Photovoltaic Science and Technology

Solar Photovoltaics (SPV) forms an integral part of renewable energy systems that are crucial for combating global warming. Given the widespread availability of solar energy, direct conversion to electricity has the advantages of easy installation, modular nature ranging from small to large scale power generation, low maintenance costs and a long life of more than 25 years. Solar PV has become more attractive over the last decade due to increasing efficiency and fast reduction of cost per kWh. This book presents a comprehensive coverage of the science and technology of SPV. The initial chapters introduce the basic physical principles, bulk and thin film materials used for solar cells, and the design and efficiency considerations. Concentrator and tandem cells are discussed along with recent advances using perovskite and organic cells.

The text discusses thoroughly the technology behind the production of, both, SPV cells and modules. These aspects are related to the efficiency, overall cost, balance-of-system (BOS), energy payback time and financing considerations. A dedicated chapter covers details of characterization, testing and reliability of SPV modules. The contents of the book have been enriched with experimental data and models. Several aspects such as cell and module manufacture, characterization, testing, reliability and system design are described taking into account commercial SPV manufacturing plants. Photovoltaic applications are explained for different types of SPV systems: from grid-connected to stand-alone, with plenty of solved examples and exercises for readers.

J. N. Roy is Visiting Professor at the Advanced Technology Development Centre (ATDC) and School of Energy Science and Engineering (SESE) at the Indian Institute of Technology Kharagpur. He teaches courses relating to SPV and microelectronics including IC fabrication, device modeling, circuit simulation and modeling. He has co-authored the book *Introduction of VLSI Design and Technology*. He is a Senior Member of IEEE and Fellow of Indian Microelectronics Society (IMS) and Indian National Academy of Engineering (INAE).

D. N. Bose is a leading researcher on Semiconductor Materials and Devices. He was an ICI scholar at the University of Reading and obtained his PhD in Semiconductor Physics in 1965. At the Indian Institute of Technology Kharagpur (1977–98), his group successfully completed major SPV projects on ‘Polycrystalline Silicon from rice-husk’ and ‘Study of PEC solar cells using III–V compounds and ternary alloys’. In 1982, as a Visiting Professor at the University of Neuchatel, Switzerland, he gave a course of 32 lectures on ‘The Physics and Technology of Solar Cells’. He was a Visiting Professor at Virginia Polytechnic Institute, USA (1985–86) and a Visiting Scientist at MIT, USA, in 2003. He has more than 200 publications in various international journals and conferences. He is a Senior Member of IEEE. He was elected Fellow of the Indian Academy of Science and the National Academy of Science. Presently he is Visiting Professor at St. Xavier’s College, Kolkata.

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To Mahua, my loving wife and companion for more than 32 years.

— J. N. Roy

To my students at the Indian Institute of Technology, Kharagpur and the Indian Institute of Science, Bangalore.

— D. N. Bose

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Preface

The growth and demand for Solar Photovoltaic (SPV) energy systems has been strong and in line with the increasing importance of renewable energy. Worldwide demand and production of SPV systems has been growing at a compound annual growth rate of more than 30% over the last decade. There have been significant advances in technology, spanning the entire value chain consisting of solar cells, modules and balance-of-system (BOS) components. This has resulted in an increase in efficiency and a significant cost reduction over the years, making SPV systems viable both in small stand-alone and large grid-connected applications.

Solar energy, which is the Earth's most available energy source, can be converted to electricity providing scalable and clean power requiring minimal maintenance. This book deals with the subject of Solar Photovoltaics in some detail covering the basics as well as advanced topics. All the important areas of SPV, covering both science and technology, have been addressed in this book. Commencing with the basic principles, different types of solar cells from bulk silicon (Si) to thin film cells are described comprehensively. Tandem concentrator cells now provide the highest efficiencies of 43%. Newer low cost alternatives, such as organics and perovskites, are also discussed. Manufacturing details have been covered in great detail. The basic cost and investment calculations of SPV manufacturing and systems leading to economic viability have also been included. These aspects are generally not covered in most of the books published in this field. Several practical and state-of-the art manufacturing and system design details have been presented based on the experience of one of the authors (J. N. Roy). This book should be useful for students studying this important subject, who eventually want to pursue careers in this field. The book should be also useful for researchers and industry personnel who want to have a thorough understanding of the subject. Each chapter has illustrations and tables. There are several examples and exercises throughout the book to help consolidate thorough learning of the subject.

Chapter 1 presents a general introduction to the subject of solar energy in the context of global warming. Solar insolation and distribution are presented and some basic terms are defined. This is followed by the principles of operation of SPV devices, device characteristics, criteria for choice of materials, and critical parameters for efficient operation. Different types of cells are introduced and the invention of Si and CdS-based PV cells described.

Chapter 2 deals with the dominant type of PV cells viz. c-Si and mc-Si that presently have 85% of market share. Starting with the often-neglected subject of the production of semiconductor-grade polysilicon, this chapter discusses single crystal growth, directional solidification and properties of single crystal vs multi-crystalline silicon materials and solar cells. These growth techniques were perfected in the laboratory of one of the authors (D. N. Bose). Progress in thin film silicon cells and structure and performance of a few high-efficiency Si cells are also discussed.

In Chapter 3, thin film solar cells, alternatives to cells based on bulk Si, are compared with reference to their advantages and disadvantages. The principal types are amorphous Si (a-Si), CdS-CIGS and CdS-CdTe, whose operation and performance are described. New emerging types include Earth-abundant CZTE and newly discovered perovskite cells. Stability is a major concern especially for a-Si and for perovskite cells. The physics and operating principles of these materials have novel features, not incorporated so far in textbooks.

Chapter 4 deals with special type of thin film cells based on III-V compounds GaAs, InP and their alloys, capable of highest efficiencies. These cells are grown epitaxially on single crystal substrates by MOVPE, a technique employed in the laboratory of one of the authors (D. N. Bose). When used in tandem, these cells form the basis of concentrator solar cells that operate at higher temperatures and require Sun tracking. The PEC cells developed in the laboratory of one of the authors (D. N. Bose) are another type that use semiconductor materials as photoelectrodes immersed in a suitable electrolyte. An example is dye-sensitized TiO_2 cells called Grätzel cells. Though simple in concept, these cells still have stability problems.

Chapter 5 describes the operation of novel solar cells based on polymers and organic materials whose principles of operation are presented. Illumination results in the generation of bound excitons in these materials that decay into free carriers. The cells may be classified into bulk and heterojunction types and can consist of organic/inorganic composites and nanocrystals. These cells are projected to have advantages of low-cost methods of preparation over large areas. Their laboratory efficiencies are rising rapidly, but environmental stability remains a challenge.

Chapter 6 covers the manufacturing details of important types of solar cells. One of the authors (J. N. Roy) has experience of setting up and running a cell manufacturing plant. Characterization techniques, which are an integral part of the manufacturing, have also been discussed in some detail. Apart from c-Si, high efficiency multi-junction (MJ) cell manufacturing has also been addressed. Chapter 7 deals with module manufacturing starting with c-Si. Other thin film SPV manufacturing processes, including those for a-Si, CIGS and CdTe, have also been described in this chapter. Some of the detailed modelling, such as high voltage insulation, cell-to-module (CTM) conversion loss, are based on one of the author's (J. N. Roy) experience during his tenure in a reputed SPV company. The cost structure and selling price have been explained so that these important aspects are kept in mind during technology development and manufacturing.

Chapter 8 discusses, in detail, characterization techniques employed during SPV module manufacturing. Electrical testing, which is the most important aspect of SPV characterization, has been discussed separately, giving details of some of the popular testers, known as 'Sun Simulators', used for R&D and high volume manufacturing. The reliability and certification standards have also been discussed in this chapter. Reliability prediction through modelling and reliability tests and standards presently employed for SPV industry has been discussed in some detail. Since the authors have significant expertise in the field of VLSI, a comparison with the reliability test and standards employed in the VLSI industry has been highlighted in this chapter. Important topics such as potential induced degradation (PID), which has recently been found to cause reliability problems, have also been taken up in this chapter. Such a comprehensive coverage of the subjects covered in this chapter is probably not available in any other book.

Chapters 9 and 10 cover the design and implementation of SPV systems. The introduction of SPV systems is presented in Chapter 9. The cost aspects, which are very important for the viability and return-of-investment (ROI) point of view, are discussed taking some real life examples. Simple methods of energy calculation, which have been widely used for smaller systems, have been elaborated on with practical examples. This chapter is intended to give an overview of SPV systems. Specific design details of important BOS components have been discussed in Chapter 10. Energy calculations, benchmarking, viability, etc. of large SPV systems have been dealt with in detail in this chapter. These chapters (9 and 10) together give a comprehensive overview covering all categories of SPV systems.

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Although the materials presented in this book are primarily based on my learning at Solar Semiconductor Inc., the tenure at IIT Kharagpur helped me a great extent to decide about the final content and presentation style. The class notes for teaching and interaction with students had a great influence on the final shape of my portion of the manuscript. I am thankful to all my students and the faculty colleagues in Energy School (SESE) at IIT Kharagpur. I am also thankful to the present IIT Kharagpur Director, Professor P. P. Chakraborty, popularly known as PPC, for giving me a conducive atmosphere for writing this book.

Encouragement from my family, particularly my wife Mahua and daughter Sanjukta (Puja), played a motivating role for taking up writing my second book. My first book in the area of VLSI was also jointly written with Professor D. N. Bose, who was my mentor during my doctoral work at IIT Kharagpur. His deep knowledge of the subject has always inspired me. I deeply acknowledge his support for reviewing my part of the manuscript and providing valuable inputs.

J. N. Roy

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D. N. Bose