Preface

This book attempts to present a bigger picture of solar photovoltaics. It goes beyond the commonly discussed topics in solar photovoltaics such as solar cell physics, manufacturing, cost, and efficiency. The question it intends to provide some insights into is: what will prevent solar photovoltaics from becoming a noticeable source of energy in the future? In other words, how big a role will solar photovoltaics play in our future energy mix? This is certainly not an easy task, especially for one author. As the reader will find out, the book contains more questions than answers.

The deployment scale of solar photovoltaics has to reach tens to hundreds of peak terawatts for solar electricity to become an important source of energy in our life. The sheer scale required for solar photovoltaics results in many roadblocks and bottlenecks which are unprecedented in other semiconductor technologies. In this book, roadblocks refer to showstoppers which, if not removed, will prevent solar photovoltaics from reaching a terawatt scale. Bottlenecks are difficulties in solar photovoltaics which we prefer to overcome, but can live with if push comes to shove. Efficiency and cost are bottlenecks, and there are more fundamental limitations to terawatt-scale deployment of the current commercial solar cell technologies.

This book reflects the author's view on some of the roadblocks and bottlenecks for terawatt solar photovoltaics. Availability of raw materials, energy input in solar cell manufacturing, storage of solar electricity, and recycling of end-of-life solar modules can all prevent or hinder a tangible impact by solar photovoltaics. After brief discussions on the status, physics, and manufacturing of current solar cell technologies, the book presents analyses, as quantitative as possible, on these roadblocks and bottlenecks to terawatt solar photovoltaics. Thought-provoking ideas to overcoming some of these roadblocks and bottlenecks are discussed.

The author purposely stayed away from many "third-generation concepts" for solar photovoltaics which open up many possibilities for innovative ideas. Instead, the book focuses on demonstrated physics for solar photovoltaics and explores how today's solar photovoltaics can be expanded to a terawatt scale. Predicting the future is always difficult. It becomes practically impossible when there are so many uncertainties at this time for many of the third-generation concepts for solar photovoltaics.

The book is divided into seven chapters. Chapter 1 answers the question: why do we need solar photovoltaics? Chapter 2 reviews the current status of solar photovoltaics including cell technologies and their cost, efficiency, and market. Chapter 3 outlines the physics of solar cells in an across-the-board and less mathematical manner. Chapter 4 focuses on the manufacturing processes, and their costs and energy inputs, for wafer-Si solar cells and modules. Chapter 5 analyzes several roadblocks and bottlenecks for terawatt-scale deployment of current commercial solar cell technologies. Chapter 6 discusses ideas to overcoming some of the roadblocks and bottlenecks in solar cell technologies and in storage of solar electricity. Chapter 7 summarizes the major roadblocks and bottlenecks for potentially terawatt-capable solar cell technologies.

The book is intended for readers with a general interest in energy and a minimal technical background. For this reason, the mathematics required to understand the physics of solar cells is purposely kept to a minimum. Nevertheless, the book involves many disciplines of science and engineering, in particular semiconductor physics, semiconductor processing, and materials chemistry. It is assumed that the reader is technically literate, maybe with a science or engineering bachelor degree, but not necessarily a specialist in the subject of solar photovoltaics. The multidisciplinary nature of solar photovoltaics is illustrated in the book as it requires a broad knowledge base to go through the entire book.

The author got interested in these long-term big-picture issues for solar photovoltaics by accident, which occurred through the establishment of the U.S. Photovoltaic Manufacturing Consortium under SEMATECH in Albany, New York. In summer 2006 when SEMATECH was looking for new research directions, the author made a suggestion for solar photovoltaics. For the next 5 years, the author helped Mr. Dan Holladay, the person in charge of SEMATECH's strategic initiatives at the time, push through the idea. By early 2009, Dan was approaching the U.S. Department of Energy for a nationwide SEMATECH-style industrial consortium for photovoltaic manufacturing technologies. When the initiative became national, it forced the author to think about longer-term, bigger-picture, national, and then global issues in solar photovoltaics. In summer 2009, the author went to Hong Kong University of Science and Technology for a short sabbatical, which provided more free time for the author to ponder through these issues and complete the preliminary analysis on resource limitations to terawatt solar photovoltaics. The first presentation by the author on this analysis was made in January 2010 at the U.S. Photovoltaic Manufacturing Consortium Strategy Workshop in Washington, DC. The first analysis has been revised and expanded multiple times since then, and takes its current form as presented in this book.

There are many people to whom the author is indebted. Mr. Dan Holladay of SEMATECH is the person who got the author into this subject. His determination and dedication to bring industry and academia together for a prosperous U.S. solar cell industry have been a constant inspiration to the author. Prof. Qiming Zhang of the University of Texas at Arlington is a long-time collaborator of the author. His first-principles studies on Earth-abundant solar photovoltaic materials have guided the experiments of the author and his students. Prof. Ellen Stechel

of Arizona State University and the author have had enlightening discussions on solar-powered electrolysis for storage of solar electricity. These discussions led to the idea of metals as solid fuels for a closed, sustainable energy loop. The author would also like to thank the students and postdoctoral fellows who have worked with him over the years. In particular, Dr. Xiaofei Han, who completed his Ph.D. under the author, made several important and original contributions to the research in the author's group on terawatt wafer-Si and post-Si solar photovoltaics. The many graduate and undergraduate students who have taken the author's classes on solar photovoltaics at Arizona State University, the University of Texas at Arlington, and Hong Kong University of Science and Technology have contributed to this book through their intuitive comments and questions. Last but not least are the family members of the author, Lilly, Coby, and Della, for their unconditional love and support. Coby, son of the author, did all the calculations in the first few analyses on resource limitations to terawatt solar photovoltaics between 2009 and 2010, when he was a high-school junior. He now majors in Chemical Engineering in college.

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