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Solar Cells and Their Applications

SECOND EDITION

LEWIS FRAAS • LARRY PARTAIN

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SOLAR CELLS AND THEIR APPLICATIONS

Second Edition

Edited by

LEWIS FRAAS

LARRY PARTAIN

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SOLAR CELLS AND THEIR APPLICATIONS

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KAI CHANG, Editor
Texas A&M University

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Preface

This Second Edition is intended to be a comprehensive survey, review, and analysis of all the major factors related to the continuing technical development of solar cell electricity and its market development into a major worldwide source of electric power in response to powerful political and economic influences. It is divided into six major sections plus a Summary section including conclusions and recommendations.

In contrast to the First Edition, Part I contains three initial chapters written so that nonspecialists and the more general readers and investors and policy makers can follow their contents without the need for specialized training or understanding. The goal is to allow a broad spectrum of readers to at least comprehend the market history, the influence of public policy, the likely costs of solar cell-generated electricity, and the special role that near-perfect, single-crystal semiconductor fabrication materials can have on overall performance. Chapter 4 in this part, on Solar Cell Device Physics (like the First Edition), is again aimed at advanced undergraduate and graduate college courses and other technical professionals involved in teaching, research, and commercial development. It not only covers the traditional abrupt p/n junction configuration of the First Edition but also expands into the very non-abrupt p-i-n geometries that characterize a whole new class of high-performance solar cells including interdigitated back-contact cells, point-contact cells, and heterojunction-with-intrisinsic-thin-layer (HIT) cells. It further addresses the special resistive restrictions that can limit p-i-n-type device performance as well as proposed paths to performance levels well beyond 50% efficiency levels. However, to maintain a reasonable length, this physics chapter does use the First Edition as a reference.

Part II addresses the current state of terrestrial solar cell electricity technology and development programs. This includes the dominant crystalline silicon abrupt p/n junction devices and their large-scale fabrication and the emerging thin-film amorphous and polycrystalline semiconductor cells and modules. The amazing recent growth of the Chinese terrestrial solar cell program is presented in some detail. The potential advantages of tracking the sun are explored along with a detailed description of 3 years of field experience with fixed-axis crystalline silicon modules of 12% efficiency (under standard test conditions) in the Arizona desert. The emerging utility-scale installations are summarized along with their important cost-determining characteristics.

Part III attempts to present a comprehensive overview of the terrestrial concentrator approach to solar cell electricity production and its special advantages and challenges. This includes both low and high sunlight concentration levels with various system approaches as well as early results of small field tests at the University of Nevada and of substantial utility-scale field tests of multiple and varied concentrator systems in Spain.

Part IV takes a broad look at space systems and all of the unique approaches, needs, accomplishments, plans, and future needs for space.

Part V contains a chapter giving precise descriptions of the solar resource both terrestrially and in space. It also contains a chapter describing a sophisticated and detailed cost and performance model from the National Renewable Energy Laboratory (NREL). This Solar Advisor Model is reviewed and summarized. Finally, the special challenges of large-scale solar electricity production are explored.

Part VI is a special four-chapter addition of the Second Edition that discusses how thin-film solar cells can be transformed into X-ray imaging devices when devices are reduced to submillimeter sizes and are aligned in columns and rows that are covered by a scintillator film that converts X-ray photons into visible light photons. If these are then attached to an array of the thin-film transistor switches, a flat-plate X-ray imager is produced. The market analysis of this whole X-ray imager field shows that its current market size of $2 billion per year should continuously evolve into a $15 billion per year wholesale market over the next 10 years or so as these devices continually improve in performance and drop in price.

The final chapter summarizes the amazing growth of this solar cell electricity technology and market over the 15 years since the publication of the First Edition. It provides recommendations for how major countries and unions can play major roles from both technology and public policy perspectives and how continuing cost reduction and improved performance demands should be met under both near- and medium-term time frames.

In summary, this book describes today's baseline planar solar cell power systems as well as innovations in high-efficiency solar cells and concentrated sunlight systems that have occurred in the last 15 years, which now promise lower cost electricity competitive with other mainstream electric power sources.

In addition to describing these technical breakthroughs in clear and simple terms, this book also describes the path from research breakthrough to high-volume production, emphasizing the cooperation required between government and private enterprise. Given this cooperation, solar cells can be a major contributor to the electric power production mix within the next 10 years.

This book has been written for a large audience, not just a technical audience. It is hoped that any educated reader will find this book interesting, especially any reader who seeks to understand how the world's energy supply problems can be increasingly addressed by exploiting direct solar energy resources available within a country's borders. It further describes how most countries can start moving away from increasingly intense competition for decreasing depletable energy supplies and how they can continue moving toward a long-term, sustainable solution with inherently positive attributes.

The thesis of this book is that solar energy can be cost competitive with other forms of electric power production and that the technical innovations required for this have already been made. Incentives for investment are needed to bring these innovations into high-volume production. It is hoped that this book will help educate the public, possible investors, as well as policy makers worldwide about the potential for a bright sunny energy future.

Lewis Fraas
Issaquah, WA

Larry Partain
Mountain View, CA

Contributors

Sheila Bailey, NASA Glenn Research Center at Lewis Field, Space Environments and Experiments Branch, Cleveland, OH; email: sheila.g.bailey@nasa.gov

Pedro Banda, Instituto de Sistemas Fotovoltaicos de Concentración (ISFOC) S.A., Puertollano (Ciudad Real), Spain; email: pbanda@isfoc.com

Andreas Bett, Fraunhofer Institut für Solare Energiesysteme (ISE), Freiburg, Germany; email: olandreas.bett@ise.fraunhofer.de

Robert Birkmire, Institute of Energy Conversion, University of Delaware, Newark, DE; email: rwb@udel.edu

Nathan Blair, National Renewable Energy Laboratory, Golden, CO; email: Nate_Blair@nrel.gov

Chuck Blouir, Varian Medical Systems, Cleveland, OH; email: chuck.blouir@varian.com

Robert Boehm, Center for Energy Research, Department of Mechanical Engineering, University of Nevada, Las Vegas, NV; email: rboehm@unlv.nevada.edu

Christopher Bunner, Spire Corporation, Bedford, MA; email: cbunner@spirecorp.com

Christopher Cameron, Sandia National Laboratories, Albuquerque, NM; email: cpcamer@sandia.gov

Matthew Campbell, Utility Power Plant Products, SunPower Corporation, Richmond, CA; email: Matt.Campbell@sunpowercorp.com

Richard Colbeth, Varian Medical Systems, Mountain View, CA; email: richard.colbeth@varian.com

Elmer Collins, Sandia National Laboratories, Microsystems Science & Technology, Albuquerque, NM; email: ewcolli@sandia.gov

Ron Corio, Array Technologies, Inc., Albuquerque, NM; email: rcorio@wattsun.com

David Faiman, Department of Solar Energy and Environmental Physics, Jacob Blaustein Institutes for Desert Research, Ben-Gurion University of the Negev, Israel; email: faiman@bgu.ac.il

Lewis Fraas, President, JX Crystals Inc., Issaquah, WA; email: lfraas@jxcrystals.com

Paul Gilman, Consultant, Chicago, IL; email: paulgilman@earthlink.net

Christian A. Gueymard, Solar Consulting Services, Colebrook, NH; email: Chris@SolarConsultingServices.com

Geoffrey Kinsey, Amonix, Inc., Seal Beach, CA; email: GKinsey@amonix.com

Carl LaCasce, Varian Medical Systems, Salt Lake City, UT; email: carl.lacasce@varian.com

Michael Ludowise, SolFocus, Inc., Mountain View, CA; email: mike_ludowise@solfocus.com

María Martínez, Instituto de Sistemas Fotovoltaicos de Concentración (ISFOC) S.A., Puertollano (Ciudad Real), Spain; email: mmartinez@isfoc.com

Larry Moore, Sandia National Laboratories, Microsystems Science & Technology, Albuquerque, NM

Daryl Myers, National Renewable Energy Laboratory, Golden, CO; email: Daryl.Myers@nrel.gov

Larry Partain, Varian Medical Systems, Mountain View, CA; email: larry.partain@varian.com

Gerhard Peharz, Fraunhofer Institut für Solare Energiesysteme (ISE), Freiburg, Germany; email: gerhard.peharz@ise.fraunhofer.de

Ryne Raffaelle, U.S. Department of Energy, National Center for Photovoltaics, National Renewable Energy Laboratory, Golden, CO; email: Ryne.Raffaelle@nrel.gov

Michael Reed, Array Technologies, Inc., Albuquerque, NM; email: mreed@arraytechinc.com

Leonid Rubin, Day4 Energy Inc., Burnaby, BC, Canada; email: lrubin@day4energy.com

Francisca Rubio, Instituto de Sistemas Fotovoltaicos de Concentración (ISFOC) S.A., Puertollano (Ciudad Real), Spain; email: frubio@isfoc.com

Suresh Sadineni, Center for Energy Research, Department of Mechanical Engineering, University of Nevada, Las Vegas, Las Vegas, NV; email: sbsadineni@yahoo.com

Wang Sicheng, Energy Research Institute, National Development and Reform Commision, Beijing, China; email: wangsc@eri.org.cn

Jason Strauch, Sandia National Laboratories, Integrated Microdevice Systems, Microsystems Science & Technology, Albuquerque, NM; email: jestrau@sandia.gov

Robert Street, Palo Alto Research Center, Palo Alto, CA; email: street@parc.com

George Zentai, Ginzton Technology Center, Varian Medical Systems, Mountain View, CA; email: george.zentai@varian.com

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PART I

INTRODUCTION TO SOLAR CELLS

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SOLAR CELLS: A BRIEF HISTORY AND INTRODUCTION

LEWIS FRAAS[1] AND LARRY PARTAIN[2]
[1]*JX Crystals Inc.*, [2]*Varian Medical Systems*

1.1 BRIEF HISTORY

The history of the solar cell is really quite interesting [1]. In 1839, Edmond Becquerel found that two different brass plates immersed in a liquid produced a continuous current when illuminated with sunlight. We now believe that he had made a copper-cuprous oxide thin-film solar cell. Later in the 1870s, Willoughby Smith, W. G. Adams, and R. E. Day discovered a PV effect in selenium. A few years later, an American named C. E. Fritts placed a sheet of amorphous selenium on a metal backing and covered the selenium with a transparent gold leaf film. He reported that this selenium array produced a current "that is continuous, constant, and of considerable force—with exposure to sunlight." At the time, there was no quantum theory and there was considerable skepticism about his claim of converting sunlight into electricity. So he sent a sample to Werner Siemens in Germany, who was one of the most respected experts in electricity at the time. Siemens's observation verified Fritts's claims. However, the conversion efficiencies of both the thin-film cuprous oxide and the amorphous selenium solar cells were less than 1%.

Around 75 years passed while quantum mechanics was discovered, the importance of single-crystal semiconductors was recognized, and p/n junction behavior was explained (see Chapter 3). By 1954, Chapin et al. [2] at Bell Labs had discovered, invented, and demonstrated the silicon single-crystal solar cell with 6% efficiency. Over the few following years, researchers brought the silicon solar cell efficiency up to 15%. The timing was fortunate because Sputnik was launched in 1957 and solar cells were the perfect lightweight low-maintenance remote electric power source. Today, silicon solar cells are being used to power the space station.

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The solar cell industry remained small until the first Arab oil embargo in 1973. Up until that time, the solar cell industry established a firm foothold with low-level but consistent cell and array production and performance. During those first 20 years, reliability was the driver and cost was not as important. After 1973, the flat-plate silicon module was brought down to earth and modified for weather resistance. This transition also included major improvements in cell and module fabrication that brought down costs dramatically (Fig. 2.3, chapter 2). Flat-plate "champion" silicon cell efficiencies (defined in Section 2.1, Chapter 2) have improved to values as high as 25%. Production module efficiencies have improved from around 10% for early modules to as high as 19% today (SunPower Corporation). Most important, annual production quantities have grown dramatically. Worldwide production exceeded 1 GW/year in 2002 and rose to over 3.8 GW/year by 2006 (Fig. 2.1, Chapter 2).

In the late 1970s, it was discovered that good cells could be made with multicrystalline wafers as long as the crystal size is at least 20 times larger than the optical absorption length [3]. Only those carriers within an optical absorption length from the crystal boundaries are lost. This is less than 5% of the carriers. Typical production quantity multicrystalline cell efficiencies are around 14%, whereas comparable single-crystal cells have efficiencies around 15%. By 2007, modules with multicrystalline cells accounted for about 45% of sales and modules with single-crystal cells accounted for about 40% of sales. Planar silicon cell modules dominated the market in 2007 because of their early well-funded foundation years for space satellites and their huge learning curve support (Fig. 2.3, Chapter 2) from single-crystal silicon and integrated circuit technology development.

While silicon-based cells still dominate the solar cell electricity market today, several other cell types have now entered the market. (Solar cells are also known as PV cells.) These newer cell types have added diversity in potential applications as well as offered alternate paths to lower-cost solar electric power. These alternate cell types include hydrogenated amorphous silicon, cadmium teluride and CIGS thin-film cells (Chapter 6), as well as concentrator cells with efficiencies as high as 41% (Chapters 13–17).

1.2 APPLICATIONS AND MARKETS

In the late 1970s and early 1980s, the traditional solar cell electricity applications [4] were at remote locations where utility power was unavailable, for example, campers and boats, temporary power needs for disaster situations, and power for remote communication station repeaters. In the late 1980s and early 1990s, solar cells began to be routinely used to provide site-specific energy for urban and suburban homes, office buildings, and a multitude of other mainstream grid-connected applications. Also, solar cell electricity systems have become very important sources of energy in the developing world. Today, for an increasing number of power needs, solar cell electricity is the cheapest and best way to generate electricity.