SOLAR CELLS

Operating Principles, Technology, and System Applications

MARTIN A. GREEN

PRENTICE-HALL SERIES IN SOLID STATE PHYSICAL ELECTRONICS
Nick Holonyak, Jr., *Editor*

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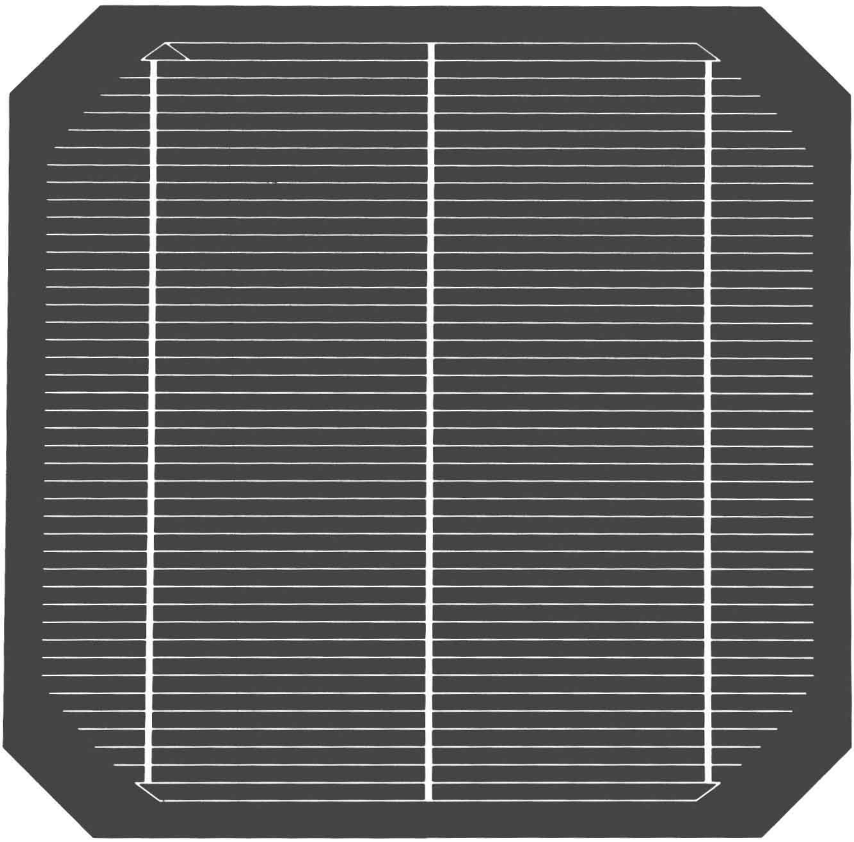

This solar cell is made from a thin wafer of the semiconductor silicon, about 10 cm square and only a fraction of a millimeter thick. When the cell is illuminated, it converts the energy of the photons in the incident light into electrical energy. Under bright sunshine, the cell can supply a current of up to 3 A at a voltage of about $\frac{1}{2}$ V to an electrical load connected between the metallic contact grid apparent here and a second contact at the rear of the cell. (Photograph courtesy of Motorola, Inc.)

PREFACE

When sunlight strikes a solar cell, the incident energy is converted directly into electricity without any mechanical movement or polluting by-products. Far from being a laboratory curiosity, solar cells have been used for over two decades, initially for providing electrical power for spacecraft and more recently for terrestrial systems. There are very real prospects that the manufacturing technology for these cells can be improved dramatically in the near future. This would allow solar cells to be produced at prices where they could make significant contributions to world energy demands.

This book concentrates on providing descriptions of the basic operating principles and design of solar cells, of the technology used currently to produce cells and the improved technology soon to be in operation, and of considerations of importance in the design of systems utilizing these cells. Accordingly, the early chapters of the book review the properties of sunlight, the relevant properties of the semiconductor material from which the cells are constructed, and the interaction between these two elements. The next group of chapters treat in some detail the factors important in the design of solar cells, current technology for fabricating them, and probable technological developments in the future. The final chapters deal with system applications, ranging from the small systems commercially available at present to residential and central power systems that may be available in the future.

The book is intended primarily for the increasing numbers of engineers and scientists attracted to this rapidly expanding field. As such, it is suitable for use as a textbook for both undergraduate and graduate courses. A deliberate attempt has been made not to exclude the material contained within from those readers who are entering the field through a different route. For example, a rather pictorial review of the properties of semiconductors relevant to the understanding of solar cell operation is included. Although this may serve as a quick review for many readers, for other readers it may provide a framework on which the material in subsequent chapters can be supported. Irrespective of background, working through the text and associated exercises would place the reader in a very strong position for future activity in this area.

I would like to acknowledge the large number of people, too numerous to mention individually, who have stimulated my interest in solar cells over the last decade. I would particularly like to thank Andy Blakers, Bruce Godfrey, Phill Hart, and Mike Willison for their suggestions and indirect encouragement in this venture. Special thanks are due to Gelly Galang for her help in preparing the manuscript and to John Todd and Mike Willison for preparing photographs incorporated into the text. Finally, I would like to thank Judy Green for her support and encouragement during the fairly intense period in which this book was developed.

Martin A. Green

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Chapter

1

SOLAR CELLS AND SUNLIGHT

1.1 INTRODUCTION

Solar cells operate by converting sunlight directly into electricity using the electronic properties of a class of material known as semiconductors. In the following chapters, this elegant energy-conversion process will be examined starting from the basic physical principles of solar cell operation. From this basis, the mathematical equations quantifying the energy transformation are developed. This is followed by a description of the technology used to produce present commercial solar cells, based predominantly on a particular semiconductor, silicon. Improvements in this technology, as well as alternative technologies that hold the promise of significantly lower cost, are then described. Finally, the design of solar cell systems is discussed, ranging from small power supplies for remote-area use to possible future residential and central power-generating plants.

In this chapter, the history of solar cell development is outlined briefly, followed by a review of the properties of the sun and its radiation.

1.2 OUTLINE OF SOLAR CELL DEVELOPMENT

Solar cells depend upon the *photovoltaic effect* for their operation. This effect was reported initially in 1839 by Becquerel, who observed a light-dependent voltage between electrodes immersed in an electrolyte. It was observed in an all-solid-state system in 1876 for the case of selenium. This was followed by the development of photocells based on both this material and cuprous oxide. Although a silicon cell was reported in 1941, it was not until 1954 that the forerunner of present silicon cells was announced. This device represented a major development because it was the first photovoltaic structure that converted light to electricity with reasonable efficiency. These cells found application as power sources in spacecraft as early as 1958. By the early 1960s, the design of cells for space use had stabilized, and over the next decade, this was their major application. Reference 1.1 is a good source of more detailed material up to this stage.

The early 1970s saw an innovative period in silicon cell development, with marked increases in realizable energy-conversion efficiencies. At about the same time, there was a reawakening of interest in terrestrial use of these devices. By the end of the 1970s, the volume of cells produced for terrestrial use had completely outstripped that for space use. This increase in production volume was accompanied by a significant reduction in solar cell costs. The early 1980s saw newer device technologies being evaluated at the pilot production stage, poised to enable further reduction in costs over the coming decade. With such cost reductions, a continual expansion of the range of commercial applications is ensured for this approach to utilizing the sun's energy.

1.3 PHYSICAL SOURCE OF SUNLIGHT

Radiant energy from the sun is vital for life on our planet. It determines the surface temperature of the earth as well as supplying virtually all the energy for natural processes both on its surface and in the atmosphere.

The sun is essentially a sphere of gas heated by a nuclear fusion reaction at its center. Hot bodies emit electromagnetic radiation with a wavelength or spectral distribution determined by the body's temperature. For a perfectly absorbing or "black" body, the spectral distribution of the emitted radiation is given by *Planck's radiation law* (Ref. 1.2). As indicated in Fig. 1.1, this law indicates that as a body is heated, not only does the total energy of the electromagnetic