm Corporation*, subsequently formed by him in 1999, has been successful in licensing the GD-TMBS power rectifier technology to several major semiconductor companies for world-wide distribution. These devices have application in power supplies, battery chargers, and automotive electronics. In June 2000, Prof. Baliga founded another company, *Silicon Wireless Corporation*, to commercialize a novel superlinear silicon RF transistor that he invented for application in cellular base-stations and grew it to 41 employees. This company (renamed *Silicon Semiconductor Corporation*) is located at Research Triangle Park, NC. It received an investment of $10 million from *Fairchild Semiconductor Corporation* in December 2000 to co-develop and market this technology. Based upon his additional inventions, this company has also produced a new generation of power MOSFETs for delivering power to microprocessors in notebooks and servers. This technology was licensed by his company to Linear Technologies Corporation with transfer of the know-how and manufacturing process. Voltage regulator modules (VRMs) using his transistors are currently available in the market for powering microprocessor and graphics chips in laptops and servers.

In 2010, Dr Baliga was inducted into the Engineering Design Magazine's Engineering Hall of Fame for his invention, development, and commercialization of the IGBT, joining well-known luminaries (e.g., Edison, Tesla, and Marconi) in the electrical engineering field. The award announcement states: *While working at General Electric in the late 1970s, Baliga conceived the idea of a functional integration of MOS technology and bipolar physics that directly led to the IGBT's development … it remains undeniable that Baliga's vision and leadership played a critical role* *in moving the IGBT from a paper-based concept to a viable product with many practical applications.*

President Obama personally presented Dr B. Jayant Baliga with the National Medal of Technology and Innovation, the highest form of recognition given by the United States Government to an Engineer, in a ceremony at the White House on October 21, 2011. Dr Baliga's award citation reads: For development and commercialization of the Insulated Gate Bipolar Transistor and other power semiconductor devices that are extensively used in transportation, lighting, medicine, defense, and renewable energy generation systems. His IGBT innovation has saved world-wide consumers $15 trillion while reducing carbon dioxide emissions by 75 trillion pounds over the last 20 years.

In October 2012, Governor Beverly Purdue presented Dr Baliga the North Carolina Award for Science. This is the highest award given by the State of North Carolina and the Governor to a civilian. On October 4, 2013, he was inducted into the Rensselaer Alumni Hall of Fame by Rensselaer Polytechnic Institute President Shirley Jackson. The ceremony included unveiling his portrait etched on a window in Thomsen Hall in the Darrin Communications Center.

On August 23, 2014, Dr Baliga received the IEEE Medal of Honor *For the invention, implementation, and commercialization of power semiconductor devices with widespread benefits to society* in a ceremony held in Amsterdam, The Netherlands. This award has been given since 1917 to recognize great achievements in the field of electrical engineering.

Foreword

When I joined the General Electric Company R&D Center in 1970, the world of power electronics was a completely different environment than exists today. There I worked under the tutelage of some of the legends of power electronics such as Bill McMurray, Bernie Bedford, Fred Turnbull, and many others. Those days were still during the era of thyristor technology, dating from 1956, in which the inverters of its day called upon the use of resonant circuits to turn off the thyristors. The McMurray–Bedford inverter, McMurray inverter, and Verhoef inverter were just some of the developments during this period. Because of the numerous modes of operation (leading or lagging power factor, no load or full load, low or high frequency, etc.), analyses of these circuits were both at one time a nightmare and a joy to those who loved to solve differential equations!

While some solutions for self-switching were being attempted at the time (e.g., FETs—small power only, Darlington BJTs—heavy monstrous bricks), they seemed to be going nowhere. This era ended in the late 1970s when it was announced by corporate management in the GE R&D center that a new switching device had been developed at the R&D Center by Jay Baliga, which removed the need for the turnoff resonant circuit and achieved turnoff with an FET style gate pulse. By the mid-1980s, some of the remaining problems with this device had been solved (latch-up and secondary breakdown) and a new era of power electronics was set in motion. In the last 30 years we have seen continuous expansion of IGBT technology, with the aid of 6000 V devices, even into high-voltage DC applications. To think that a turnoff device could ever make inroads into that last bastion of thyristor technology, i.e., HVDC power conversion, would make one's head spin in 1970. We have all benefitted greatly by Prof. Baliga and those of his contemporaries working in the field of solid-state device technology. In this book, we learn from the master.

Thomas A. Lipo
University of Wisconsin
Madison, WI, USA

Preface

In 1977, I submitted a patent disclosure on vertical MOS-gated thyristors that contains the basic IGBT structure while working for the General Electric (GE) Company. After developing a V-grove process for making the structure, the fabrication of the devices was started in November 1978 and completed in July 1979. In addition to the latched-up thyristor mode of operation, my measurements clearly showed the IGBT-mode of operation. In response to the need for an improved power switch for adjustable speed drives for heat pump applications by GE, I prepared a patent disclosure in September 1980 that described all the characteristics for the IGBT that we now take for granted. It was immediately apparent that this new device would have a widespread impact on the company's products in the small appliance, large appliance, medical, factory automation, and lighting business units. Due to its impact across the company, my proposal received the attention of the Chairman Jack Welch who supported its commercialization. I was fortunately able to deliver a 600-V, 10-A IGBT within a year by fabricating the device in the existing power MOSFET production facility with my chip and process design which included suppression of the latch-up of the parasitic thyristor. I simultaneously developed an electron irradiation lifetime control process with a unique annealing step that healed the damage created by electron irradiation to the gate oxide. This allowed production of IGBTs optimized for a wide range of switching frequencies and applications. The availability of these IGBTs spurred power electronics designers to rapidly apply them to a large variety of products at GE. GE eventually announced the commercially available IGBT product in 1983. This prompted a worldwide interest in the manufacturing of the device leading to products from other companies after 1985.

A few years ago, the new Department Head for the Electrical and Computer Engineering Department at North Carolina State University suggested that I prepare a report about the impact of my work on the IGBT to post it on our Website. The outcome of my effort was a 140-page document, with over 300 references, titled: "The IGBT Compendium: Applications and Social Impact." GE had recognized the impact of the IGBT on most of the company's product divisions immediately after my invention of the device. I was personally involved with the design of IGBTs suitable for GE's adjustable speed drives for Trane and Carrier air-conditioners (heat-pumps), for GE's early efforts on creating more efficient lighting products, and a variety of small and large appliance controls. However, preparing the report on the IGBT after a time span of 30 years was a voyage of discovery. It was apparent that the IGBT had now penetrated literally every sector of the economy and enhanced the comfort, convenience, and health for billions of people around the globe.

Improving the efficiency for power management and delivery is in the very nature of power electronics and it is well recognized that power semiconductor devices play a dominant role in achieving this outcome. However, the impact of the improvements in efficiency on power savings had not been quantified using a rigorous methodology. Without this metric, it was also not possible to evaluate the environmental consequences of this technology. Since two-thirds of the electricity in the world is used to run motors, I decided to quantify the power savings derived from IGBT-based adjustable speed drives for motors. In addition, since one-fifth of the electricity in the world is used for lighting, I decided to quantify the impact of compact fluorescent lamps (CFLs) because IGBTs are used in the electronic ballast. The third sector of the economy which has benefitted from IGBTs was the transportation sector. It became quickly apparent that the electronic ignition systems, enabled in the late 1980s with the availability of the IGBT, for controlling the spark plugs of internal combustion engines in cars and trucks had enhanced fuel efficiency. With the huge quantities of gasoline consumed around the world, it became important to quantify the impact of this innovation. With just these three applications of the IGBT, I determined that society had derived a savings of over 50,000 terawatt hours in electricity consumption (equivalent to not building 600 coal-fired power plants) and over 1 trillion gallons of gasoline consumption. This had not only saved worldwide consumers more than $15 trillion but reduced carbon dioxide emissions by more than 75 trillion pounds over the period from 1990 to 2010.

In 2012, I was encouraged by colleagues to consider writing a book on the IGBT with the above report as a foundation. My reaction was a proposal for creating a comprehensive book on the IGBT that firstly includes the device operation, device chip design, device fabrication technology, device packaging, and gate drive circuits; and then provides an extensive discussion of its applications in all sectors of the economy with elaboration of the circuit topologies used in each case and the optimized IGBT device structures developed by the power semiconductor industry for each application. I was very pleased that the editors at Elsevier Inc. found my proposal compelling. The reaction from the reviewers of my IGBT book proposal was also very positive with the suggestion that I include a discussion of how the IGBT was invented, developed, and successfully commercialized by me in the early 1980s.

This book is the result of two years of my effort to create a single resource for the reader regarding the operation and design of the IGBT as well as its social impact. The first chapter provides a high-level perspective of the applications of the IGBT and its power ratings. It includes a discussion of the history behind the conception of the device and its commercialization. The second chapter describes various IGBT structures that have evolved over the years. The very first IGBT developed by me at GE in 1981 was a 600-V symmetric blocking device followed soon after with the 600-V asymmetric blocking devices. The power semiconductor manufacturers focused their attention on the asymmetric structure for motor drive applications during the next 20 years. More recently, interest in the symmetric blocking IGBT has been generated by its use for current source inverters and matrix