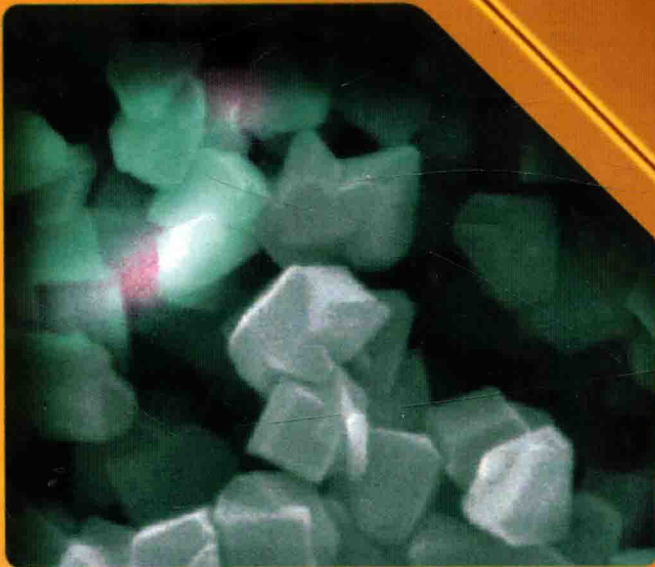


Edited by

**Jef Poortmans and
Vladimir Arkhipov**

Thin Film Solar Cells

Fabrication,
Characterization
and Applications



 **WILEY**

Wiley Series
in Materials for
Electronic
& Optoelectronic
Applications

Thin Film Solar Cells Fabrication, Characterization and Applications

Edited by

Jef Poortmans

and

Vladimir Arkhipov

IMEC, Leuven, Belgium



John Wiley & Sons, Ltd

Copyright © 2006 John Wiley & Sons Ltd, The Atrium, Southern Gate, Chichester,
West Sussex PO19 8SQ, England
Telephone (+44) 1243 779777

Email (for orders and customer service enquiries): cs-books@wiley.co.uk
Visit our Home Page on www.wileyeurope.com or www.wiley.com

Reprinted with corrections December 2006

All Rights Reserved. No part of this publication may be reproduced, stored in a retrieval system or transmitted in any form or by any means, electronic, mechanical, photocopying, recording, scanning or otherwise, except under the terms of the Copyright, Designs and Patents Act 1988 or under the terms of a licence issued by the Copyright Licensing Agency Ltd, 90 Tottenham Court Road, London W1T 4LP, UK, without the permission in writing of the Publisher. Requests to the Publisher should be addressed to the Permissions Department, John Wiley & Sons Ltd, The Atrium, Southern Gate, Chichester, West Sussex PO19 8SQ, England, or emailed to permreq@wiley.co.uk, or faxed to (+44) 1243 770620.

Designations used by companies to distinguish their products are often claimed as trademarks. All brand names and product names used in this book are trade names, service marks, trademarks or registered trademarks of their respective owners. The Publisher is not associated with any product or vendor mentioned in this book.

This publication is designed to provide accurate and authoritative information in regard to the subject matter covered. It is sold on the understanding that the Publisher is not engaged in rendering professional services. If professional advice or other expert assistance is required, the services of a competent professional should be sought.

Other Wiley Editorial Offices

John Wiley & Sons Inc., 111 River Street, Hoboken, NJ 07030, USA
Jossey-Bass, 989 Market Street, San Francisco, CA 94103-1741, USA
Wiley-VCH Verlag GmbH, Boschstr. 12, D-69469 Weinheim, Germany
John Wiley & Sons Australia Ltd, 42 McDougall Street, Milton, Queensland 4064, Australia
John Wiley & Sons (Asia) Pte Ltd, 2 Clementi Loop #02-01, Jin Xing Distripark, Singapore 129809
John Wiley & Sons Canada Ltd, 6045 Freemont Blvd, Mississauga, Ontario, L5R 4J3

Wiley also publishes its books in a variety of electronic formats. Some content that appears in print may not be available in electronic books.

Library of Congress Cataloging-in-Publication Data

Thin film solar cells : fabrication, characterization, and applications /
edited by Jef Poortmans and Vladimir Arkhipov.

p. cm.

Includes bibliographical references and index.

ISBN-13: 978-0-470-09126-5 (cloth : alk. paper)

ISBN-10: 0-470-09126-6 (cloth : alk. paper)

1. Solar cells. 2. Thin film devices. I. Poortmans, Jef. II. Arkhipov, Vladimir.

TK2960.T445 2007

621.31'244—dc22

2006010650

British Library Cataloguing in Publication Data

A catalogue record for this book is available from the British Library

ISBN-10 0-470-09126-6 (HB)

ISBN-13 978-0-470-09126-5 (HB)

Typeset in 10/12pt Times by TechBooks, New Delhi, India.



Disclaimer

The publisher and the author make no representations or warranties with respect to the accuracy or completeness of the contents of this work and specifically disclaim all warranties, including without limitation any implied warranties of fitness for a particular purpose. This work is sold with the understanding that the publisher is not engaged in rendering professional services. The advice and strategies contained herein may not be suitable for every situation. In view of ongoing research, equipment modifications, changes in governmental regulations, and the constant flow of information relating to the use of experimental reagents, equipment, and devices, the reader is urged to review and evaluate the information provided in the package insert or instructions for each chemical, piece of equipment, reagent, or device for, among other things, any changes in the instructions or indication of usage and for added warnings and precautions.

The fact that an organization or Website is referred to in this work as a citation and/or a potential source of further information does not mean that the author or the publisher endorses the information the organization or Website may provide or recommendations it may make. Further, readers should be aware that Internet Websites listed in this work may have changed or disappeared between when this work was written and when it is read. No warranty may be created or extended by any promotional statements for this work. Neither the publisher nor the author shall be liable for any damages arising herefrom.

Thin Film Solar Cells Fabrication, Characterization and Applications

Wiley Series in Materials for Electronic and Optoelectronic Applications

Series Editors

Dr Peter Capper, SELEX Sensors and Airborne Systems Infrared Ltd, Southampton, UK

Professor Safa Kasap, University of Saskatchewan, Canada

Professor Arthur Willoughby, University of Southampton, Southampton, UK

Published Titles

Bulk Crystal Growth of Electronic, Optical and Optoelectronic Materials, Edited by P. Capper

Properties of Group-IV, III-V and II-VI Semiconductors, S. Adachi

Optical Properties of Condensed Matter and Applications, Edited by J. Singh

Charge Transport in Disordered Solids with Applications in Electronics, Edited by S. Baranovski

Forthcoming Titles

Liquid Phase Epitaxy of Electronic, Optical and Optoelectronic Materials, Edited by P. Capper and M. Mauk

Dielectric Films for Advanced Microelectronics, Edited by K. Maex, M. R. Baklanov and M. Green

Dedication

The unexpected death of Vladimir Arkhipov on December 10, 2005 was a sad loss for the scientific community and even more so for his young family. Shortly after returning from a conference in Boston, he went to Moscow to visit his mother and while in his hometown he suffered a heart attack. Strangely enough this happened when there was good reason to expect that he could finally settle down in Leuven. However, his destiny was to go back to his Russian roots. His family, friends and colleagues can only mourn the loss of a great personality and a great scientist.

Vladimir Arkhipov was born on January 18, 1952. He studied physics at the Moscow Institute of Physics and Engineering. For his PhD, completed in 1980, he joined the theoretical group of Professor Alexander Rudenko who stimulated his interest in the properties of semiconductors, in particular disordered inorganic materials. Their joint work on dispersive charge transport in amorphous semiconductors featuring an exponential distribution of trap states was well received in the literature. It attracted the interest of the international community and started the reputation of the young scientist. For a young, gifted scientist full of ideas, success is, indeed, an important stimulant for expanding his range of interest. Energetic as he was, he began exploring the fascinating world of charges diffusing, drifting, and recombining in the rough energy landscape of amorphous semiconductors, such as chalcogenides. However, by interacting with a group working on polymers he became aware that his theoretical methodologies could be applied to organic materials as well. A new door was opened to him.

In 1992, Vladimir Arkhipov, a professor at his home institution, received a scholarship from the German Humboldt foundation for a two years' visit to a research group in the Department of Physical Chemistry in Marburg, Germany. This started a very fruitful collaboration. Like chemical bonding, such an interaction does not simply involve addition of the expertise of two individuals but it creates a new state in which exchange interaction plays an important and stabilizing role. His input was his profound knowledge of the theory of hopping phenomena in amorphous solids. He did not only use it to solve problems in the course of our work on optoelectronic properties of organic solids but he set up a comprehensive conceptual framework for hopping transport in organic glasses and polymers featuring a Gaussian distribution of states. Highlights included experimental and theoretical investigations on injection of charge carriers from an electrode into the dielectric layer of a light emitting diode, the intrinsic and extrinsic optical generation of charge carriers in conjugated polymers, charge transport in neat and doped conjugated polymers, and thermally stimulated luminescence caused by the recombination of geminately bound electron hole pairs. One of the last topics he dealt with was photovoltaics. He introduced a new concept for explaining efficient charge carrier generation in organic solar cells.

Altogether Vladimir spent more than five years in Marburg, both the members of my group and I profited greatly from daily discussions. The cooperation continued when he moved to the Catholic University of Leuven and, after 2001, as a senior researcher to IMEC.

Over the years, Vladimir and I became personal friends. I liked his kind, gentle, warm-hearted personality, his keen intellect and his intuition. He was an exceptionally good and open-minded scientist with deep insight into the essence of a physical problem including experiments and, above all, he was able to listen. This is one reason why the research groups at IMEC, at the KU University of Leuven and in Marburg were so eager to interact with him, get his advice and sit together and solve problems. It is sad that he is no longer among us. We will miss him.

Heinz Bässler,
University of Marburg, Germany

Series Preface

WILEY SERIES IN MATERIALS FOR ELECTRONIC AND OPTOELECTRONIC APPLICATIONS

This book series is devoted to the rapidly developing class of materials used for electronic and optoelectronic applications. It is designed to provide much needed information on the fundamental scientific principles of these materials, together with how these are employed in technological applications. The books are aimed at postgraduate students, researchers and technologists, engaged in research, development and the study of materials in electronics and photonics, and industrial scientists developing new materials, devices and circuits for the electronic, optoelectronic and communications industries.

The development of new electronic and optoelectronic materials depends not only on materials engineering at a practical level, but also on a clear understanding of the properties of materials, and the fundamental science behind these properties. It is the properties of a material that eventually determine its usefulness in an application. The series therefore also includes such topics as electrical conduction in solids, optical properties, thermal properties, etc., all with applications and examples of materials in electronics and optoelectronics. The characterization of materials is also covered within the series in as much as it is impossible to develop new materials without the proper characterization of their structure and properties. Structure–property relationships have always been fundamentally and intrinsically important to materials science and engineering.

Materials science is well known for being one of the most interdisciplinary sciences. It is the interdisciplinary aspect of materials science that has led to many exciting discoveries, new materials and new applications. It is not unusual to find scientists with chemical engineering backgrounds working on materials projects with applications in electronics. In selecting titles for the series, we have tried to maintain the interdisciplinary aspect of the field, and hence its excitement to researchers in this field.

Peter Capper
Safa Kasap
Arthur Willoughby

Preface

P.1 STATUS OF PHOTOVOLTAICS AND THE ROLE OF THIN FILM SOLAR CELLS

The large scale production of solar cells during the year 2004 surpassed the symbolic threshold of 1 GW_p [1] and the total cumulative worldwide PV capacity installed is above 3 GW. Photovoltaic applications range from large scale stand alone/grid connected power stations to low power electronics.

The photovoltaic (PV) sector has been growing with a compounded annual growth rate of nearly 30 % over the last five years and in 2004 the growth rate even amounted to a breath-taking 60 % as can be seen in Figure P.1.

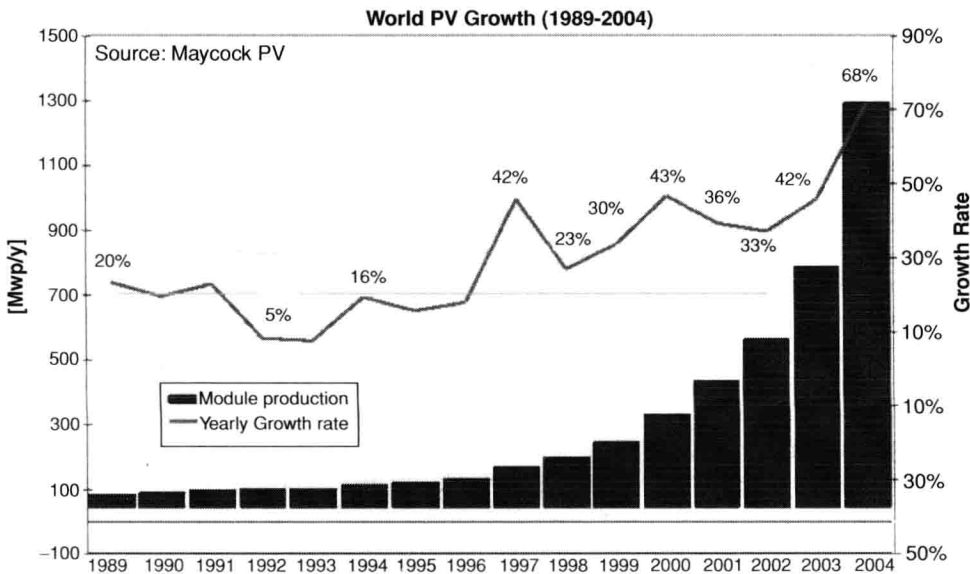


Figure P.1 Evolution of the yearly produced PV modules in terms of MW_p.

The production of solar cells was and is still based mainly on crystalline silicon (Si). More specifically 36 % of the 2004 production is based on single crystal Si but the main part is based on multicrystalline Si cells – substrates and ribbons (58 %). The remainder is based on thin

film solar cell technologies and consists of 4 % based on thin film amorphous Si solar cells and 2 % on polycrystalline compound solar cells based on CdTe and CuInSe₂ (Figure P. 2).

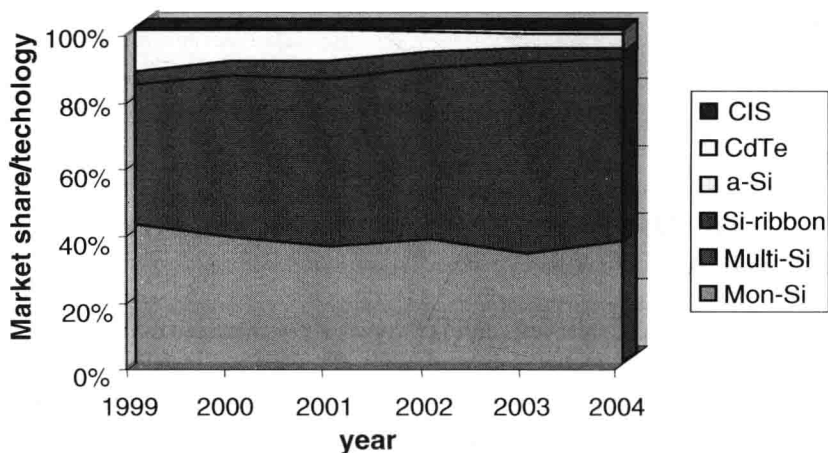


Figure P.2 Market share evolution taken by the different solar cell technologies over the last five years.

Despite tremendous progress in all aspects of production of Si based solar cells and the rapid decrease of production cost for PV modules [2] from 5 \$/W_p at the beginning of the nineties to 2.5\$/W_p in 2004, the cost/kWh is still too high to compete with other sources of electricity generation. In the Northwestern European climate and taking into account the system costs, one arrives at a cost of 0.7\$/kWh, which is definitely still too high.

The single most important factor in determining the cost of production is the cost of the 250–300 μm thick Si wafer used for the fabrication of solar cells. It accounts for more than 50 % of the costs at the module level. The problem of the high cost of electronic grade Si was recognized right from the beginning and a lot of effort is being put into developing a source of polysilicon feedstock, which is suited for Si substrate production for solar cells. This solar grade Si will have relaxed specifications in terms of impurities as compared with electronic grade Si. Additionally, thinner wafers, a more efficient usage of Si and an increase of the module efficiency from 13–15 % to 18–20 % will have to contribute to a further reduction by a factor of two to three before 2020 [3]. At the time of publication of this book, there is a tendency for the crystalline Si substrate costs to increase their contribution as there is a situation of scarcity for the polysilicon feedstock material. This situation of scarcity is probably temporary according to the editors' opinion, but it is clear that, presently, there is a real window of opportunity to introduce thin film solar cells on a larger scale onto the market and to set in motion the necessary evolution towards module costs below 1\$/W_p. This cost reduction will have to be brought about by a combination of upscaling – that is why it is important for thin film solar cells to increase their market share and to use the present opportunity – and intense R&D to tackle the remaining weaknesses of the different thin film solar cell technologies.

Another major consideration when comparing different PV technologies is the energy pay-back period, which refers to the number of years in which the electrical energy generated by the devices will be equal to the energy required for production of these devices. On the module level the thin film technologies perform better by at least a factor of two – less than one year – than multicrystalline Si modules (2–3 years) in southern regions. The comparison of the payback

time can be done at the level of the PV module should also include the other components [4] to find which application field is most suited for the different technologies. In reference [4] it was noted that for grid connected rooftop and array fields, thin film solar cell technology is the better choice. On the other hand, the multicrystalline Si estimates point to its use in free standing applications because of the higher balance of system (BOS) cost associated with these applications. The higher efficiency of multicrystalline Si modules reduces the impact of the higher BOS costs.

P.2 THIN FILM MATERIALS FOR SOLAR CELLS

P.2.1 Thin film: definition

The reader might remark at this point that the term ‘thin film solar cell technology’ has not yet been defined in the context of this book. The definition given by Chopra *et al.* [5] provides a good starting point and also yields a criterion to discriminate the term ‘thin film’ from ‘thick film’. They define a thin film as a material ‘created *ab initio* by the random nucleation and growth processes of individually condensing/reacting atomic/ionic/molecular species on a substrate. The structural, chemical, metallurgical and physical properties of such a material are strongly dependent on a large number of deposition parameters and may also be thickness dependent. Thin films may encompass a considerable thickness range, varying from a few nanometers to tens of micrometers and thus are best defined in terms of the production processes rather than by thickness. One may obtain a thin material (not a thin film) by a number of other methods (normally called thick-film techniques) such as by thinning bulk material, or by depositing clusters of microscopic species in such processes as screen-printing, electrophoresis, slurry spray, plasma gun, ablation, etc.’ The given definition still leaves room for a broad field of technologies to deposit the thin film (plasma, sputtering, evaporation, deposition from the liquid phase, etc.) and to tailor its electrical and morphological properties (crystalline, amorphous and intermediary forms). These techniques and their relation with the final morphology and the photovoltaic performance will be discussed in the separate chapters dealing with the different thin film solar cell technologies. For the inorganic non-crystalline Si materials and technologies we will follow the approach of ref. 5.

P.2.2 Thin film absorber materials

Conventionally, photovoltaic materials use inorganic semiconductors. The semiconductors of interest allow the formation of charge-carrier separating junctions. The junction can be either a homojunction (like in Si) or a heterojunction with other materials to collect the excess carriers when exposed to light. In principle, a large number of semiconductor materials are eligible, but only a few of them are of sufficient interest. Ideally, the absorber material of an efficient terrestrial solar cell should be a semiconductor with a bandgap of 1–1.5 eV with a high solar optical absorption ($10^4 - 10^5 \text{ cm}^{-1}$) in the wavelength region of 350–1000 nm, a high quantum yield for the excited carriers, a long diffusion length low recombination velocity. If all these constraints are satisfied and the basic material is widely available, the material allows in principle the manufacturing of a thin-film solar cell device.

From the point of view of processing, manufacturing and reproducibility, *elemental* semiconductors provide a simple and straightforward approach to manufacture thin-film solar cells.

The first material at hand is the material which dominates the PV market nowadays: silicon. Crystalline silicon is a semiconductor material with a bandgap of 1.1 eV. Because of the indirect bandgap character of silicon for photons with energy lower than 3.4 eV, it is clearly not an ideal material for thin-film solar cells. Nevertheless, there is a substantial R&D effort being put into developing thin-film solar cells based on crystalline Si. The thin film of crystalline Si can be grown either by low-temperature deposition techniques which yield microcrystalline Si or by high-temperature techniques. In the latter case the material properties of the grown crystalline Si film are similar to the properties of bulk crystalline Si solar material. Because of its relatively low absorption coefficient, crystalline Si layers have to be at least 30 μm thick to absorb sufficient light unless optical enhancement techniques are used to improve the effective absorption. As a result of its high refractive index (4) crystalline Si allows efficient optical confinement with optical pathlength enhancements up to a factor 50. It will come as no surprise to the reader that optical enhancement is therefore a substantial part of the research in the field of thin-film crystalline Si.

Si can also be deposited in its amorphous form. Amorphous Si as such is a material of little use for photovoltaics because of the extremely high dangling bond density and intragap state density in the material ($>10^{19} \text{ cm}^{-3}$), resulting in immediate recombination of photo-excited excess carriers and pins the Fermi level, excluding controllable doping. The properties of amorphous Si are drastically improved by alloying it with H, which passivates most of the dangling bonds and reduces the intragap state density to 10^{16} cm^{-3} or less. The alloying with H takes place in a natural way during the deposition of the film which is deposited by cracking a Si precursor (most often SiH_4) by means of a plasma and the material formed is denoted as a-Si:H. In comparison with crystalline Si, a-Si:H has a number of properties which make it attractive as an absorber layer for thin-film solar cells. The bandgap of a-Si:H, is to some extent tailorable by the method and conditions of deposition. In addition, the material is relatively easy to dope, which allows the manufacturing of homojunction devices and, last but not least, it has a high optical absorption coefficient over the wavelength range of interest. Under suitable deposition conditions and strong hydrogen dilution, nanocrystalline and microcrystalline materials are obtained. While the crystallite size and volume fraction are very small, these crystallites catalyze the crystallization of the remainder of the amorphous matrix upon annealing. Microcrystalline materials deposited by this method are found to have less defect density and are more stable against light degradation compared with a-Si. Recently developed improved efficiency materials consist of this heterogeneous mixture of the amorphous and an intermediate range order microcrystalline material.

a-Si:H has emerged as an attractive material which, for some time, was challenging the supremacy of crystalline Si cells in the Eighties. Because of stability problems and the lower efficiencies as compared with crystalline Si, the market share of a-Si:H based thin-film solar cells remained limited. Nevertheless, the present shortage of crystalline Si and the developments around multijunction structures and micro/nanocrystalline Si extensions provide a new opportunity for this technology to make it to the marketplace. Recently also carbon came into the picture as a candidate material for thin-film solar cells, with first results being reported for boron-doped diamond-like carbon [6] and fullerene films [7]. These approaches are not very well developed and therefore do not appear within this book.

III–V compound materials like GaAs, InP and their derived alloys and compounds, which most often have a direct bandgap character, are ideal for photovoltaic applications, but are far too expensive for large-scale commercial applications, because of the high cost of the necessary

precursors for the deposition and the deposition systems itself. The deposition systems for these materials are either based on molecular beam epitaxy or metalorganic chemical vapour deposition.

More appealing from the point of view of ease of processability and cost of material and deposition are the “II–VI compound materials” like CdTe or variations on this like CuInSe₂. The interest in these materials for thin-film solar cell manufacturing is essentially based on two elements. Because of the chemical structure of these materials the internal (grain boundaries, interfaces) and external surfaces are intrinsically well passivated and characterized by a low recombination velocity for excess carriers. The low recombination activity at the grain boundaries allows high solar cell efficiencies even when the material is polycrystalline with grain sizes in the order of only a few μm . This is to be contrasted with crystalline Si where grain boundaries are normally characterized by a high recombination velocity. Moreover, the polycrystallinity allows a large number of substrates (glass, steel foil, ...) and is compatible with low-cost temperature deposition techniques, as there is no need for epitaxial growth or high temperatures to obtain large grain sizes. A second important property is the possibility to tailor the bandgap e.g. replacing Se by S in CuInSe₂ results in a material with a higher bandgap. This property allows one to build in bandgap gradients aiding the collection of excess carriers and, ultimately, could even be used to develop multijunction solar cells. With the increasing number of components in ternaries and even quaternaries, the number of possible material combinations increases.

An interesting alternative to inorganic semiconductor absorbers are organic semiconductors, which combine interesting optoelectronic properties with the excellent mechanical and processing properties of polymeric/plastic materials. In organic semiconductors, absorption of photons leads to the creation of bound electron–hole pairs (excitons) with a binding energy of 0.5 eV rather than free charges. The excitons carry energy, but no net charge, and have to diffuse to dissociation sites where their charges can be separated and transported to the contacts. In most organic semiconductors, only a small portion (30 %) of the incident light is absorbed because the majority of semiconducting polymers have bandgaps higher than 2.0 eV. The typically low charge-carrier and exciton mobility require the active absorber layer thickness to be less than 100 nm. This thickness is sufficient to absorb most of the incident solar photons if light trapping is used, although the low refractive index calls for adapted approaches. More importantly, organic semiconductors can be processed from solutions at or near room temperature on flexible substrates using simple, cheap and low-energy deposition methods such as spinning or printing thereby yielding cheaper devices. Even though the efficiency of these devices is poor at present, they may find immediate applications for disposable solar cell based small power applications. Among the major issues to be addressed before reasonable market penetration of the organic devices takes place are the improvement of the stability of conjugate polymers, and the matching of the bandgap of the organic materials with the solar spectrum for higher conversion efficiency by using blended/composite polymers and suitable dyes.

P.3 DIFFERENT THIN FILM SOLAR CELL TECHNOLOGIES

Based on the available semiconductor absorber materials discussed above one can go systematically over the different related thin film solar cell technologies.

P.3.1 Crystalline silicon thin film solar cells

There are a large variety of crystalline Si thin film approaches. The one that is closest to the classical crystalline Si solar cell structure is the ‘epitaxial solar cell approach’. The basic idea behind this thin film approach, is the realization of a thin crystalline Si film of high electronic quality on a low cost Si carrier substrate by means of epitaxial growth as shown in Figure P.3a. The depicted structure strongly resembles the structure of a classical, self supporting bulk crystalline Si solar cell and, as a result, the basic solar cell process to produce the solar cell is very similar to the practices used within the photovoltaics (PV) industry nowadays. Its structural similarity would result in a low acceptance threshold in the solar cell industry, which is presently still dominated by crystalline Si. A special case is the ‘lift-off approach’ where, by means of a crystalline Si template based on porous Si, a thin cell is realized which is lifted off before or after the cell process.

The epitaxial cell approach relies on the use of a Si substrate. There are also attempts to develop thin film crystalline Si solar cell structures on non-Si substrates. Because of the high temperatures (>600 °C) used for the film deposition, glass is not suitable as a substrate. Rather, low cost ceramic substrates and graphite are the substrates of choice. In case the substrate is nonconductive, novel solar cell structures are needed to contact the solar cell as shown in Figure P.3b. The Si layer, deposited on top of these substrates, will be micro or polycrystalline with a grain size determined by the growth temperature and supersaturation conditions during the silicon layer deposition. It turns out to be difficult to realize solar cells with proper energy conversion efficiencies in material with a grain size of 1–10 μm, although substantial progress has been made recently in this field. On ceramic substrates which withstand high temperatures, liquid phase recrystallization is often applied to increase the final grain size, whereas laser recrystallization and rapid thermal annealing is being developed for substrates which can only withstand process temperatures >650 °C for a limited time.

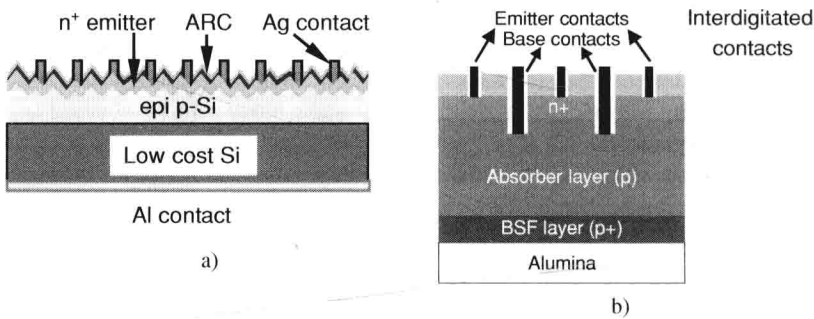


Figure P.3 a) Schematic of a epitaxial cell on a highly doped low cost Si substrate (ARC stands for anti-reflective coating; b) Novel solar cells with a nonconductive substrate.

P.3.2 Amorphous and microcrystalline silicon thin film solar cells

Because a-Si:H can be doped efficiently p- and n-type, the cell structure is based on a homojunction. As a result of the short carrier lifetime and the low carrier mobility collection by pure diffusion of excess carriers is not very effective. Therefore a-Si:H solar cells also

include a drift zone to improve the carrier collection. As a result the structure of the solar cell device is a p-i-n-structure where an intrinsic a-Si:H layer is sandwiched between a thin n^+ and p^+ -type layer. Because of the low doping in the intrinsic part, the electrical field will extend all over the intrinsic layer. As mentioned before, the properties of the material and the junction device are severely affected by the light induced creation of metastable defects, known as the Staebler–Wronski effect. Light induced degradation of a-Si:H devices and, as a consequence, a reduction of the electrical field in the intrinsic part of the cell is tackled by reducing the a-Si:H layer thickness so that the photogenerated carriers need to move only a short distance before they reach the electrode. However, thinning down also results in lower light absorption and thus optical confinement techniques employing diffusely reflecting front and back contacts are required to increase the effective layer thickness in order to absorb the photons. Over a period of time, extensive research and development work on deposition techniques and device structure have resulted in development of single junction and multijunction devices with high efficiency and moderately good stability. A typical a-Si:H based multijunction solar cell structure is shown in Figure P.4a.

As the cost of the Ge precursors is high and the electronic quality of the a-SiGe:H layers is lower than for a-Si:H layers, a lot of effort is being done in replacing the a-SiGe:H part of the cell by other solutions like microcrystalline Si. This leads to the ‘micromorph’ cell concept combining an a-Si:H topcell with a microcrystalline Si bottomcell as shown in Figure P.4b.

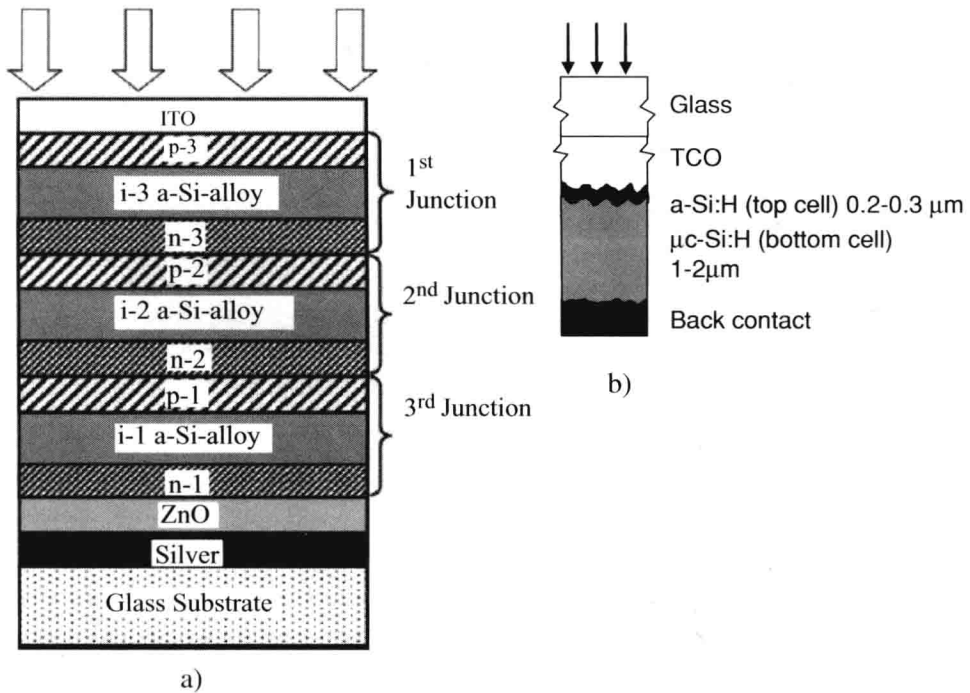


Figure P.4 a) Cross section of typical multijunction solar cell based on a-Si:H. In order to improve the performance the lower a-Si:H subcells are sometimes replaced by a-SiGe:H alloys; b) In the second approach (the micromorph concept) improved stability is obtained by replacing the a-Si:H bottom cell by a microcrystalline Si solar cell (taken from ref. 5).

P.3.3 Copper indium gallium selenide and cadmium telluride solar cell structures

Both superstrate and substrate device structures are currently being pursued for copper indium gallium selenide ($\text{CuIn}(\text{Ga})\text{Se}_2$, CIGS) device fabrication. The film growth and interdiffusion and hence the device properties are dependent on the device structure. These CIGS solar cells, based on the superstrate structure, are inferior to the substrate structure, because of the interdiffusion of CdS during high temperature CIGS film growth. A best device efficiency of 10.2 % was reported for the superstrate structure. On the other hand, a substrate configuration like the one shown in Figure P.5a with CdS buffer layer resulted in a 19.2 % efficiency device.

Cadmium telluride devices are fabricated preferably in the superstrate configuration because the CdTe surface is exposed for contacting. In addition, the benign feature of CdS diffusion during the processing reduces the lattice mismatch between CdTe and CdS. Cadmium telluride solar cells use borosilicate glass for high temperature deposition (600°C) and soda lime glass for low temperature deposition ($60\text{--}500^\circ\text{C}$). Cadmium telluride has also been deposited on thin metallic foils such as stainless steel, Mo, Ni and Cu. Molybdenum is best suited for CdTe deposition, owing to better thermal matching.

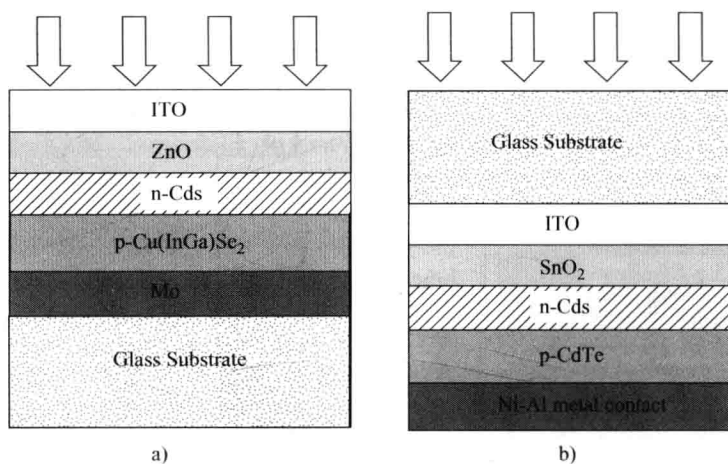


Figure P.5 a) Schematic view of the typical substrate structure of CIGS solar cells; b) Schematic view of the typical superstrate structure of CdTe solar cells (taken from ref. 5).

P.3.4 Basic structure of thin film organic solar cells

The term 'organic solar cell' has to be correctly defined. The term covers those photovoltaic devices where the organic layer is an essential part of the photovoltaic process. The basic steps in photovoltaic conversion are light absorbance, charge carrier generation, charge carrier transport and extraction/injection of charge carriers through externally accessible contacts. More specifically, the term 'organic solar cell' is applicable whenever at least the two first steps are being realized by means of an organic layer. By this definition, full organic devices as well as hybrid devices are being covered.

Organic solar cells have already been the subject of R&D efforts for a long time because of the potentially very low cost of the active layer material. Originally, most of the attempts to realize organic solar cell devices were based on essentially the same concepts as thin film p-n or p-i-n devices. This resulted in energy conversion efficiencies of about 1 % with the main limitation being the short exciton diffusion length and insufficient exciton dissociation. The breakthrough for solar cells incorporating an organic part came with the advent of concepts that radically deviated from the planar hetero- or homojunction solar cells. The generic idea behind these concepts is the existence of a bulk distributed interface to capture the excited carrier and to increase the exciton dissociation rate. The 'Graetzel cell' is a prominent example of this generic idea belonging to the class of hybrid cells. Within the pores of a porous TiO₂ layer a monolayer of an organic sensitizer is adsorbed on the pore walls as shown in Figure P.6a. After absorption of a photon, the excited electron within the sensitizer molecule is immediately transferred to the conduction band of TiO₂, after which the electron diffuses through the porous network to the contact. The oxidized sensitizer molecule is reduced to the original state by supplying electrons through a liquid electrolyte within the pores. Cells based on this hybrid concept show confirmed energy conversion efficiencies up to 11 % for small area cells, whereas upscaled modules exhibit efficiencies between 5 and 7 %. Standing issues of this type of hybrid solar cells are the replacement of the sensitizer by a material with increased absorption in the red and infrared part of the spectrum, the replacement of the liquid electrolyte by a solid state hole conductor and the improvement of the cell stability.

The full organic counterpart of the hybrid cell is the bulk donor-acceptor heterojunction concept (see Figure P.6b), which is based on blends of two organic compounds, one with donor character, the other with acceptor properties. The excitons dissociate very efficiently at the interfaces between donor and acceptor phases and flow through the percolated donor and acceptor subnetworks to the contacts, which are carrier selective. Efficiencies up to 5 % were reported for this type of cell based on the P3HT/PCBM donor-acceptor couple. This acceptor (PCBM) is often used, because exciton dissociation turns out to be extremely efficient with transfer times in the 100 fs range. Alternatives in which PCBM is replaced by a polymer with acceptor characteristics were also reported (e.g. CN-PPV/MEH-PPV pair). For this type of organic cell, standing issues are the extension of the active layer absorbance towards the red and infrared range, the use of materials with higher mobilities (in this context also tests with liquid crystal materials should be mentioned) and the critical issue of stability. In the framework of improving the red and infrared sensitivity of the donors, the majority of the activities are directed towards thiophenes, which could also improve stability.

For the sake of completeness it should be mentioned that there is also a nonorganic counterpart of these three-dimensional junction devices. These are the ETA (extremely thin absorber) structures, shown in Figure P.6c.

P.4 BASIC MODULE MANUFACTURING SCHEMES

One has to distinguish between two basic module concepts to interconnect the thin film solar cell structures discussed in this book. The first module concept is similar to the modules made with bulk crystalline Si solar cells. The same concept will apply to any thin film structure based on a wafer equivalent, like the epitaxial cell approach or a thin film crystalline Si technology on graphite. This concept is based on an interconnection by means of metallic tabs between the front side of one cell and the back contact of the neighboring cell (see Figure P.7a).