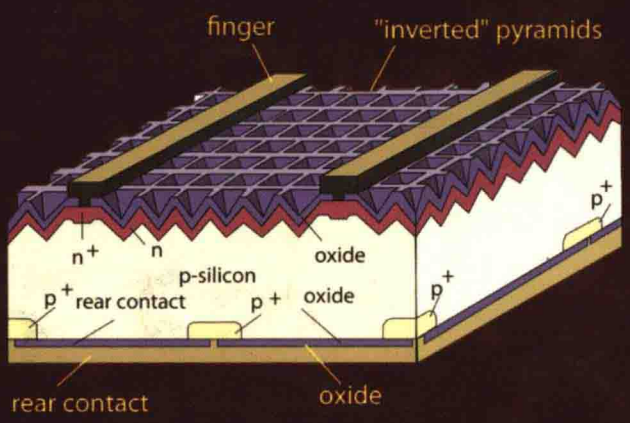
Series on Photoconversion of Solar Energy — Vol. 4

CLEAN ELECTRICITY FROM PHOTOVOLTAICS

2nd Edition



Mary D Archer and **Martin A Green** *Editors*

Imperial College Press

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ICP

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2nd Edition

SERIES ON PHOTOCONVERSION OF SOLAR ENERGY

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Vol. 1: Clean Electricity from Photovoltaics
eds. Mary D. Archer & Robert Hill

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Vol. 4: Clean Electricity from Photovoltaics, 2nd Edition
eds. Mary D. Archer & Martin A. Green

This volume is dedicated

to

Peter Theodore Landsberg

8 August 1922–14 February 2010

who saw so far beyond the detailed-balance limit

ABOUT THE AUTHORS

Mary Archer read chemistry at Oxford University and took her PhD from Imperial College London, in 1968. From 1968 to 1972, she did post-doctoral work in electrochemistry with Dr John Albery at Oxford, and she then spent four years at The Royal Institution in London, working with Lord Porter (then Sir George Porter) on photoelectrochemical methods of solar energy conversion. She taught chemistry at Cambridge University from 1976 to 1986. From 1991 to 1999, she was a Visiting Professor in the Department of Biochemistry at Imperial College London, and from 1999 to 2002, she held a Visiting Professorship at ICCEPT (Imperial College Centre for Energy Policy and Technology). She is President of the UK Solar Energy Society and the National Energy Foundation and a Companion of the Energy Institute. She was awarded the Melchett Medal of the Energy Institute in 2002 and the Eva Philbin Award of the Institute of Chemistry of Ireland in 2007. In 2012, she was appointed a Dame Commander of the British Empire for services to the UK National Health Service.

Christophe Ballif received his MSc and PhD degrees in physics from the Federal Polytechnic School of Lusanne, Switzerland, in 1994 and 1998, respectively, focusing on novel photovoltaic materials. Following post-doctoral research at the National Renewable Energy Laboratory, Golden, USA, on CIGS and CdTe solar cells, he moved to the Fraunhofer Institute for Solar Energy Systems, Freiburg, Germany, where he focused on crystalline silicon photovoltaics until 2003. He then joined the Swiss Federal Laboratories for Materials Testing and Research, Thun, Switzerland, before becoming a full professor at the Institute of Microengineering, University of Neuchâtel, Switzerland, in 2004. In 2009, the Institute of Microengineering was transferred to EPFL. He is the Director of the Photovoltaics and Thin-Film Electronics Laboratory in the Institute, and since 2013 he has also been the Director of the PV-Centre of the Swiss Centre for Electronics and Microtechnology (CSEM), Neuchâtel. His research interests include thin-film silicon, high-efficiency heterojunction crystalline cells, module technology, contributing to technology transfer, and industrialisation of novel devices.

Dieter Bonnet was born in Stuttgart, Germany, in 1937 and obtained his PhD on the photoelectric properties of organic materials at Frankfurt University in 1963. In 1965, he joined Battelle Institute in Frankfurt, where in 1968 he started work on thin-film solar cells based on II–VI compounds, including CdTe. In 1970, he made

the world's first CdTe/CdS thin-film solar cell in the presently known configuration. After a period working on other solar cell materials, he resumed work on CdTe technology in 1990, and initiated the successful EU (European Union) projects EUROCAD in 1992 and the CdTe interest group SOLARPACT in 2005. In 1993, he co-founded the pioneer company ANTEC GmbH to manufacture CdTe modules. In May 2001, the road in which ANTEC is located in Arnstadt, Germany, was named Dr. Bonnet Weg in honour of his accomplishments, and he was awarded the Becquerel Prize of the European Commission for outstanding achievements in photovoltaics in 2006. He retired in 2001 and is now an independent consultant.

Dan Credgington received his MSci in Natural Sciences from the University of Cambridge in 2004, and was awarded the Herchel Smith scholarship to study at Harvard University. In 2010, he obtained his PhD for work on the nanoscale microscopy and lithography of conjugated molecules from University College, London, under the supervision of Professor Franco Cacialli, and went on to conduct post-doctoral research on organic solar cells with Professor James Durrant at Imperial College London. He is currently a post-doctoral researcher in the group of Professor Sir Richard Friend at the Cavendish Laboratory of the University of Cambridge, where his interests lie in the study of recombination processes in organic light emitting diodes and solar cells, and hybrid organic/inorganic technologies.

Matthieu Despeisse received his degree in electrical engineering from INSA, Lyon, France, in 2002. He then joined CERN in Geneva, Switzerland, to work on low-noise, low-power and radiation-hard microelectronic circuits and silicon detectors. He obtained his PhD in 2006 for his work on amorphous silicon radiation sensors vertically integrated onto integrated circuits. He then pursued a fellowship from 2006 to 2008 at CERN, working on the design of a beam tracker and the transfer of CERN technologies to medical imaging and biotechnologies. He worked on fast Si 3D sensors, SiPM for PET-scan imaging, MCP-based systems for time-resolved spectroscopy, and high-speed readout electronics. He then joined the PVLAB group of Professor Christophe Ballif, which was part of the University of Neuchâtel, Switzerland, until 2009 and of the Federal Polytechnic School of Lusanne since then. He worked first on the development of amorphous and microcrystalline silicon and silicon alloys, thin-film silicon (TF-Si) single, tandem and triple junction solar cells and metrology equipment. He then became R&D manager of the PVLAB TF-Si activities, leading a research team of 15 people providing innovation to enhance performance and lower the costs of TF-Si PV. Since January 2013, he has headed research activities on crystalline silicon solar cells developments at the CSEM PV-Centre, in Neuchâtel, with special focuses on silicon heterojunction technology, passivating contacts and metallisation. He has

authored or co-authored more than 70 papers in peer-reviewed journals, and he is inventor/co-inventor on 5 patents/patent applications.

James Durrant is Professor of Photochemistry in the Department of Chemistry at Imperial College London. After completing his undergraduate studies in physics at the University of Cambridge, he obtained a PhD in biochemistry at Imperial College London, in 1991, studying the primary reactions of plant photosynthesis. After post-doctoral positions and a BBSRC Advanced Fellowship, he joined the Chemistry Department at Imperial College in 1999, taking up his current post in 2005. His additional responsibilities include being Deputy Director of Imperial's Energy Futures Lab 2009–2014 and, from 2013, Sêr Cymru Solar Professor, University of Swansea. His interests are in photochemical approaches to solar energy conversion, including both excitonic solar cells and solar-driven fuel synthesis (artificial photosynthesis). He has published over 280 research papers and was awarded the 2012 Tilden Prize by the Royal Society of Chemistry.

Ned Ekins-Daukes is a Senior Lecturer in the Department of Physics of Imperial College London. He is also director of the IC Energy Futures Centre for Doctoral Training. He researches high efficiency, 'third generation' approaches to photovoltaic energy conversion, in particular III–V multijunction solar cells, intermediate-band and hot-carrier solar cells. He also works on modelling the energy yield from III–V solar concentrator systems. He previously worked in Australia as a lecturer at the School of Physics at the University of Sydney, and later as a visiting research fellow at the ARC Photovoltaics Centre of Excellence, UNSW. Prior to that, he was a JSPS research fellow at the Toyota Technological Institute, Japan.

Timothy Gessert is a Principal Scientist in the National Center for Photovoltaics at the National Renewable Energy Laboratory (NREL) in Golden, Colorado. He holds degrees in physics from the University of Wisconsin-River Falls (BSc), Colorado School of Mines (MSc), and University of Wales — College of Cardiff (PhD). He joined NREL (then known as the Solar Energy Research Institute — SERI) in 1983 where he has worked on various aspects of photovoltaic and thermophotovoltaic devices related to GaAs, InP and CdTe material systems. Activities have also included the development of vacuum and photolithographic processes, transparent-conducting oxides and related electrical contacts. His current research is directed at understanding how choices in processes and device design affect the dominant defects and ultimate performance/stability of thin-film photovoltaic devices. Apart from these research activities at NREL, he is active in the American Vacuum Society, the Materials Research Society and the IEEE. He also teaches specialised

courses on photovoltaics and vacuum technology for professional societies and academic institutions.

Michael Grätzel is a Professor at the Federal Polytechnic School of Lusanne, where he directs the Laboratory of Photonics and Interfaces. He pioneered studies of mesoscopic materials and their use in energy conversion systems, in particular photovoltaic cells and photoelectrochemical devices for the solar generation of chemical fuels, as well as lithium ion batteries. He discovered a new type of solar cell based on sensitised nanocrystalline oxide films. His most recent awards include the Leonardo Da Vinci Medal of the European Academy of Science, the Marcel Benoist Prize, the Albert Einstein World Award of Science, the Paul Karrer Gold Medal, the Balzan Prize and the 2010 Millennium Technology Grand Prize. He received a doctoral degree in Natural Science from the Technical University Berlin and holds honorary doctorates from ten European and Asian Universities. He is a member of the Swiss Chemical Society and a Fellow of the European Academy of Science as well as the Royal Society of Chemistry (UK) and the Max Planck Society. He is also an elected honorary member of the Société Vaudoise de Sciences Naturelles and the Bulgarian Academy of Science. As the author of over 1000 publications and inventor of 50 patents, he is with some 120,000 citations and an h–index of 162 one of the three most highly cited chemists in the world.

Martin Green is a Scientia Professor at the University of New South Wales, Sydney, and the Director of the Australian Centre for Advanced Photovoltaics. He was born in Brisbane and educated at the University of Queensland and then McMaster University, Canada. His contributions to photovoltaics include heading the team that has improved silicon solar cell performance by over 50% since the 1980s, and the commercialisation of several different solar cell technologies. Major international awards include the IEEE William R. Cherry Award in 1990, the 1999 Australia Prize, the 2002 Right Livelihood Award, also known as the Alternative Nobel Prize, the 2007 SolarWorld Einstein Award and the 2010 Eureka Prize for Leadership. In 2012, he was appointed as a Member of the Order of Australia in recognition of his contributions to photovoltaics and photovoltaics education. He has been elected to Fellowship of the Australian Academy of Science, the Australian Academy of Technological Sciences and Engineering, the Institute of Electrical and Electronic Engineers and the Royal Society of London. He is the author of four books on solar cells, several book chapters and numerous reports and papers in the area of semiconductor properties, microelectronics and solar cells.

Franz-Josef Haug studied physics at the Universities of Ulm, Germany, and Waikato, New Zealand. For his diploma he investigated nucleation and coalescence phenomena during the initial stages of chemical vapour epitaxy of silicon. He

undertook his PhD program at ETH Zürich, Switzerland, working on $Cu(In,Ga)Se_2$ solar cells in the superstrate configuration. After graduation, he worked on plasma processing of super-hard nano-composite coatings of TiN/SiN_x before joining the Jülich Research Centre in Germany, where he worked on surface modifications of the transparent front electrode of thin-film silicon solar cells. In 2005, he joined the Institute of Microengineering, initially affiliated to the University of Neuchâtel, Switzerland, and since 2009 part of the EPFL. There he leads a research group devoted to thin-film silicon solar cells on glass and flexible plastic substrates, investigating novel texturing techniques for light scattering and absorption enhancement. He is author or co-author of some 70 peer-reviewed papers and 4 patents. His research interests include solar cells, semiconductor physics, and optoelectronics.

Arnulf Jäger-Waldau received his Dr. rer. nat. from the Physics Department of the University of Konstanz, Germany, in 1993. He has worked in the field of material research for solar cells since 1987 and holds patents on semiconductor material deposition for thin-film solar cells and solar module design. In 1994 and 1995 he worked as a post-doctoral JSPS fellow at Shinshu University, Nagano, Japan, before joining the Hahn–Meitner Institute Berlin in 1996. Since 2001 he has been a Scientific Officer and Senior Scientist at the Renewable Energy Unit, Institute for Energy and Transport of the European Commission's Joint Research Centre, where he works on the assessment of renewable energy technologies, the effectiveness of their implementation, their integration into energy infrastructures and the role of renewable energy for climate change mitigation. Among other roles, he has been the Technical Chairman of the European Photovoltaic Solar Energy Conference (EUPVSEC) since 2011, and he was a Lead Author for Solar Energy of the Special Report of the IPCC on Renewable Energy and Climate Change Mitigation. He also serves as a member of the Executive Committee of the European Materials Research Society, the Academic Advisory Board of the Chinese Trina State Key Laboratory for Photovoltaics, the International Advisory Board of the Warsaw University Photovoltaic Centre and the Scientific Advisory Board of the Solar Research Centre of the Bulgarian Academy of Science, and he is Vice-Chairman of the Academic Committee of the Asian Photovoltaic Industry Association (APVIA).

Antonio Luque obtained his Doctor of Engineering degree from the Polytechnic University of Madrid in 1967. Today he is also Doctor Honoris Causa of three other Spanish universities. In 1969, he joined the university staff and founded its Semiconductor Laboratory. In 1979, this centre became the Institute of Solar Energy that he leads at present. In 1981, he founded the company Isofotón to manufacture the bifacial cells he had invented, and he chaired its board until 1990. He has written

some 300 papers and registered around 20 patents, of which some are in exploitation. He has won several scientific awards, among which are the Spanish National Prize for Technology in 1987 and 2003, the King Jaime I Prize for environmental protection, the Becquerel Prize awarded by the European Commission for PV in 1992, the IEEE William Cherry Award in 1996 and the SolarWorld Einstein Award in 2008. Among other distinctions, he is a member of the Royal Academy of Engineering, and of the Russian Academy of Sciences. He has also been a member of the Advisory Council for Science and Technology, which advises the Spanish Prime Minister.

Ignacio Luque-Heredia is CEO of BSQ Solar, a high concentration photovoltaics (HCPV) manufacturing company that he co-founded in 2009. He received his MSc and PhD degrees in electrical engineering from Polytechnic University of Madrid in 1995 and 2010 respectively. He was co-founder in 1995 of the company Inspira, also operating in the CPV field, which was acquired by the Silicon Valley leading CPV manufacturer Solfocus in 2007. From 2007 to 2009 he was CTO for Solfocus Europe. Leading Inspira's and BSQ Solar's engineering, he has participated in 23 collaborative projects in the field of CPV, 11 of them funded by the European Commission. These range from the EUCLIDES project in 1995, which resulted in the biggest CPV plant of its time, to the most recent NGCPV project, on 3rd generation photovoltaic devices and their integration in CPV technologies. He holds four patents and has led the deployment of CPV pilot systems and large-scale plants, as well as several technology transfer programs in the USA, China, India, Japan, Australia, MENA, Brazil, Mexico and Europe. He is a member of the Scientific Committee of the International Conference on CPV Systems, and of Work Group 7 for the development of CPV standards in Technical Committee 82 for Solar Photovoltaic Energy Systems of the International Electrotechnical Commission. He is also a Senior Member of the IEEE.

Jenny Nelson is a Professor of Physics at Imperial College London, where she has researched novel types of solar cell since 1989. Her current research focuses on photovoltaic energy conversion using molecular materials, characterisation of the charge transport, charge separation and morphological properties of molecular semiconductors, the theory of charge transport in organic semiconductors and modelling of photovoltaic device behaviour. She has published over 200 papers on photovoltaic materials and devices, and a book on the physics of solar cells.

Nicola Pearsall is a Professor at Northumbria University, where she leads their photovoltaic research activities. She holds a degree in physics from the University of Manchester Institute of Science and Technology and obtained her PhD from Cranfield Institute of Technology for her research on indium phosphide solar cells

for satellite applications. She has been involved in research in photovoltaics for 30 years, and her current interests relate to the performance and implementation of photovoltaic systems. She is a member of the Steering Committee of the European Photovoltaic Technology Platform and has contributed to the development of their Strategic Research Agenda, as well as working with the Solar Europe Industry Initiative.

Uwe Rau received his PhD in physics in 1991 from the University of Tübingen, Germany, for his work on temporal and spatial structure formation in the low-temperature electronic transport of bulk semiconductors. From 1991 to 1994, he worked at the Max Planck Institute for Solid State Research, Stuttgart, on Schottky contacts, semiconductor heterojunctions and silicon solar cells. From 1994 to 1997, he worked at the University of Bayreuth, Germany, on electrical characterisation and simulation of Si and $CuInSe_2$ solar cells. In 1997, he joined the Institute for Physical Electronics at the University of Stuttgart, where he became leader of the Device Analysis Group. His research interests centre on transport phenomena, especially electrical transport in solar cell heterojunction devices and interface and bulk defects in semiconductors. He has authored or co-authored more than 100 scientific publications.

Hans-Werner Schock received his diploma in electrical engineering in 1974, and doctoral degree in electrical engineering in 1986, from the University of Stuttgart's Faculty of Electrical Engineering. Since the early 1970s, he has worked on the development of polycrystalline II–VI and I–III–VI_2 compound semiconductor thin-film solar cells, taking the development of chalcogenide solar cells from research to pilot fabrication. A series of successful research projects on thin-film solar cells under his guidance resulted in several production lines for thin film solar cells in Europe. From 2004 to 2012, he was director of the Institute of Technology at the Helmholtz Zentrum Berlin for Materials and Energy and he is an Honorary Professor at the Technical University Berlin. He received the Becquerel Prize of the European Commission in 2010 for his achievements in the development of thin-film solar cells. At present he is a consultant in the field of photovoltaics. He is the author or co-author of more than 300 contributions in books, scientific journals and conference proceedings.

Masafumi Yamaguchi is a Professor of the Toyota Technological Institute. He received his BS and PhD degrees from Hokkaido University, Japan, in 1968 and 1978, respectively. In 1968, he joined the NTT Electrical Communications Laboratories, working on radiation damage to Si and III–V compounds, ZnSe blue-light-emitting diodes and III–V compound solar cells. In 1983, he discovered the superior radiation-resistance of InP materials and solar cells, thereby showing

the great potential of InP cells for space applications. His group also developed high-efficiency InP, GaAs-on-Si, and AlGaAs/GaAs tandem cells by proposing a double-hetero structure tunnel junction for realising a high performance and stable multijunction cell interconnection in 1987. As Japanese team leader of the EU–Japan Collaborative Research on Concentrator Photovoltaics, he contributed to the attainment of InGaP/GaAs/InGaAs 3-junction cells with efficiencies of 44.4% at 302 Suns of AM1.5D and 37.9% at AM1.5G. He is also the project leader of the Next Generation High Performance Photovoltaics Research and Development Project of the Japanese New Energy Development and Industrial Technology Development Organisation, and the Research Supervisor in the Research Area of the Creative Clean Energy Generation using Solar Energy programme of the Japan Science and Technology Agency. He has published more than 300 original papers and received numerous awards, such as the Becquerel Prize from the European Commission in 2004 and the William Cherry Award from the IEEE in 2008 for outstanding contributions to science and technology development of high-efficiency photovoltaics.

PREFACE TO THE FIRST EDITION

And there the unregulated sun
Slopes down to rest when day is done
And wakes a vague, unpunctual star...

Rupert Brooke, *The Old Vicarage, Grantchester*, May 1912

Since the dawn of history, man has been fascinated by the Sun, the provider of the light and warmth that sustains life on Earth. In pre-industrial times, our major sources of energy — wood, wind and water power — derived from solar energy. The subsequent discovery and massive exploitation of fossil fuels laid down in the Earth's crust by early aeons of photosynthetic activity have conditioned the developed world to be dependent on convenient, readily available energy. But we are living on our energy capital. The Earth's reserves of coal, oil and gas are finite and likely to become resource-depleted in the course of this century. A sense of living on borrowed time was therefore appropriate even before concerns about global climate change, sustainability and energy security combined to raise interest in renewable energy to its current encouraging level.

This book is the first in a series of four multi-authorial works on the photoconversion of solar energy. It was created from my long-held conviction that, despite slow starts and setbacks, solar energy — broadly defined to encompass other renewable energy forms that derive from solar — will become the Earth's major energy source within this century. The Sun is a source of both radiant heat and light, and techniques for using solar energy correspondingly divide into thermal methods (solar power towers, water heaters and so on) and photoconversion (sometimes called direct) methods. Photoconversion is the subject of this book series. A photoconverter is a device that converts sunlight (or any other source of light) into a useful form of energy, usually electrical power or a chemical fuel, in a process that relies, not on a raised temperature, but on the selective excitation of molecules or electrons in a light-absorbing material and their subsequent de-excitation in a way that produces energy in a useful form. Volume I covers the most developed of the man photoconversion devices, photovoltaic (PV) cells, which are solid-state semiconductor devices that produce electrical power on illumination. Volume II will cover the natural photoconversion system of photosynthesis, the potential of biomass as an energy source and the global carbon budget. Volume

III will explore the less developed but exciting possibilities of synthesising artificial 'molecule-based' photoelectrochemical or photochemical photoconverters. Finally, Volume IV will draw together the common themes of photoconversion and provide some background material.

The series is intended mainly for senior undergraduates, graduate students and scientists and technologists working on solar photoconversion. Chapters 1–12 of this book deal with PV cell design, device physics and the main cell types — crystalline and amorphous silicon, cadmium telluride and copper indium diselenide — as well as more advanced or less developed options such as quantum-well and thermophotovoltaic cells. These chapters are mainly technical, requiring sound knowledge of physics, chemistry or materials science for ready understanding. Chapters 13–18 deal with PV systems, manufacturers, markets and economics and are accessible without specialist knowledge.

A multi-authorial work owes its very existence to its authors, and my wholehearted thanks must go to the twenty-five distinguished individuals, all recognised authorities in their own fields, who have contributed to this book and patiently answered my queries during the editing stage. I have also been helped by discussions about PV with many friends and colleagues, and visits to installations throughout the world: I have been up Swiss mountains, onto Japanese rooftops and into the Arizona desert, and thoroughly enjoyed every minute. I am most grateful to those who have read and commented on various parts of this book or provided specialist information in advance of publication: Dennis Anderson, Jeffrey and William Archer, Stephen Feldberg, Martin Green, Eric Lysen, Larry Kazmerski, Bernard McNelis and Nicola Pearsall. I also warmly thank Alexandra Anghel, Barrie Clark, Stuart Honan and my PA Jane Williams for editorial assistance, and Ellen Haigh and John Navas of IC Press and Alan Pui of World Scientific Press for guiding the book to publication.

For me the sad part of writing this preface is that I must do so in the first person, for my co-editor Professor Robert Hill died suddenly on 26 November 1999. Bob was the most knowledgeable champion of photovoltaics in the UK, and his premature death has deprived the British PV community of its cornerstone. He had drafted his chapter with Nicky Pearsall some months before he died, and the flow of emails delivering his astute editorial comments on other chapters continued until the day before his death.

Bob believed unshakeably in the future of PV. Although he knew that system costs will have to fall by another factor of 2–3 if PV is to become cost-competitive in major new grid-accessible markets, there are good grounds for believing this is possible. PV technology is still young, and significant further economies of scale from larger manufacturing facilities, as well as further advances in the fundamental