edited by Jan Valenta and Salvo Mirabella

# Nanotechnology and Photovoltaic Devices

## Light Energy Harvesting with Group IV Nanostructures

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Pan Stanford Publishing

*Published by*

Pan Stanford Publishing Pte. Ltd.
Penthouse Level, Suntec Tower 3
8 Temasek Boulevard
Singapore 038988

Email: editorial@panstanford.com
Web: www.panstanford.com

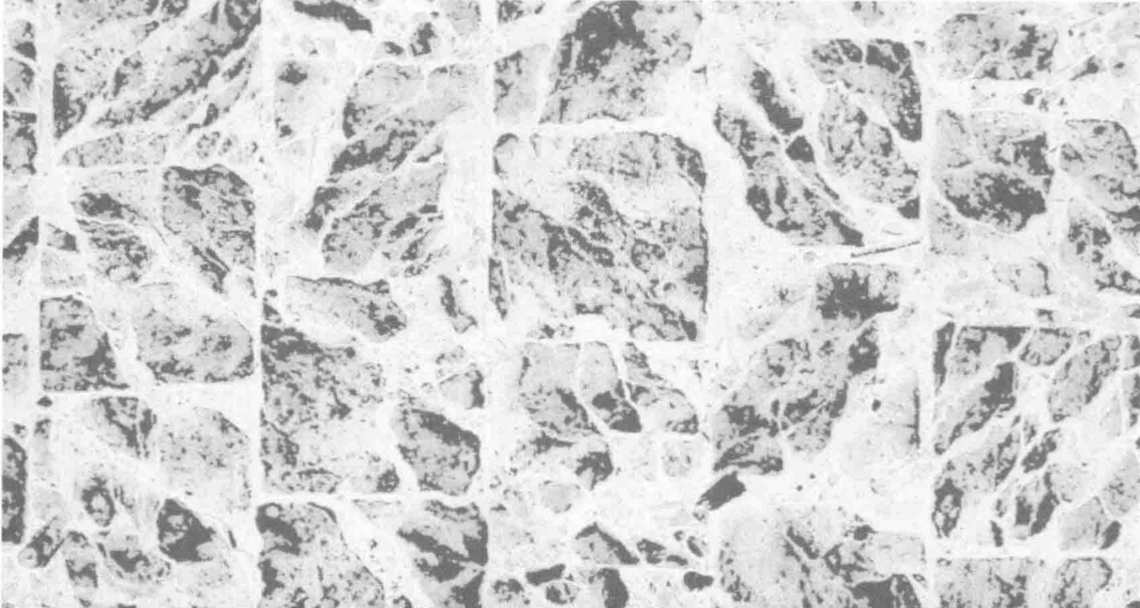
**British Library Cataloguing-in-Publication Data**
A catalogue record for this book is available from the British Library.

**Nanotechnology and Photovoltaic Devices: Light Energy Harvesting with Group IV Nanostructures**

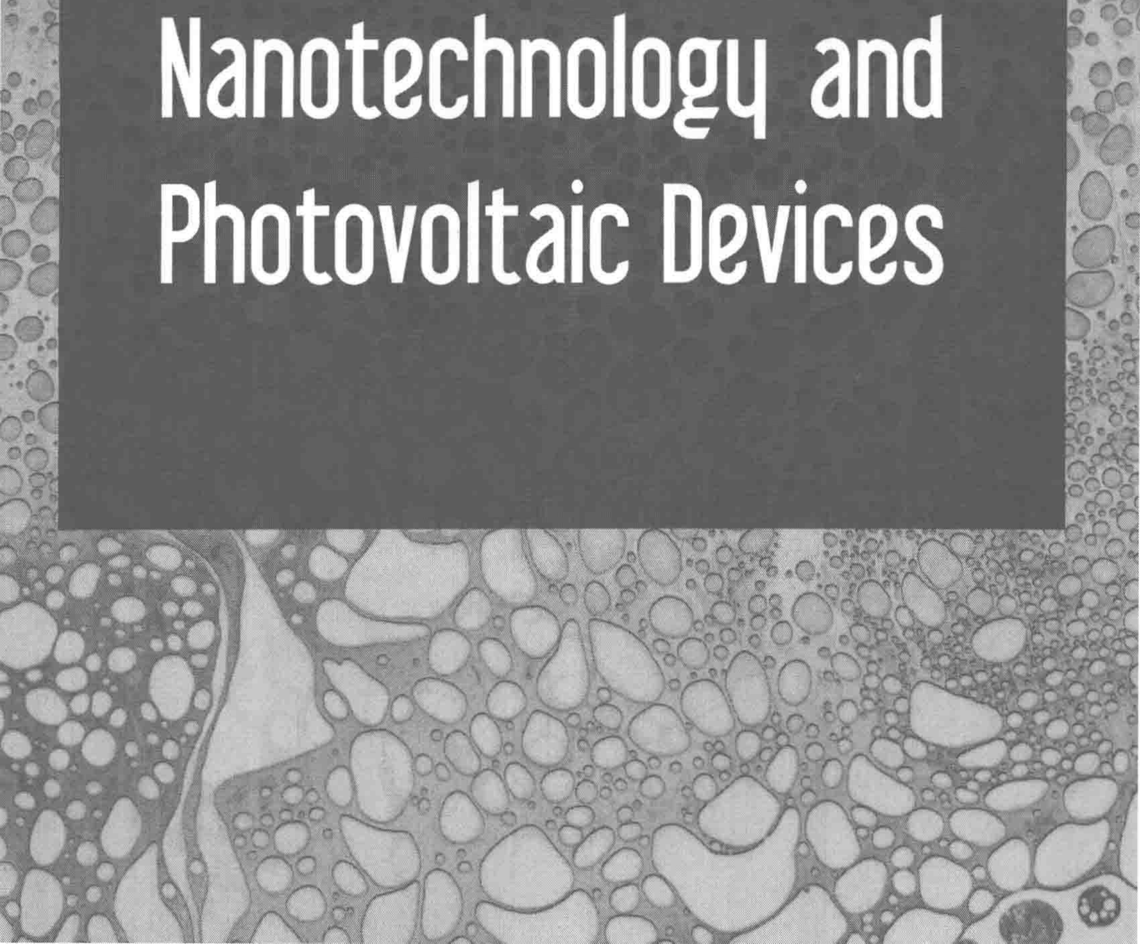


ISBN 978-981-4463-63-8 (Hardcover)
ISBN 978-981-4463-64-5 (eBook)

Printed in the USA



# Nanotechnology and Photovoltaic Devices



# Preface

The increasing energy demand of humankind on the Earth cannot be reasonably sustained by prolonged exploitation of fossil fuels. Therefore we have to turn toward efficient usage of the most abundant renewable supply of energy—it means the Sun. When considering Photovoltaics' aim, the direct transformation of solar photon flux into electrical energy, the most practical materials for this transformation are semiconductors whose absorption matches quite well solar photons' energy and whose conductivity can be adjusted so that photogenerated charge carriers are separated and directed to make useful work in an external circuit. Fortunately, some of these materials are very abundant, especially silicon, but other elements from group IV of the periodic table of elements are also extremely interesting. However, the maximum efficiency in energy conversion of the solar spectrum by a single semiconductor material is limited, as described by the famous Shockley–Queisser limit. To overcome this constraint, most of the proposed ideas, commonly labeled as third-generation Photovoltaics, are based on Nanotechnology employing materials whose energy scheme is more complex and variable. There are such materials, namely, semiconductor nanostructures, that enable us to tune their energy levels, density of electronic states, transition probabilities, etc., with large potential benefits for light energy conversion.

The purpose of this book is to summarize the knowledge and current advances of group IV semiconductor nanostructures potentially applicable in the next generations of solar cells. Considering the increasing research efforts devoted to nanostructure applications in Photovoltaics, our intention was to provide a clear background to students and newcomer researchers as well as to point out some open questions and promising directions of future development.

The book presents a broad overview on group IV nanostructures in Photovoltaics, beginning with a theoretical background, presentation of main solar cell principles, technological aspects, and nanostructure characterization techniques and finishing with the design and testing of prototype devices. The limited space of one book did not allow us to include some special nanostructure-related subjects, such as nanocrystal-sensitized solar cells (Grätzel cells or polymer cells), microcrystalline and amorphous silicon materials, rare-earth-doped nanostructures, plasmonic structures, etc. It is not intended to be just a review of the most up-to-date literature, but the contributing authors' ambition was to provide an educative background of the field. In view of the harsh economic competition in the solar cell business it might be that nanostructures will never be a commonly used material in Photovoltaics' massive production; still the solid background knowledge gained by researchers and summarized in this book will help in applying nanostructures to this and other fields.

The idea to compile this book was born in 2012 within the framework of a successful European research project (NASCEnT, Silicon nanodots for solar cell tandem, 2010–2013, 7FP project contract 245997), and in fact, many authors of the book participated in that project. Therefore we shall thank the European Commission for the support and Pan Stanford Publishing for its effort and helpful cooperation. The main acknowledgment goes to all chapter authors, who invested a lot of time and effort into the success of this book.

**Jan Valenta and Salvo Mirabella**
Prague and Catania
January 2015

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# Chapter 1

# Introduction to Photovoltaics and Potential Applications of Group IV Nanostructures

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The human population increase along with the raise of living standards is about to cause doubling of the global primary energy consumption in less than 50 years [1]. Such continuous increase of energy demand will soon become unsustainable when considering that most of the currently exploited energy comes from fossil fuels whose resources are, obviously, limited. Moreover, burning of fossil fuels by the humankind in the past 250 years released such a quantity of carbon (in the form of $CO_2$—an important greenhouse gas) that it took our planet about 250 million of years to sequester [2]. An increasing awareness comes up on the energy demand issue and new pressing challenges arise to provide people with enough energy within a sustainable development scenario.

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ISBN 978-981-4463-63-8 (Hardcover), 978-981-4463-64-5 (eBook)
www.panstanford.com

Among other means, the research and development of new technologies and materials for energy is particularly important. In this context, a wide and exciting range of possible solutions is provided by nanotechnologies offering innovative materials with unique properties exploitable for energy production, distribution and saving.

In this book we deal with nanostructures based on group IV elements (e.g., Si quantum dots, C nanotubes, Ge nanowires, etc.) which attracted great attention during the last two decades. Their main advantages are abundance, nontoxicity, high attainable purity, and mature technology, which promise effective exploitation of these nanomaterials in advanced photovoltaic devices.

## 1.1 Energy from the Sun

The solar photon flux is the only sustainable source of energy for the earth (the current knowledge predicts that this flux will be slowly increasing during next billion years (Gyr) for which the life can survive on the earth[a]) [3]. On the other hand electricity is currently the most versatile form of energy used by human civilization. Therefore the direct transformation of photon energy into electricity in devices called solar cells (SCs) attracts still more interest and motivates effort of scientific research and industry.

The photon emission comes from the solar outer shell called photosphere, which has temperature around 5800 K and the spectrum corresponds to the thermal radiation of the black body with this temperature (Fig. 1.1a). On the surface of the earth the sunshine spectrum is modified by absorption in the earth atmosphere; the main absorption occurring in the ultraviolet (UV) and infrared (IR) spectral regions.

[a]The sun is now about 4.6 Gyr old and will remain in the main sequence of star evolution in total for about 10 Gyr. Then, after ~5 Gyr, it will enter the red giant stage (expanding and cooling down). However, luminosity of the sun is—in the current main sequence state—increasing by about 10% per billion years. This will probably disable the life on the earth in about 1 Gyr [3]. The possible lifetime of humankind is another question.