

**BASIC
PHOTOVOLTAIC
PRINCIPLES
AND METHODS**

Solar Energy Research Institute

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Foreword

We are all very familiar with the photosynthetic process, which utilizes sunlight to biochemically fix carbon dioxide in the growth of plants. However, there are other ways in which sunlight can interact with matter, from simply heating it to releasing electrons from its atomic structure to produce a voltage. This latter phenomenon, which occurs in certain materials known as semiconductors, is the so-called photovoltaic effect; i.e., sunlight (*photons*) is absorbed to produce a low voltage (*voltaic*).

The purpose of this book is to introduce the concept of photovoltaics, discuss the underlying physics, review the research and development status, and, finally, to consider the potential applications for such systems. The content of the book would be valuable to the engineer unfamiliar with solid state physics, the business manager looking for new opportunities in solar energy, and the engineering student considering his future specialty.

The book is liberally complemented with excellent diagrams and figures to allow one to clearly visualize the phenomena taking place. This greatly enhances the value of the material in translating the abstract quantum mechanics of semiconductors into easily visualized voltage differences. Further, it elucidates the mechanisms which limit the efficiency of conversion of sunlight to electricity and illuminates the necessity of careful material and device design to obtain satisfactory performance.

If we look back for a moment, it was only 30 years ago that the key pioneering work on photovoltaics was conducted at the Bell Laboratories, with the development of the single-crystal silicon solar cell. Until the early 1970s, there were very few solar cell research programs and even fewer organizations prepared to provide "market quantities" in the tens-of-kilowatt production levels. However, in the mid-1970s, the nation began to commit more of its research and development funds to solar energy research and development, with photovoltaics becoming one of the central focuses

of this research program. In the modest period of less than a decade, both the development and application potential for photovoltaic systems have become apparent and are being initially realized.

Photovoltaics are being utilized for numerous specific remote applications, the foremost being space power systems; however, there is a great deal of research and development remaining to assure that these systems can provide economical, reliable power in large-scale dispersed or central station terrestrial applications. This book does not discuss the alternate power systems with which photovoltaics must compete.

From numerous evaluations which have been performed for the Electric Power Research Institute and the government, it is apparent that photovoltaic systems must achieve lifetimes of 15 to 20 years, with module efficiencies of over 15% and production costs of \$100/m² or less for non-concentrating systems and 20% to 30% efficiencies for concentrating systems with concentrator costs of \$120 to \$150/m² plus photovoltaic device costs of \$10 to \$20/m² to be economically competitive with other alternative systems. These are very difficult performance and cost targets to achieve; however, they provide the stimulus for an active, exciting research challenge.

SERI is answering that challenge with a diversified research program to develop advanced processes to produce single-crystal silicon, amorphous silicon single- and multi-junction cells, and thin film cells such as copper-indium diselenide. Significant advances in improving the performance of these alternate photovoltaic cells has already been made by SERI and other leading photovoltaics organizations and many more will come.

A recent assessment of the status of photovoltaics research by experts in the field indicates that we are likely to see economically competitive concentrating photovoltaic systems deployed within 10 years, and non-concentrating systems, most likely utilizing thin films such as copper-indium diselenide or amorphous silicon, within 15 to 20 years. Truly we are on the brink of a new major technological success story that will impact all of our daily lives and enhance the energy security of our country. I am delighted to be a part of that

story and to have the opportunity to provide the foreword to this most stimulating book. Read it and become excited about one of our principal opportunities to utilize our true gift from the heavens, sunlight.

DWAIN F. SPENCER
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Systems Division, Electric
Power Research Institute;*
Member, Solar Energy Research
Institute Advisory Board

Preface

This book presents a nonmathematical explanation of the theory and design of photovoltaic (PV) solar cells and systems. It is written to address several audiences: engineers and scientists who desire an introduction to the field of photovoltaics, students interested in PV science and technology, and end users who require a greater understanding of theory to supplement their applications.

The book is effectively sectioned into two main blocks: Chapters 2 through 8 cover the basic elements of photovoltaics—the individual electricity-producing cell. The reader is told why PV cells work, and how they are made. There are also chapters on advanced types of silicon cells and on so-called thin-film cells. Chapters 9 to 12 cover the designs of systems constructed from individual cells—including possible constructions for putting cells together and the equipment needed for a practical producer of electrical energy. In addition, Chapter 13 deals with PV's future. Chapter 1 is a general introduction to the field.

The principal authors of this document are Kenneth Zweibel (Photovoltaics Program Office) and Paul Hersch (Technical Information Branch). They would like to thank their colleagues at the Solar Energy Research Institute's Solar Electric Conversion Division who reviewed the manuscript for technical accuracy: Richard Bird, Kathryn Chewey, Satyen Deb, Keith Emery, Kay Firor, Steve Hogan, Larry Kazmerski, Jack Stone (Solar Electric Division Deputy Manager and SERI's Manager of the PV Advanced R & D Program), Thomas Surek, and Simon Tsuo. Joe Milstein and Harv Mahan of SERI's Solar Electric Conversion Research Division were of inestimable help in assembling the material on polycrystalline silicon and amorphous silicon; Alan Postlethwaite (DOE Photovoltaic Energy Technology Division) reviewed the drafts and suggested important improvements. Barbara Glenn (Technical Information Branch) produced the document. Gary Cook and Richard Piekarski of the Technical Information Office, who designed the document,

« PREFACE

were also helpful readers. Graphic Directions of Boulder, Colorado, was responsible for the text's figures, often with valuable improvements. Vincent Rice of the Photovoltaics Program Office at DOE was supportive throughout, giving impetus to the project.

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1

Introduction

Photovoltaic systems behave in an extraordinary and useful way: They react to light by transforming part of it into electricity. Moreover, this conversion is novel and unique, since photovoltaics:

- *Have no moving parts* (in the classical mechanical sense) to wear out.
- *Contain no fluids or gases* (except in hybrid systems) that can leak out, as do some solar-thermal systems.
- *Consume no fuel* to operate.
- *Have a rapid response*, achieving full output instantly.
- *Can operate at moderate temperatures*.
- *Produce no pollution* while producing electricity (although waste products from their manufacture, and toxic gases in the event of catastrophic failure and disposal may be a concern).
- *Require little maintenance* if properly manufactured and installed.
- *Can be made from silicon*, the second most abundant element in the earth's crust.
- *Are modular*, permitting a wide range of solar-electric applications such as
 - Small scale* for remote applications and residential use
 - Intermediate scale* for business and neighborhood supplementary power
 - Large scale* for centralized energy farms of square kilometers size.
- *Have a relatively high conversion efficiency*, giving the highest overall conversion efficiency from sunlight to electricity yet measured.
- *Have wide power-handling capabilities*, from microwatts to megawatts.
- *Have a high power-to-weight ratio*, making them suitable for roof application.

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- *Are amenable to on-site installations*, i.e., decentralized or dispersed power.

Clearly, photovoltaics have an appealing range of characteristics.

However, there are ambivalent views about solar, or photovoltaic, cells' ability to supply a significant amount of energy relative to global needs.

- Those pro, contend that solar energy is abundant, inexhaustible, clean, and cheap.
- Those con, claim that solar energy is tenuous, undependable, and expensive beyond practicality.

There is some truth to both of these views. The sun's energy, for all practical purposes, is inexhaustible. However, even though sunlight striking the earth is abundant, it comes in rather a dilute form.

THE SUN

The sun is an average star. It has been burning for more than four billion years, and it will burn at least that long into the future before erupting into a giant red star, engulfing the earth in the process.

Some stars are enormous sources of X-rays; others mostly generate radio signals. The sun, while producing these and other energies, releases 95% of its output energy as light, some of which cannot be seen by the human eye. The peak of its radiation is in the green portion of the visible spectrum. Most plants and the human eye function best in green light since they have adapted to the nature of the sunlight reaching them.

The sun is responsible for nearly all of the energy available on earth. The exceptions are attributable to moontides, radioactive material, and the earth's residual internal heat. (Even these are present only because of processes in the early solar system.) Everything else is a converted form of the sun's energy: Hydropower is made possible by evaporation-condensation due to solar radiant heat; the winds are caused by the sun's uneven heating of the earth's

atmosphere; fossil fuels are remnants of organic life previously nourished by the sun; and photovoltaic electricity is produced directly from sunlight by converting the energy in sunlight into free charged particles within certain kinds of materials.

The Nature of Light Energy

Light is energy. You need only be exposed to its rays to realize this fact. An understanding of the nature of light will help in comprehending how solar cells work.

The sun's light looks white because it is made up of many different colors that, combined, produce a white light. Each of the visible and invisible radiations of the sun's spectrum has a different energy. Within the visible part of the spectrum (red to violet), red is at the low-energy end and violet is at the high-energy end—having half again more energy as red light. Light in the infrared region (which we can't see but feel as heat) has less energy than that in the visible region. Light in the ultraviolet region (which is invisible but causes the skin to tan) has more energy than that in the visible region.

Visible light represents only a tiny segment of a vast radiation spectrum. Studies of light and similar radiation show that the way in which one light ray interacts with another or other physical objects often can be explained as if light were moving as a wave. For this reason it is useful to characterize light radiation by parameters associated with waves. All waves have a certain distance between peaks (called the wavelength) (Figure 1-1). This wavelength can also be expressed as a frequency (the number of peaks in a specified distance or during a specified time of propagation). Thus a wave with a long distance between peaks (long wavelength) has a lower frequency than one with a shorter wavelength (many peaks). (Note that frequency and wavelength vary inversely.) For any wave, the energy associated with the wave increases as the frequency increases (wavelength decreases). Red light has a wavelength of about 0.66 micrometers* (453 terahertz, or about 3×10^{-12} ergs [3×10^{-24} kW-h per "particle" of light, or photon), violet light, about 0.44 micro-

* A micrometer (μm) is one millionth of a meter.

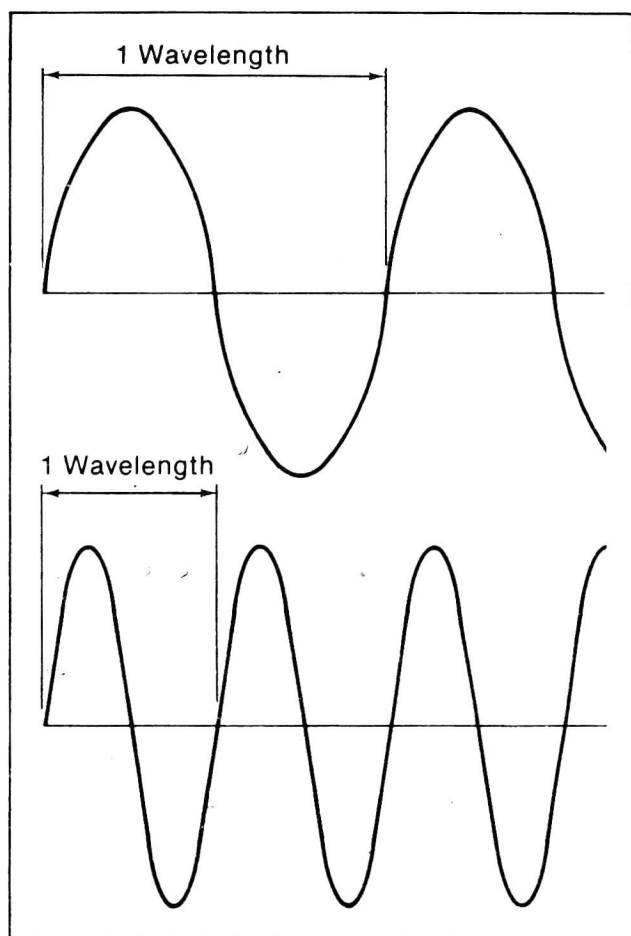


Figure 1-1. Light interacts with itself and objects in a way that suggests it is a wave. Two ideal waves are depicted in the illustration. The top wave has a wavelength (the distance between two points where its shape repeats) that is twice that for the bottom one. Every wave also has a frequency of propagation that is *inversely* related to the wavelength in a manner depending on the velocity of propagation of the wave: Specifically, wavelength equals velocity of propagation divided by frequency. In the illustration the bottom wave has half the wavelength but twice the frequency of the one above it.