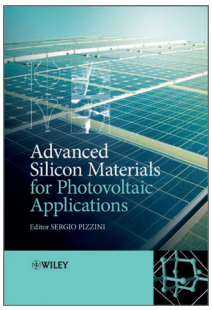
Advanced Silicon Materials for Photovoltaic Applications

Edited by *Sergio Pizzini*

Wiley, Chichester 2012, 405 pp., hardcover, €129.00—ISBN 978-0-470-66111-6



Silicon is a magic material with unique properties that can meet a variety of applications with low cost and with environmental benignancy. Since the 1950s, nearly perfect bulk-single-crystal substrates have been developed for the semiconductor industry. The development of the photovoltaics (PV) industry in the late 1970s due to the 2nd oil crisis also triggered a new demand for silicon materials. Nowadays, dislocation-free single crystals up to 18 inches in diameter can be grown by using the Czochralski method. Even for multicrystalline silicon produced by casting, solar cells made from it could reach near 20% conversion efficiency. In addition, high-quality silicon thin films, amorphous and crystalline, for large solar panels up to $2.4 \times 2.6\ m^2$ in size can be fabricated by plasma-enhanced chemical vapor deposition (PECVD) reactors. Silicon nanowires, tubes, and particles have also been synthesized in research laboratories showing promising properties for various applications including energy storage and biotechnology. With these developments, a number of books have been dedicated to silicon materials. Therefore, as I received this new book, the question that came to my mind was simple. Is this new book edited by Prof. Sergio Pizzini special enough and quite different from the existing ones? After I read it, my answer is "Yes", even though my personal favorite is the section on bulk silicon, the first two-thirds of the book.

There are three points that I feel make this book worthy of reading. The first is that most existing volumes for Si PV are out of date. In fact, many important advances in silicon materials for PV happened in the past decade, and the major driving force for these advances was the explosive development of PV industry in the recent years, which was stimulated initially by the Feed-in Tariff (FiT) program in Germany. Since the year 2000, the annual PV market has increased more than 100 times. The total annual PV installation in 2012 was more than 30 GW; the accumulated installation also exceeded 100 GW in the same year. The market share of Si PV was close to 90%, so that tremendous effort was put in to develop advanced silicon materials. The cost of solar panels now is only 60 cents W_p^{-1}, as compared with 4–5 USD W_p^{-1} in 2000. The polysilicon price in 2013 also hit \$15 kg^{-1} as well, the record low in silicon history. Many advances in silicon materials science and technology during these booming years, from solar grade (SoG) silicon, defect engineering, industrial materials standards, nanomaterials, etc., are absent in the existing volumes. However, one can find some interesting topics and critical issues for PV Si discussed in this book.

Secondly, the topics in this book are quite broad from silicon feedstock, defect engineering, characterization, thin films, and nanomaterials, to third-generation solar cells, but in 400 pages. This is about the right size to carry, and it should be a good reference book for engineers, researchers, and students who are interested in silicon materials and PV. Last but not the least, most chapters are written by leading experts in the field with extensive literature reviews and in-depth discussions. The cited references with complete titles are useful.

This book consists of ten chapters. The first chapter gives a short introduction of silicon, but its linkage to the following chapters is weak because it is focused on thermonuclear applications rather than on PV. Chapter 2 is dedicated to Si feedstock processes. Low-cost production technologies for SoG Si are reviewed including the traditional Siemen's and fluidized-bed reactor processes, as well as the newly developed free-space and tubular reactors. More importantly, the commercialization of early-stage processes, such as the metallurgical route by Elkem and the SRI process by Muto, is also discussed. Some innovative developments in research laboratories are also reviewed. This chapter on PV Si feedstock is the most up-to-date, and quite comprehensive, one among the existing books. Chapter 3 on the role of impurities in PV Si is excellent, covering the most important issues and findings in recent years. This topic is very important to Si PV. Through the understanding of the impurity impacts, one could customize SoG Si for low-cost and high-efficiency solar cells. The discussions on upgraded metallurgical grade (UMG), compensated silicon, and the industrial standards for Si feedstock are also very good. One can read about the role of impurities in Chapter 3, and then how to remove impurities through gettering from the wafer or cell processing is discussed in Chapter 4; this is a nice arrangement. The review of gettering and the discussion of the role of extended defects in Chapter 4 are extensive with up to 240 references.

The characterization in Chapter 5 is also quite informative; some discussion on the extended defects and nanostructures is interesting. Although this chapter is short, the focus on meso- and nanoscale seems to be a right decision, not to repeat some common topics that are available in other books. Chapter 6 is again a short one contributed by Dr. Hockett from Evans Analytical Group, a well-known company for analytical measurement service. The in-depth discussion of the industrial standards for impurity measurements in Si feedstock is a good reference for engineers to understand the common test methods and techniques used in the industry.

Chapters 7–9 are devoted to the thin-film processes, including CVD, modeling, and solar cells. Although many books have been dedicated to the same topics, the review in these chapters is also quite up-to-date. The discussion in Chapter 7 is focused on the fundamental mechanisms and the in situ diagnostic techniques; the reaction and deposition kinetics are discussed quite well. Special attention on the high-speed deposition of high-quality thin films, as well as the structure control, makes this

chapter a successful one. The recent industrial development of large-area deposition is discussed, but it falls too short of a complete treatment. Nevertheless, the critical issues, such as dust formation and how to reduce it during deposition, are reviewed and discussed. This chapter is quite informative to researchers and engineers who use PECVD or hot-wire CVD reactors for silicon thin films.

The introduction of CVD modeling of the thin-film deposition is Chapter 8 is in great depth, from the detailed gas and surface reactions to morphological evolutions. Although the plasma physics and detailed kinetics are extremely complicated, and cannot be addressed sufficiently in a single chapter, the systematic modeling approaches introduced in this chapter are a good reference for researchers and students who are working on this field.

Chapter 9 is for thin-film silicon solar cells. Again, similar reviews could be found elsewhere. However, this chapter gives an up-to-date review and discussion, especially on the recent progress of Si thin-film solar cells in research laboratories and companies; up to 164 references are cited. Some critical technological issues, such as thin cells and intermediate reflectors for optical management, are discussed. The discussions on the third-generation and flexible solar cells on plastics, as well as hybrid cells, are interesting. The challenges of silicon thin-film solar cells and how they can compete with other technologies, such as CdTe and CIGS, are discussed.

The final chapter on the quantum properties of nanosilicon and how they can be applied to solar cells is an extensive review, and 152 references are cited. Although the applications of silicon nanocrystals or quantum dots and third-generation concepts on up/down conversion, intermediate bands, multiple excitons, and hot carriers, are still in an early stage, the research activity in this area is very high in the past decade. The review from the fabrication of a variety of nanosilicon materials to their properties and potential applications is comprehensive and extensive.

In summary, the editor did a good job in putting these interesting topics together and linking them well. Besides some shortcomings, such as uneven topical discussion and a bit of divergence in covering too many things in a small volume, this book provides an excellent and up-to-date overview and discussion of the essential topics and critical issues in PV Si. It should be a good reference for people who are interested in silicon materials. Although many existing volumes are available in similar topics, this book should be the most up-to-date one for PV silicon.

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DOI: 10.1002/ente.201305015