

PRACTICAL PHOTOVOLTAICS

ELECTRICITY FROM SOLAR CELLS



3rd edition revised

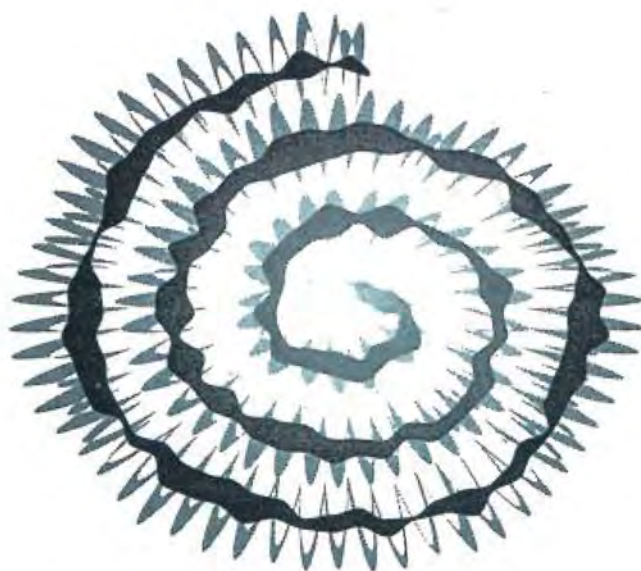
Richard J. Komp, Ph.D.

Introduction by John Perlin

HANWHA 1072

PRACTICAL PHOTOVOLTAICS

ELECTRICITY FROM SOLAR CELLS



3rd edition revised

Richard J. Komp, Ph.D.

Introduction by John Perlin



aatec publications • Ann Arbor, Michigan

Second Printing, 2002

Third Edition Revised, 2001

© 1995 **aatec publications**

aatec publications PO Box 7119 Ann Arbor, Michigan 48107
800.995.1470 (outside the U.S. 734.995.1470) FAX 734.995.1471
aatecpub@mindspring.com

Library of Congress Cataloging-in-Publication Data

Komp, Richard J.

Practical photovoltaics: electricity from solar cells / Richard

J. Komp. — 3rd ed.

p. cm.

Includes bibliographical references and index.

ISBN 0-937948-11-X

1. Solar cells. 2. Photovoltaic power generation. I. Title

TK2960.K65 1995

621/31'224—dc20

95-22580

CIP

All Rights Reserved. No part of this publication may be reproduced or transmitted in any form or by any means, electronic or mechanical, including photocopy, recording, or any information storage and retrieval system, without the written permission of the publisher.

"The History of Solar-Generated Electricity" © 1995 John Perlin

Manufactured in the United States of America

Translations by Catherine McCargar

Cover by Hesseltine & DeMason Design, Ann Arbor, Michigan

The author and **aatec publications** assume no responsibility for any personal injury, property damage, or other loss suffered in activities related to the information presented in this book. Please practice caution and follow proper safety procedures.

Contents

Preface and Acknowledgments	<i>vii</i>
Preface to the First Edition	<i>ix</i>
Introduction: The History of Solar-Generated Electricity <i>by John Perlin</i>	<i>xi</i>
Chapter 1 Solar Cells: What They Are and How They Work	<i>1</i>
What Solar Cells Are	<i>1</i>
Physical Characteristics	<i>1</i>
Electrical Characteristics	<i>2</i>
Cell Performance Ratings	<i>4</i>
How Solar Cells Work	<i>5</i>
The Nature of Sunlight	<i>5</i>
Solid-State Physics	<i>7</i>
Doping	<i>11</i>
Junction Photovoltaic Cells	<i>13</i>
Homojunctions	<i>13</i>
Factors Which Influence Cell Efficiency	<i>18</i>
Band Gap Width	<i>18</i>
Recombination	<i>19</i>
Reflectivity and Light Absorption	<i>20</i>
Heterojunctions	<i>20</i>

	Schottky Barrier Junctions	21
	Advanced Semiconductor Devices	22
	Recommended Readings	23
Chapter 2	How Solar Cells Are Made	25
	Silicon	25
	Metallurgical-Grade Silicon	26
	Semiconductor-Grade Silicon	26
	Growing Single Crystals	27
	Slicing the Crystal into Wafers	29
	Polishing and Etching the Wafer	29
	Forming the p-n Junction	30
	Applying the Fingers and Back Contact	32
	The Antireflection Coating	33
	Assembly into Modules	34
	New Production Techniques for Silicon	36
	Solar-Grade Silicon	36
	Polycrystalline Silicon	37
	Ribbon Growth Systems	39
	Amorphous Silicon	40
	Recommended Readings	47
Chapter 3	Solar Cells and Modules	49
	Series and Parallel Strings	49
	Module Construction Techniques	50
	Encapsulation	53
	Module Failure Mechanisms	53
	Joints Between Cells	53
	Encapsulant Problems	54
	Shunt Diodes	55
	Concentrator Systems	56
	Two-Axis Tracking	58
	One-Axis Tracking	59
	Recommended Readings	62
Chapter 4	Using Photovoltaics	63
	Current Cost of Solar Electricity	63
	Sizing the Array	69
	Calculating Load	69
	Sizing Methodology	70
	Installing Solar Cell Arrays	74
	Array Orientation	74
	Wiring the Array	76
	Combination Systems	76

	Inverters	77
	Rotary Inverters	78
	Solid-State Inverters	78
	Synchronous Inverters	79
	Recommended Readings	80
Chapter 5	Batteries and Other Storage Systems	81
	Storage Batteries	81
	The Lead-Acid Battery	82
	The Deep-Discharge Lead-Acid Battery	84
	Lead-Acid Cell Characteristics	87
	A Practical Battery Storage System	94
	Maintenance	95
	Sulfation	95
	Used Batteries	96
	Nickel-Cadmium Batteries	97
	Nickel-Iron Batteries	99
	Nickel-Hydride Batteries	100
	Small Storage Systems	101
	Mechanical Storage Systems	102
	Flywheels	102
	Hydrogen	103
	Recommended Readings	106
Chapter 6	New Developments in Photovoltaic Technology	107
	Other Junction Structures	108
	Tin Oxide and Indium Oxide	108
	Metal-Semiconductor Junctions	109
	Photoelectrochemical Cells	109
	Cadmium Sulfide/Cadmium Telluride and	
	Other II-VI Heterojunction Cells	110
	III-V Semiconductor Combinations	114
	Electroplated Cells	115
	Organic Semiconductors	117
	Clever Optical Systems	119
	Cascade Cells	120
	Luminescent Concentrators	122
	The Solar Thermophotovoltaic Systems	123
	Recommended Readings	124
Chapter 7	The Future of Photovoltaics	125
	U.S. Governments and Photovoltaics	126
	The Multinationals and Photovoltaics	128
	Photovoltaic Power Farms	131

	Foreign Solar Cell Activity	136
	Japan	136
	Western Europe	138
	Underdeveloped Countries	139
	The Solar Electric Home	141
	Solar Cells in Space	143
	The Solar Power Satellite	145
	A Proposed Alternative	146
	Recommended Readings	148
Appendix A	Assembling Your Own Modules	149
	Testing Solar Cells	150
	A Simple Solar Simulator	151
	A Simple Sample Holder	151
	Current-Voltage Measurements	153
	How Cells are Connected	154
	Soldering Solar Cells	158
	Building a Flat Plate Module	159
	Laying Out the Case	159
	Cutting the Plastic	160
	Gluing the Plastic Case	161
	Fastening the Cover	162
	Installing the Solar Cells	162
	Building a Hybrid Concentrator Module	163
	The Backing Support	164
	Isolating and Encapsulating the Cells	166
	The Reflector Wings	171
	Design	171
	Making the Reflector Wings	171
	A Hybrid Hot Air System	173
Appendix B	Manufacturers	175
Appendix C	Current Carrying Capacity of Copper Wire	177
Appendix D	Conversion Factors	179
Glossary		181
Index		191
About the Author		198

Preface

Since the first edition of *Practical Photovoltaics* was published, both the alternative energy field and the photovoltaics industry have experienced considerable change. While the pressing need for energy conservation and alternative energies continues, the panic has abated and government involvement in research and development has declined drastically. [Note to Edition 3.1: In 2001, the panic returned.] Nonetheless, the photovoltaics industry has become international in scope with an existence that goes far beyond the programs set up by the Department of Energy or other government agencies. More solar cell companies have started up, making photovoltaic cells by new processes, while the original companies have evolved and grown.

The amorphous silicon solar cell has come into its own, powering millions of calculators and other small devices; polycrystalline silicon blocks are being made into solar cells in Germany and Japan, as well as in the United States. Sales of solar cell modules and systems are growing fast, increasing from about five megawatts per year when the first edition was published in 1981 to better than 200 megawatts a year now, reflecting our increasing dependence on this subtle, silent energy source.

Solar cells are now an accepted and important product, the industry is maturing, and the future looks bright. PV cells are becoming more

efficient as their cost decreases. Research is continuing, not only to better understand the physics and chemistry of the present crystalline and amorphous solar cells, but also to develop entirely new cell concepts, such as high-efficiency tandem cells, and new materials, such as cadmium telluride, that are now being used in commercial products.

This third edition of *Practical Photovoltaics* has been extensively reorganized, offering an improved, even more clear presentation of its contents. Throughout, material has been brought up to date and new data added. To reflect the changes of the past few years, the chapters on "New Developments in Photovoltaic Technology" and "The Future of Photovoltaics" have been updated and expanded. The chapters on using and installing systems report recent developments and improvements. *Practical Photovoltaics, Third Edition*, is more comprehensive, useful, and current, and I look forward to its being as well received as its predecessors.

—RJK

ACKNOWLEDGMENTS

I gratefully acknowledge the aid of Dr. Dan Trivich, Dr. Edward Wang, and others who furnished a good deal of the information on photovoltaic cells and inspired me to develop this book.

I also am happy to thank Vicky Patton, who typed the manuscript; Lawrence Komp, who drew the diagrams; David Ross Stevens, who furnished many of the workshop photographs; and the manufacturers who kindly supplied illustrations.

Finally, I wish to acknowledge the help of my workshop participants, who have assisted in the development and testing of procedures used to make practical use of photovoltaics.

Chapter 1

Solar Cells: What They Are and How They Work

WHAT SOLAR CELLS ARE

Solar cells are solid-state devices that absorb light and convert light energy directly into electricity. This is done entirely within their solid structure; solar cells have no moving parts.

Physical Characteristics

When you look at a solar cell, you see a metallic-blue or black disc covered with thin silvery lines. (Figure 1.1 shows both typical silicon solar cells and the silicon materials from which they are made.) The actual work of converting sunlight into electricity occurs in the dark metallic area because dark colors absorb light more readily. The silvery lines are the **front contact fingers** and are used to make the electrical contact to the front of the cell. The fingers must be very fine so that as little sunlight as possible is blocked out. The back contact is a solid metal layer that both reflects light back up through



Figure 1.1. Silicon ingot, cylinder, wafers, and finished solar cells.
(Jet Propulsion Laboratory, California Institute of Technology)

the cell and makes a good electrical contact. A detailed explanation of how solar cells work appears later in this chapter.

Electrical Characteristics

In order to use photovoltaic cells, we should have a basic understanding of their electrical characteristics. When illuminated, the solar cell acts somewhat like a battery in that it produces a voltage between front and back. This voltage is developed across a junction that is built into the cell structure. This voltage can be used to produce a current, just like from a battery, but the amount of current is limited by the amount of light falling on the cell.

We can use a simple circuit, as shown in Figure 1.2, to explain the electrical behavior of solar cells. A load resistor connects the front and back of a solar cell. The resistance of the load can be varied from a short-circuit zero resistance to a very high value. Two meters—a voltmeter and an ammeter—measure the voltage developed across the cell and the current passing through the load.

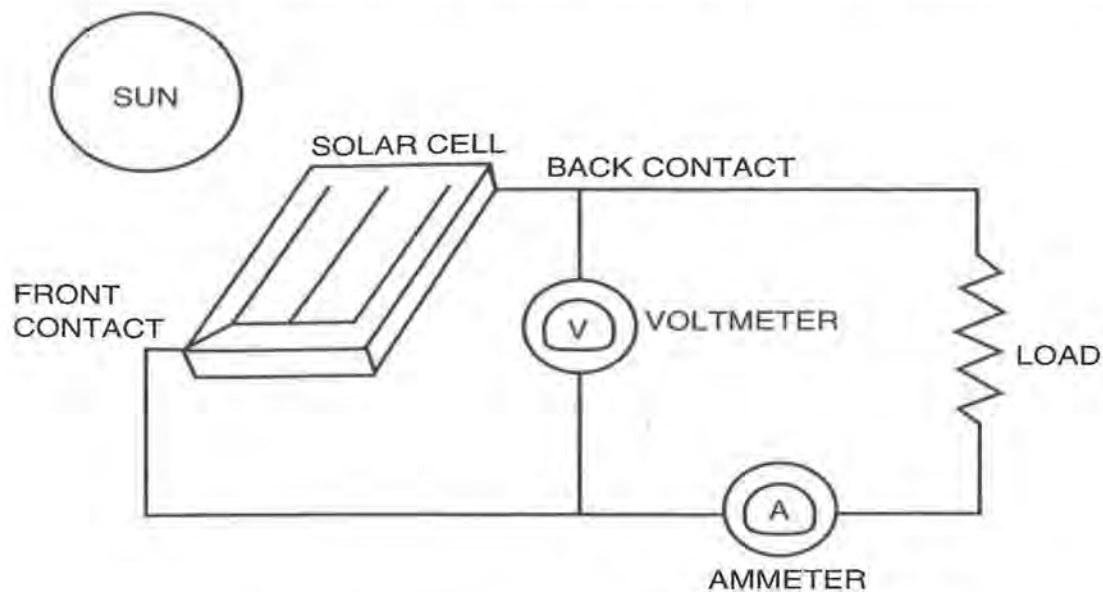


Figure 1.2. A simple circuit to test a solar cell.

If sunlight shines on the cell when the load resistance is very high or the load is disconnected (essentially giving infinite resistance), the voltmeter will read a maximum voltage. This is **open-circuit voltage**. For example, the voltmeter would read 0.58 volts on the typical silicon solar cell. No current is being drawn from the cell under these conditions.

Conversely, if the load resistance is made zero, we will short-circuit the cell (which does a solar cell no harm whatsoever) and draw the maximum possible current from the cell. This **short-circuit current** is directly proportional to the amount of light falling on the cell.

It is possible to adjust the load resistor between these two extremes and measure the voltages and corresponding current produced by the cell under different load conditions. The **current-voltage curve (I-V curve)** in Figure 1.3 shows the results of such an experiment. This figure plots the current on the vertical axis versus the voltage on the horizontal axis. The short-circuit current is shown on the current axis at zero voltage. As the load resistance increases, causing the voltage output of the cell to increase, the current remains relatively constant until the “knee” of the curve is reached. The current then drops off quickly, with only a small increase in voltage,

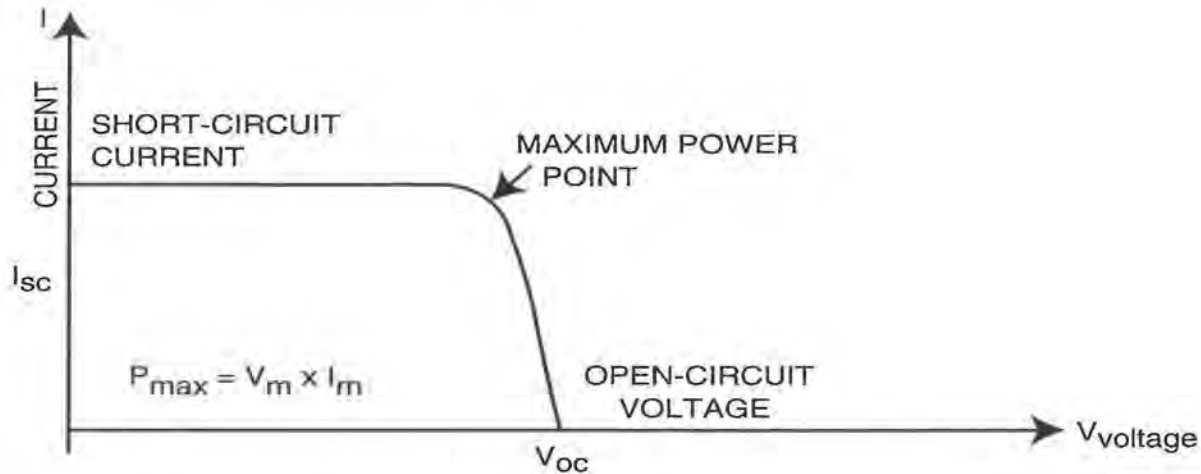


Figure 1.3. Current–voltage (I–V) characteristics of a silicon solar cell.

until the open circuit condition is reached. At this point, the open-circuit voltage is obtained and no current is drawn from the device.

The power output of any electrical device, including a solar cell, is the output voltage times the output current under the same conditions. The open-circuit voltage is a point of no power: the current is zero. Similarly, the short-circuit condition produces no power because the voltage is zero. The maximum power point is the best combination of voltage and current and is shown in Figure 1.3. This is the point at which the load resistance matches the solar cell internal resistance.

Figure 1.4 shows a series of I–V curves for a solar cell under different amounts of sunlight. The peak power current changes proportionally to the amount of sunlight, but the voltage drops only slightly with large changes in the light intensity. Thus, a solar cell system can be designed to extract enough usable power to trickle-charge a storage battery even on a cloudy day.

Cell Performance Ratings

To compare the performance of different solar cells, the cells are rated at specified amounts and types of sunlight. The most common rating parameter for terrestrial cells is **air mass 1 (AM1)**. This is the amount of sunlight that falls on the surface of the earth at sea level when the sun is shining straight down through a dry, clean atmo-

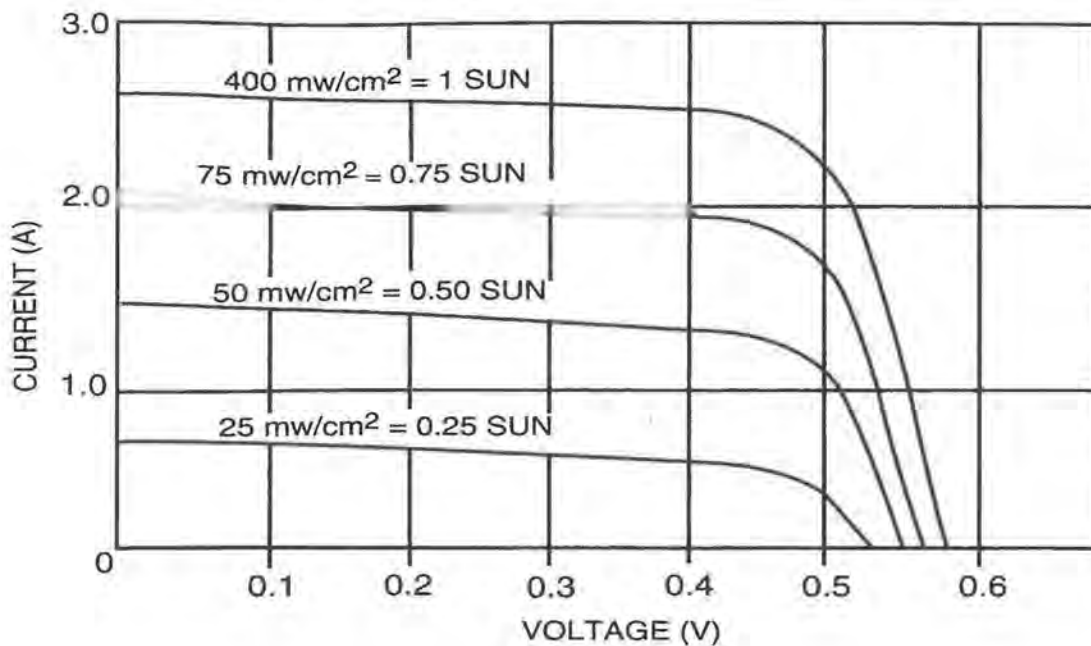


Figure 1.4. Series of I–V curves showing solar cell characteristics versus sunlight intensity.

sphere. The Sahara Desert at high noon, with the sun directly overhead, is a close approximation. The sunlight intensity under these conditions is very close to 1 kilowatt per square meter (1 kW/m^2). A closer approximation to the sunlight conditions usually encountered is **air mass 2 (AM2)**, an illumination of 800 W/m^2 .

HOW SOLAR CELLS WORK

The Nature of Sunlight

In order to understand how solar cells work, you first need to know something about the nature of sunlight. All light, including sunlight, is a form of electromagnetic radiation similar to radio waves or microwaves. The sun gives off this radiation simply because it is hot. This **black-body radiation** is composed of a broad mixture of different wavelengths, some of which—the visible spectrum—can be seen by the naked eye and many wavelengths shorter or longer than these. The sun is a black body; if it were cold, it would appear black because it would only absorb radiation.

Figure 1.5 diagrams the solar spectrum. The curve labeled **AM0** illustrates the **air mass 0** spectrum the sun emits as it appears in outer space; the other curve is the **air mass 1** spectrum as seen from the surface of the earth. The difference is caused by our atmosphere. In Figure 1.5, the visible spectrum is in the middle, from 400 to 700 nanometers in wavelength [a nanometer (nm) is 10^{-9} meters or one-millionth of a millimeter]. At 700 nm, the visible spectrum appears red; at the shorter wavelength end of 400 nm, it appears violet; the other colors of the rainbow appear between. Our eyes are most sensitive to the wavelengths around 500 nm where the peak of the solar spectrum on earth occurs. Over half of the sun's energy that reaches the earth's surface is in the form of visible radiation.

Ultraviolet (UV) wavelengths are shorter than 400 nm and are present in the solar spectrum in small but significant amounts. Ozone and most transparent materials absorb or filter out most of these energetic wavelengths, which is fortunate because short wavelength ultraviolet light can be destructive to organic materials and living things. The small amount of UV light that does make it to the earth's

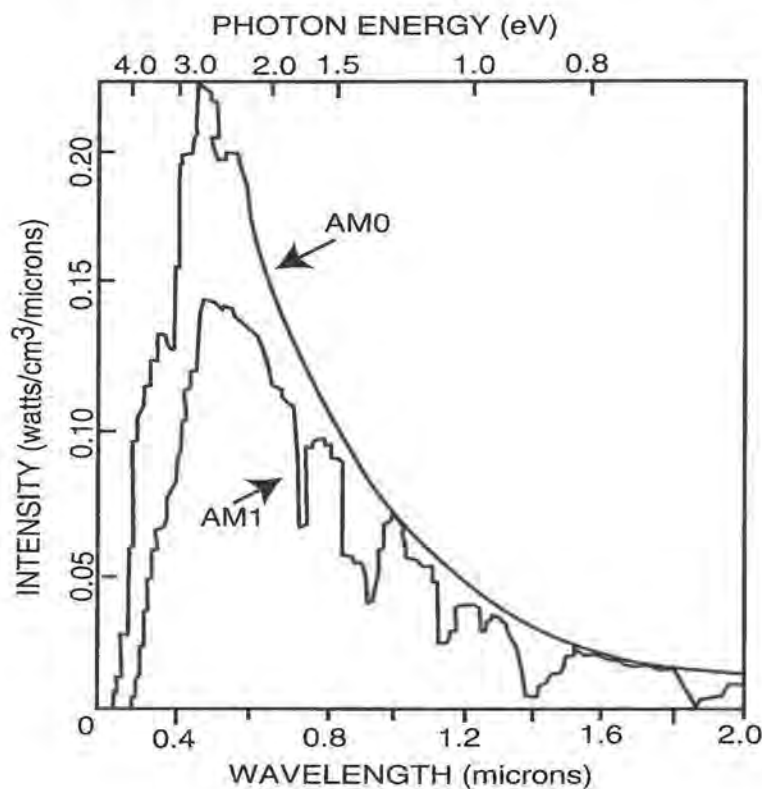


Figure 1.5. The solar spectrum. The dips in the intensity of the AM1 spectrum seen from the surface of the earth are mostly caused by water vapor in our atmosphere.

surface is responsible for the tan—or burn—we receive when exposed to the sun.

Infrared wavelengths are longer than 700 nm and, though invisible, are perceived by our skin as radiant heat. As the diagram shows, a great deal of the sun's energy is infrared radiation. Large bands of infrared are absorbed by water vapor, carbon dioxide, and other substances in our atmosphere, but because most of this absorption takes place at longer wavelengths, a solar device that does not effectively collect wavelengths longer than 2 microns (2,000 nm) suffers only a small loss in efficiency.

According to the theory of quantum mechanics, light is composed of particles called photons. Photons, which travel through a vacuum at the speed of light, have no mass, but each is a packet of energy related to the wavelength of the light. The shorter the wavelength, the larger the packet. The energy of individual photons of different wavelengths, as shown at the top of Figure 1.5, is expressed in electron volts. One electron volt is the energy an electron acquires when it accelerates in a vacuum across a potential of one volt. This unit of energy is commonly used by solar cell physicists since it is a convenient size when considering individual electrons.

Solid-State Physics

Although the solar cell was accidentally discovered in the nineteenth century, and inefficient versions of selenium and cuprous oxide photovoltaic cells were investigated and even used commercially in the early part of this century, it was only after the development of modern solid-state theory and the **band model** of semiconductors that the inner workings of photovoltaic cells have been understood.

The band model of solids, presented here in a simplified version, is based on a crystal with all the atoms fixed in a pattern. The individual atomic nuclei vibrate around a fixed spot in a three-dimensional lattice pattern, but they usually cannot jump completely out of place. Powerful electrostatic forces tie most of the negative electrons in a particular atom very closely to the positively charged nucleus. However, the outermost electrons (called the valence electrons) can be considered “delocalized”; that is, they do not belong to any particular atom, but to the crystal as a whole.

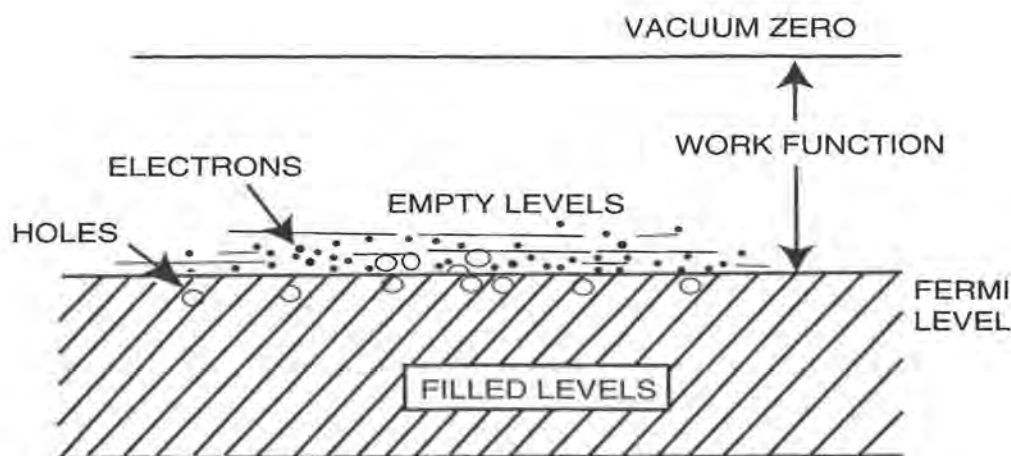


Figure 1.6. Energy level diagram for a metal.

These valence electrons balance the remaining positive charges of all the nuclei. It takes a certain amount of energy to remove one of these electrons from the crystal because of electrostatic attraction. This energy is represented in Figure 1.6 as a vertical distance. In this figure, which illustrates the band diagram for a metal, zero energy is taken as the energy of an electron at rest in empty space. This is called **vacuum zero**. The energies of the electrons in the crystal are all below this zero; the kinetic energy of a fast-moving electron in vacuum would be above the zero.

One conclusion of quantum mechanics is that electrons (or anything else, for that matter) cannot have a continuum of energies but are allowed only certain selected energies (the **energy levels** in the diagram). Another quantum mechanical principle is that no two electrons can occupy the same energy level.

It is possible to calculate the number and positions of the energy levels of a particular metal; if a count is made, it turns out that each atom contributes more energy levels than electrons. (This also is shown in Figure 1.6.) Since the band of valence levels is greater than the number of electrons, some levels must be empty. The electrons would preferentially occupy the lowest lying levels. At absolute zero, when none of the electrons are moving, they would fill the band to the fermi level, where the probability of finding an electron is one-half. In order to move, the electrons must have a bit more energy (their kinetic energy) and would occupy a level just above

the **fermi level**. Since there are many empty levels at this energy, the electron has a large number of possible kinetic energies and can move very freely throughout the crystal. These moving electrons can produce an electric current, so a metal would be expected to be a good conductor of electricity and capable of carrying a large current.

Each electron from below the fermi level that jumps to a higher empty level leaves behind an empty level. These empty levels in the “sea” of electrons are called **holes**. A hole is a level that an electron could occupy but currently does not. A hole “moves” when an electron falls into it, creating a new hole. Thus, a hole can be seen as a particle similar to an electron with a positive charge, a mobility, and even an effective mass. Holes can carry electric current and in some metals are the dominant carriers.

If the number of available levels is exactly the same as the number of electrons for each atom, the situation depicted in Figure 1.7 results. This figure also shows a band of completely empty energy levels at some higher energy. Since the number of excited electronic states in any atom is theoretically infinite, there will always be such a **conduction band**, sometimes separated from the **valence band** by a **band gap**. Because the valence band is completely filled, there are no nearby energy levels for an electron to occupy. The electrons

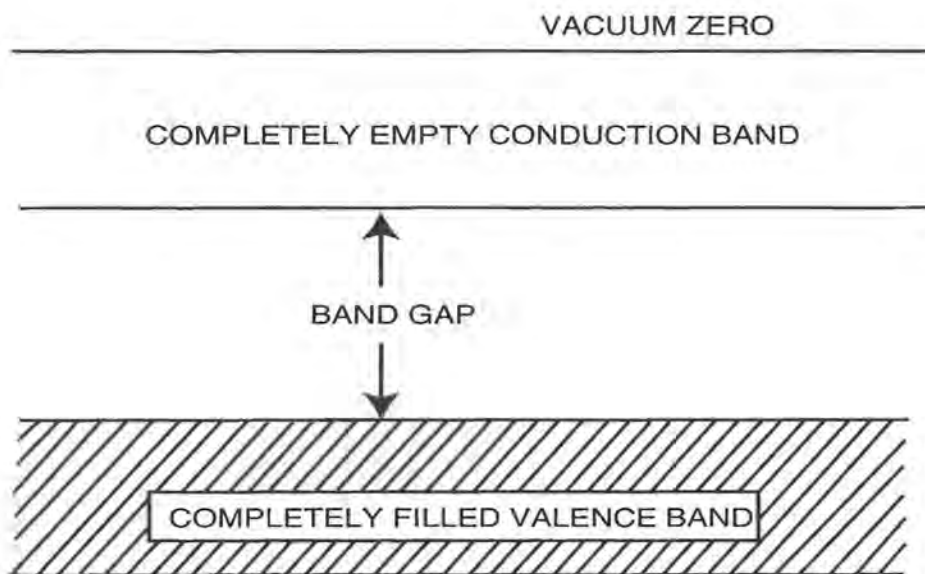


Figure 1.7. Energy level diagram for a perfect insulation.

cannot move and therefore cannot create any holes. Thus, no conduction can take place and the material is called an insulator. The energy of the band gap is in electron volts, as are all the energies shown in the diagrams.

If the band gap is sufficiently narrow (below 2.5 electron volts or so), it is possible for a particularly energetic electron to jump from the top of the valence band to one of the empty levels in the conduction band (see Figure 1.8). The electron might be thermally excited by the vibrations of the atoms in the crystal lattice or a photon of light of sufficient energy might be absorbed by the crystal and cause the electron to jump. Once the electron is in the upper conduction band, it is free to move and can act as a carrier of electricity. In addition, the hole left behind in the valence band can also be a current carrier. A material that has these properties is called a semiconductor.

In Figure 1.8, the fermi level is in the middle of the band gap. Even though there are no energy levels in the middle of the band gap, one can have the concept of a fermi level there. Were there an energy level at this place, it would be occupied by an electron half

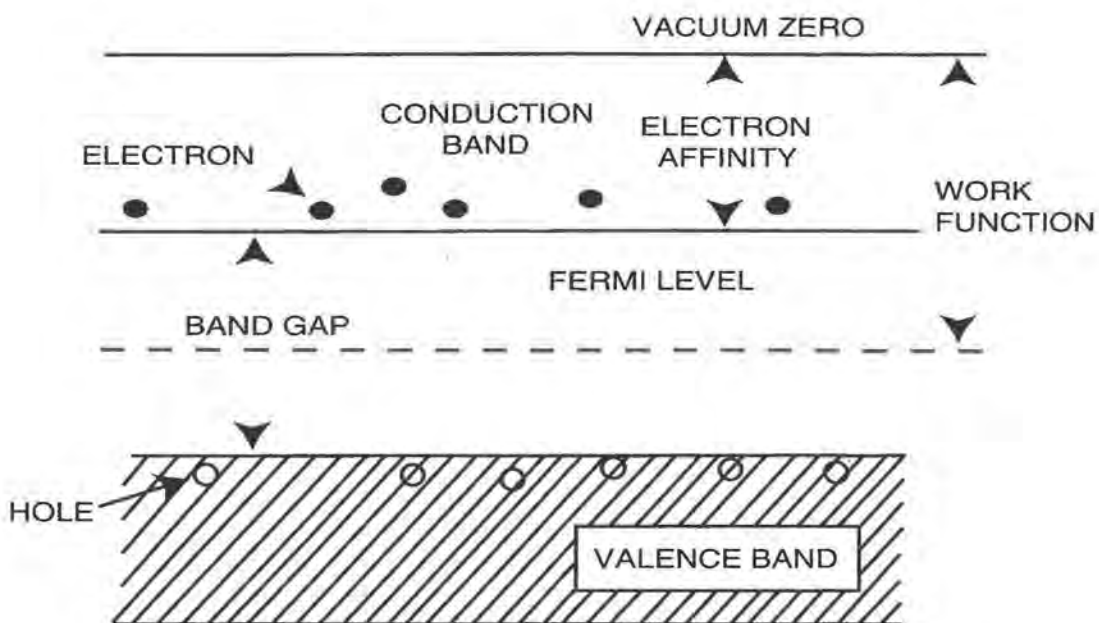


Figure 1.8. Energy band diagram for an intrinsic semiconductor.

the time, on average. Above the fermi level, fewer levels are occupied; below it, most are. The unoccupied levels are holes.

As the temperature of a solid increases, the most energetic electrons and holes can be found farther from the fermi level, but the position of the fermi level remains fixed. Only the most energetic electrons and holes are actually occupying levels. (The most important point to remember is that the closer a band is to the fermi level, the more conduction electrons—or holes, if *below* the fermi level—that will be found in the band.) For a more complete mathematical discussion of these solid-state concepts, see Kittel's *Introduction to Solid-State Physics*, 5th Edition.

Doping

The electrical conductivity discussed in the last section is called **intrinsic conductivity** because it is an intrinsic property of the particular material and its crystal lattice. The ideal **intrinsic semiconductor** cannot exist in reality because all materials have some impurities, no matter how carefully prepared. The impurity atoms will occupy various spots in the crystal lattice and disturb its perfection. In addition, these foreign atoms usually contribute a different number of levels and/or electrons to the system than the normal atoms. For example, in a single crystal of silicon each silicon atom contributes exactly 4 valence levels, 4 conduction levels, and 4 electrons since the valence of silicon is 4.

If an atom of boron (which has a valence of 3) is added to the crystal, it will contribute only 3 electrons to the system. It will also contribute 3 valence levels, plus 1 level which will be created in the band gap slightly above the top of the valence band. This situation is diagrammed in Figure 1.9 (left). These extra levels, called **acceptor levels**, are capable of accepting an electron from the valence band. Since the acceptor level is associated with a particular impurity atom, the electron that occupies it is trapped and cannot move. However, the hole created when the electron leaves the valence band can move and carry an electric current. Silicon doped with boron makes a **p-type semiconductor**, since **p**ositive holes carry the current.

The process of deliberately adding a known impurity to a pure semiconductor is called **doping** and the resulting material is an **extrinsic semiconductor**. Similarly, if a small amount of phosphorus

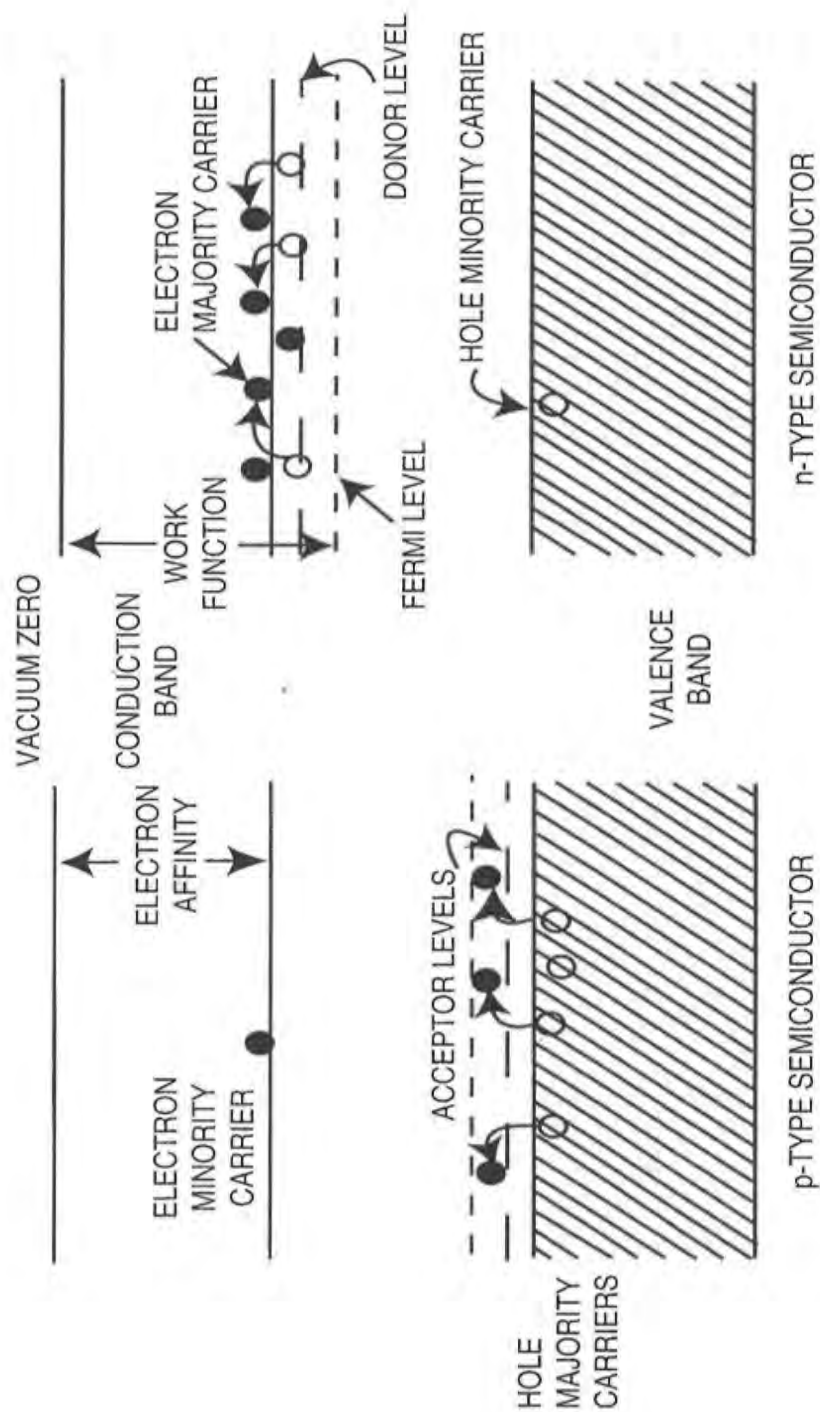


Figure 1.9. Energy band diagram for extrinsic (doped) semiconductors.
Left: p-type semiconductor. *Right:* n-type semiconductor.

is added to the silicon crystal, the atoms of phosphorus (which have 5 valence electrons) will contribute 4 electrons and 4 levels to the valence band, and the extra electron will occupy a level near the bottom of the conduction band as shown in Figure 1.9 (right). It takes very little energy for the extra electron to jump to the conduction band from this **donor level**, so-called because it can donate conduction electrons to the system. This type of material is an **n-type semiconductor**, since **negative** electrons carry the electric current.

Notice that Figure 1.9 (left) shows p-type material: the fermi level is located near the valence band and the vast majority of current carriers are holes. Figure 1.9 (right) shows n-type material: the fermi level is near the bottom of the conduction band and the majority of carriers are electrons. In p-type semiconductors, the positive holes are the **majority carriers** and the electrons are the **minority carriers**. In n-type semiconductors, the negative electrons are the majority carriers and the holes are naturally called minority carriers.

Finally, note the quantities marked **work function** and **electron affinity**. The work function is the energy difference between the fermi level and vacuum zero; the electron affinity is the energy difference between the bottom of the conduction band and vacuum zero. These definitions hold true for all semiconductors. For metals, the work function and electron affinity have the same value.

JUNCTION PHOTOVOLTAIC CELLS

Homojunctions

Figure 1.10 shows the construction of a typical n-on-p junction solar cell. This is the most common type of cell and is made by taking a wafer of p-type single-crystal silicon and diffusing phosphorus atoms into the top surface. This can be done by heating the wafers in a diffusion furnace in the presence of phosphorus-containing gas. The phosphorus atoms have a valence of 5. This means that each phosphorus atom has 5 electrons in its outermost region compared to silicon atoms which have 4. The extra electron is very loosely held near the atom, producing donor levels in the top layer of silicon, making it n-type. The n-type silicon on top of the p-type silicon produces a junction where the two types come in contact. The back

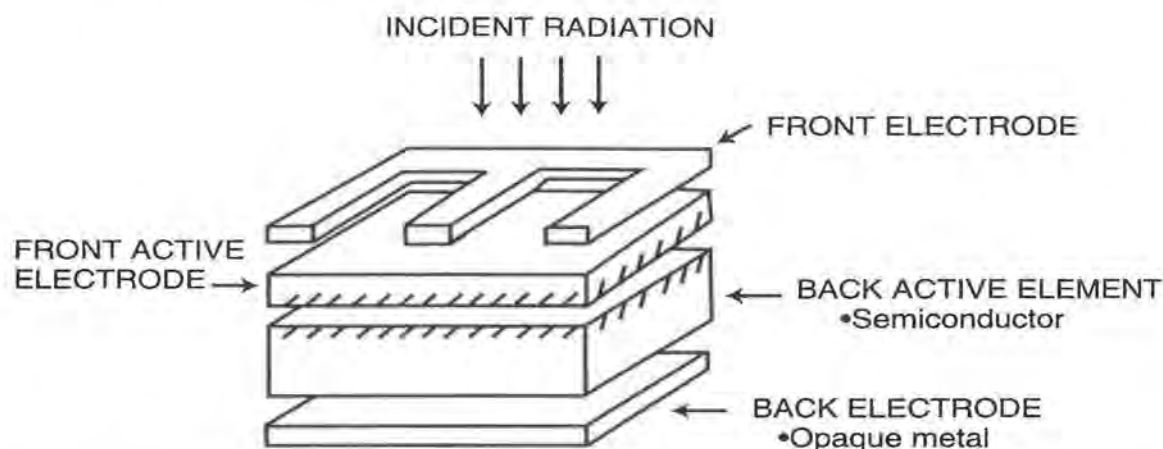


Figure 1.10. Cross section of a solar cell showing its construction.

contact and the top fingers shown are used to connect the solar cell to the external circuit. A more detailed description of the construction of these cells is given in the next chapter.

The energy band diagram for this n-on-p cell (called a **homojunction** solar cell) is shown in Figure 1.11. This diagram is made by overlaying the diagram for the n-type semiconductor with the diagram for the p-type material and then aligning the fermi levels. Notice that now there is a difference in the vacuum zero levels for the two materials. This represents the **built-in potential** that exists between the materials because of the difference in their work functions. Between the n- and p-layers is a **depletion layer** where there are essentially no carriers—neither electrons nor holes. This layer, where the bands are bent, is the actual junction. The front and back metal contacts must be **ohmic contacts**: that is, contacts that do not impede the flow of electrons into or out of the semiconductor. In the dark, if the junction device is connected to a battery so the front fingers are made positive and the back negative, the situation shown in Figure 1.12 (top) would result. The applied potential is added to the built-in potential and the uphill barrier for the electrons is increased; this results in no current flow except for the tiny current of electrons thermally excited from the valence to the conduction band. At room temperature this current would be a fraction of a microamp. On the other hand, if the battery is reversed so that the front is negative and the back positive, the applied potential can be made large enough to cancel out the built-in potential. As Figure 1.12 (bottom)

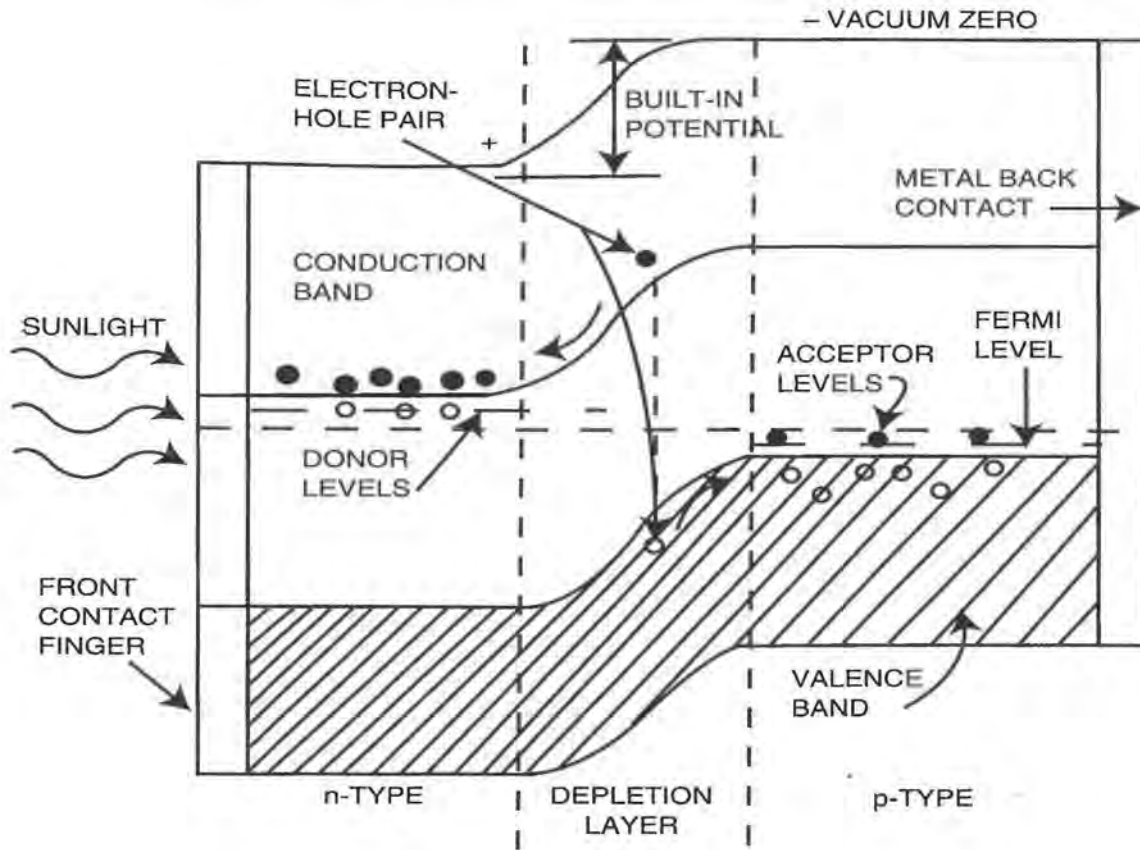


Figure 1.11. Band diagram for p-n homojunction solar cell.

shows, there is no longer any barrier to the flow of either holes or electrons and the device becomes a good conductor of electricity. So, a solar cell is a cell is a **junction diode** or **rectifier**, letting electricity pass in only one direction in the dark. The “dark” curve in Figure 1.13 is a typical current voltage plot for this type of junction.

If light falls on a solar cell, those photons with energy greater than the band gap width can excite an electron from the valence to the conduction band and create a hole-electron pair. The conduction electron, if created in the depletion layer, will slide “downhill” toward the front n-layer and the hole will slide “uphill” (like an air bubble in water) to the p-layer. Thus, the charge carriers will be separated and current will flow. The ohmic front contact allows the electron to flow through an external circuit to the back contact where it can recombine with a hole, leaving everything as it was. Even if the conduction electron is created away from the junction, if it happens

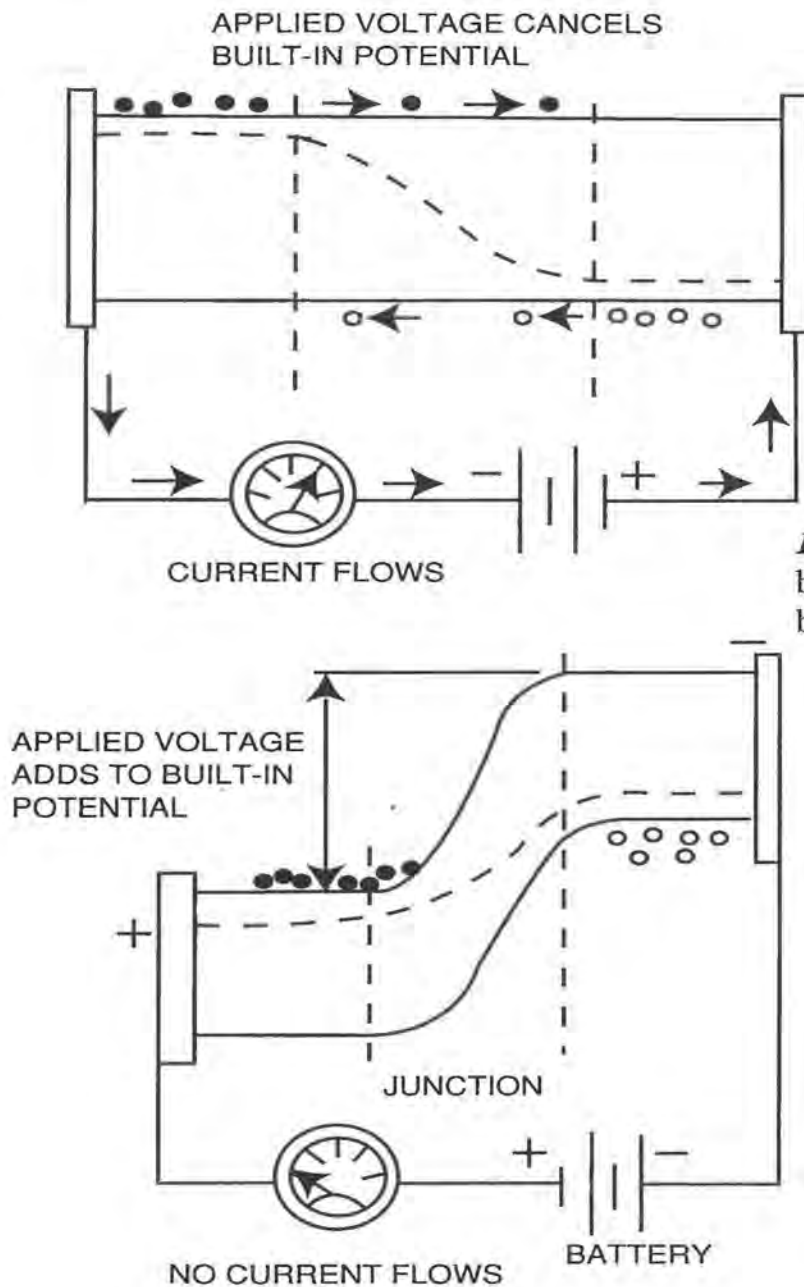


Figure 1.12. Top: Forward bias rectifier. Bottom: Reverse bias rectifier.

to drift toward the junction it will be carried down as before and produce a current in the external circuit.

If the external circuit is simply a wire and has no appreciable resistance, the current that flows is the short-circuit current (I_{sc}) and is directly related to the number of photons of light being absorbed

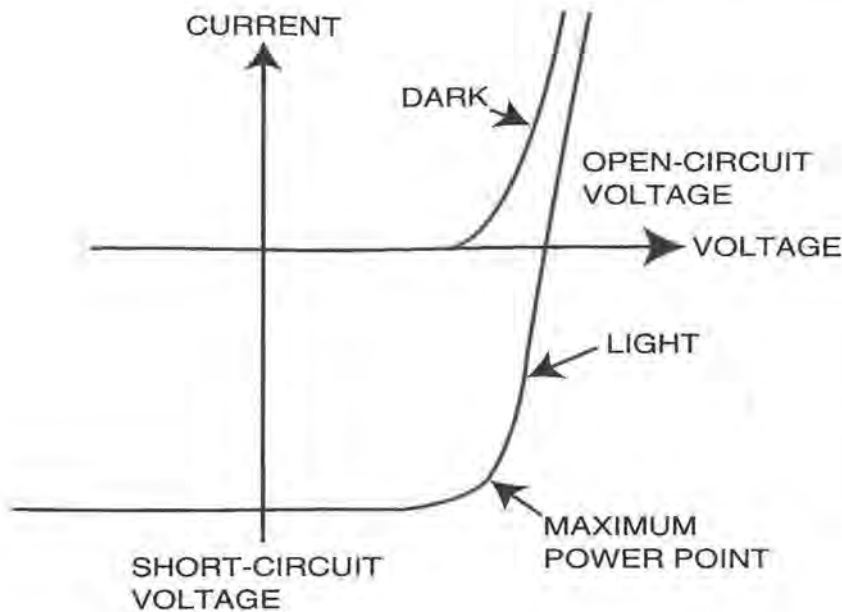


Figure 1.13. Current-voltage plots for a solar cell both in the dark and illuminated.

by the cell. This is why short-circuit current is directly proportional to light intensity.

If there is no external circuit, the incoming photons will still create hole-electron pairs and they will still travel downhill to the p- and n-layers, but they will pile up there because there is no external wire to complete the circuit. The extra negative electrons in the n-layer and the extra positive holes in the p-layer will cause a situation analogous to that shown in Figure 1.12 (bottom), except that now the battery is the solar cell itself. Soon the voltage difference between the front and the back of the cell will become large enough to flatten the barrier sufficiently to allow some holes and electrons to leak back. When the number of carriers leaking back is equal to the number being generated by the incoming light, an equilibrium voltage has been reached. This is called the **open-circuit voltage (V_{oc})** and is shown on the light current-voltage curve on Figure 1.13. The open-circuit voltage varies only slightly with large changes in light intensity.

If the resistance of the external circuit can be varied from zero (short circuit) to extremely high (open circuit), the entire current voltage curve can be plotted. As stated at the beginning of the chapter, the power emitted by the solar cell is defined as the voltage times the current:

$$P_{\text{(watts)}} = V_{\text{(volts)}} \times I_{\text{(amps)}}$$

For the short circuit, there is no voltage and hence no power output from the cell. Similarly, for the open circuit, there is maximum voltage but no current, so again there is no power output. The best combination of voltage and current to produce the maximum power lies somewhere between. That point is shown at the bend in Figure 1.13.

One way to judge the quality of a solar cell is by measuring the **fill factor (ff)**. The fill factor is the actual maximum power divided by the hypothetical "power" obtained by multiplying the open-circuit voltage (V_{oc}) by the short-circuit current (I_{sc})

$$ff = \frac{P_{\text{max}}}{V_{OC} \times I_{SC}}$$

A good silicon solar cell will normally have a fill factor above 0.75.

FACTORS WHICH INFLUENCE CELL EFFICIENCY

Band Gap Width

One of the most important factors influencing theoretical efficiency is the band gap width of the semiconductor material. Remember that only photons of energy greater than the band gap can produce current carriers. This means that only light of wavelengths shorter than a critical maximum can be used to produce a photocurrent. In fact, most semiconductors are transparent to light that is more red than this cutoff wavelength; photons will pass right through the material without interaction. Therefore, small band gap materials will absorb more of the red end of the solar spectrum and would appear to be more efficient users of sunlight. However, the open-circuit voltage of a cell is limited by the band gap width of the cell material. Also, the energetic photons of short wavelength cannot produce any more current than the photons barely able to raise an electron to the conduction band, thus they are used less efficiently by narrow band gap materials (the excess energy of the photon shows up as heat and it heats the cells). The best cells will have compromise band gap widths.

In 1953, Dr. Dan Trivich of Wayne State University made the first theoretical calculations of the efficiencies of various materials of different band gap widths based on the spectrum of our sun. Figure 1.14 is an updated version of those calculations. Although the diagram shows that silicon has too narrow a band gap for optimum efficiency, more than 35 years of development have pushed the actual working efficiency closer to the theoretical.

Care must be taken to distinguish between quantum efficiency, the number of current electrons created and delivered to the front contacts compared to the number of photons falling on the solar cell, and energy efficiency, the total electrical power output compared to the input power flux of light energy. For example, a good crystalline silicon cell may have a quantum efficiency of 85% but a total energy efficiency of 19% because the high-energy blue-light photons only produce the same energy in electrons as do the infrared photons.

Recombination

A major factor that influences attainable efficiency is recombination. Not all the hole-electron pairs created make it all the way to the

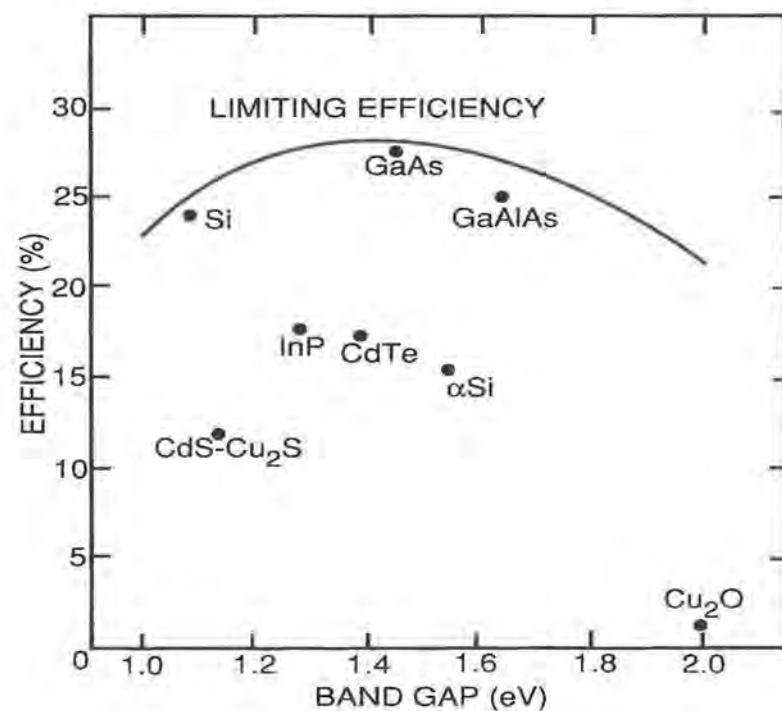


Figure 1.14. Efficiencies versus band gap for various semiconductor solar cell materials. Dots are one-sun measured values.

metal contacts; some of the carriers will recombine with a carrier of opposite sign, thus eliminating both. This usually happens at a defect or impurity in the crystal called a **recombination center**. It is especially common to find these centers at the junctions or at the surface of the material, but recombination can happen even in the main body of the material. (These are called **junction**, **surface**, or **bulk recombination**, respectively.) Using only high-quality single-crystal wafers to make solar cells will minimize recombination. Many manufacturers have learned how to suppress the recombination centers formed at crystalline boundaries, leading to the commercial use of polycrystalline silicon wafers in high-quality solar cell production.

Reflectivity and Light Absorption

Most semiconductor materials have a high reflectivity of the light they should be absorbing. To decrease reflection loss, most manufacturers etch the surface of the cell to roughen or "texturize" it and apply antireflection coatings. These coatings, similar to those on good camera lenses, are usually silicon monoxide or silicon nitride for silicon cells.

Light is also reflected by the shiny metal fingers used as the top contacts on the solar cells. The design of the finger pattern is a compromise between a very open pattern that will not block out much light and one of very low resistance that wastes little power output resistance-heating the fingers.

HETEROJUNCTIONS

The n- and p-layers in a solar cell do not have to be made of the same material. Although **heterojunctions** are composed of two different semiconductors (see Figure 1.15), they operate in essentially the same way as homojunctions. The two different semiconductors offer a great deal of design flexibility; if the top material has a wide band gap, it can serve as a window to let the light penetrate to the second layer. The window layer is heavily doped to make it a good electrical conductor, sometimes eliminating the need for metallic front fingers. The second layer is selected for its efficiency as an absorber of sunlight. With the proper choice of materials, the device can have a larger built-in potential and, hence, a higher open-circuit voltage

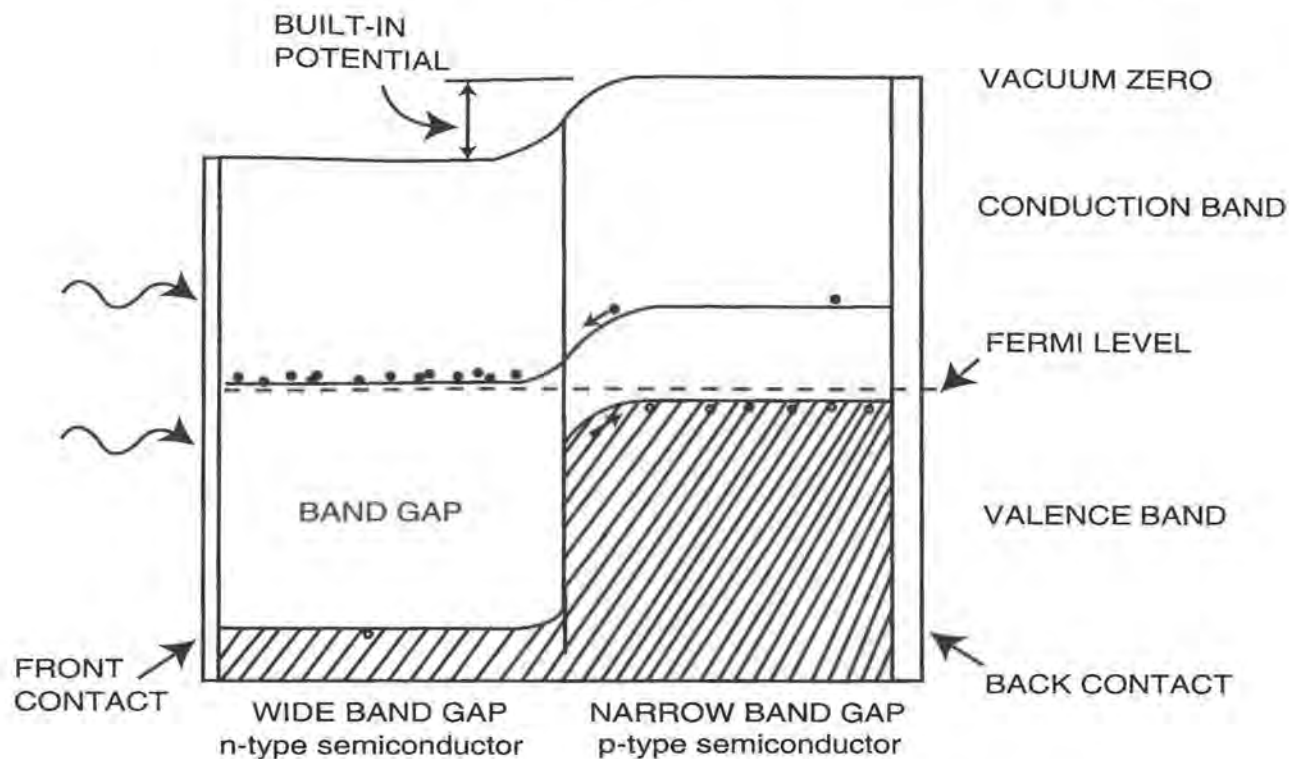


Figure 1.15. Band diagram for a heterojunction solar cell.

than a homojunction made from the narrow band gap semiconductor. Also, some semiconductors, such as cuprous oxide or tin oxide, are available in only one form—either p- or n-type—and cannot be made into homojunction cells. Heterojunctions can exploit the best properties of such materials. Examples of heterojunction solar cells include a cadmium sulfide/cuprous sulfide system and the three-layer cadmium sulfide/cadmium telluride/zinc telluride cell. In the latter, the window is n-type CdS, the light absorber is a thin layer of nearly intrinsic CdTe, and the p-layer is highly conductive ZnTe. Chapter 6 discusses new developments in heterojunction systems.

SCHOTTKY BARRIER JUNCTIONS

The metal-to-semiconductor or Schottky barrier junction (Figure 1.16) is formed when a low work-function metal is placed on a p-type semiconductor. A high work-function metal on an n-type semiconductor will also produce a Schottky barrier, one with a band diagram resembling an upside-down version of the one shown. The impor-

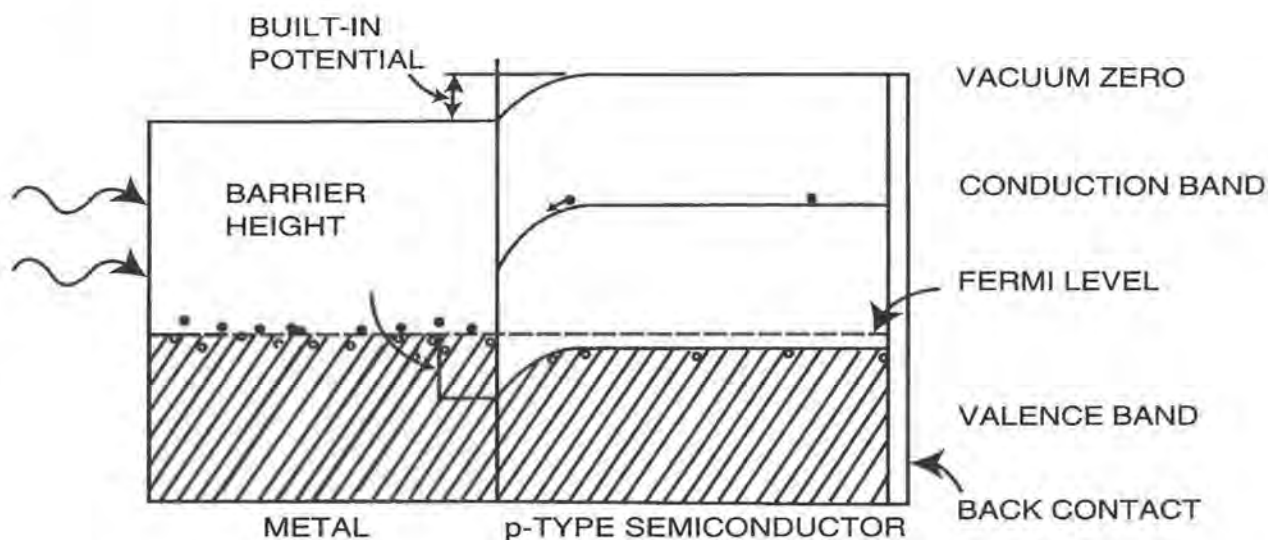


Figure 1.16. Band diagram for a Schottky barrier junction solar cell.

tant point is the creation of a barrier to the flow of majority carriers from the semiconductor to the metal and to the flow of all carriers from the metal to the semiconductor. Also, the band bending in the semiconductor produces a built-in potential that determines the open-circuit voltage in the solar cell. The built-in potential is simply the difference in work function between the metal and the semiconductor while the barrier height is the energy difference between the work function of the metal and the top of the valence band (for p-type semiconductors) or the bottom of the conduction band (for n-type). The quality of the solar cell, as measured by the reverse dark current and the fill factor, is dependent in part on the barrier height. If a high work-function metal is put onto a p-type semiconductor (or a low work-function metal onto an n-type material), an ohmic contact with no barrier at all is the result.

The first solar cells—the cuprous oxide cell and the selenium cell—were both Schottky barrier cells. However, an efficient and inexpensive Schottky barrier solar cell has yet to be constructed.

ADVANCED SEMICONDUCTOR DEVICES

There are a number of other semiconductor junctions that have been considered for use in solar cells. Two promising devices are the metal–

insulator–semiconductor (MIS) and semiconductor–insulator–semiconductor (SIS) junctions where a thin insulating layer is placed in the middle of the junction. Current carriers pass through this insulator by a quantum mechanical process called **tunneling**. Some scientists believe that all Schottky barrier junctions have an insulating layer and are MIS structures. If the insulating layer is of the proper thickness, around 20 Å, the open-circuit voltage of a cell can be increased without any significant loss in short-circuit current. For instance, MIS structures using cuprous oxide, aluminum oxide, and aluminum showed a brief open-circuit voltage of over one volt, but the structure was unstable and no further work on this combination has been attempted.

RECOMMENDED READINGS

- Angrist, Stanley W. "Photovoltaic Generators." In *Direct Energy Conversion*, 2nd ed., Chapter 5 (Boston: Allyn & Bacon Inc., 1971).
- Backus, Charles E., Ed. *Solar Cells* (New York: Institute of Electrical and Electronics Engineers, 1976).
- Commoner, Barry. "The Solar Transition." *The New Yorker* 55:53–54, Part I (April 23, 1979); 55:46–48, Part II (April 30, 1979).
- Chalmers, Bruce. "The Photovoltaic Generation of Electricity." *Scientific American* 235:34–43 (October 1976).
- Hovel, Harold. "Solar Cells." In *Semiconductors and Semimetals*, Volume 11, R. K. Willardson and A. C. Beer, Eds. (New York: Academic Press, Inc., 1975).
- Kittel, Charles. *Introduction to Solid-State Physics*, 5th ed. (New York: John Wiley & Sons, 1976).
- Landsberg, P. T. "An Introduction to the Theory of Photovoltaic Cells." *Solid-State Electronics* 18:1043–52 (1975).
- Photovoltaics Technical Information Guide*, 2nd ed. (Golden CO: NERL, NTIS, U.S. Department of Commerce, 1988)
- Zweibel, Kenneth. *Harnessing Solar Power: The Photovoltaics Challenge* (New York: Plenum Press, 1990).

Chapter 2

How Solar Cells Are Made

The present processes for manufacturing solar cells are complicated, energy-consuming and expensive, although considerable progress has been made in the last decade to lower the cost and energy consumed per cell. This chapter describes the current techniques for **single-crystal**, **polycrystalline**, and **amorphous** photovoltaic cell manufacture and examines improvements now under development. The step-by-step procedure for making cells follows.

SILICON

You start with sand. Silicon, the second most abundant element in the earth's crust, is present in almost all rocks and minerals, but the most convenient source is silicon dioxide in the form of white quartzite sand. If the sand is pure enough, the subsequent (and costly) purification steps are less complicated.

Metallurgical-Grade Silicon

Sand is reduced to silicon in an electric arc furnace. A carbon arc reacts with the oxygen in the silicon dioxide to form carbon dioxide and molten silicon. This common industrial process produces a metallurgical-grade silicon with about 1% impurities that has a number of uses in the steel and other industries. Though relatively inexpensive, this silicon contains far too many impurities for use in the microelectronics industry. Many impurities are the result of using contaminated sand and could be eliminated by the careful choice of raw materials; others are introduced during processing and could be eliminated by quality control.

Semiconductor-Grade Silicon

The electronic properties of silicon semiconductor devices are determined by a small percentage of **dopant** atoms in the crystal lattice. In order for the devices to be built, the number of impurities in the silicon starting material must be few in comparison to the dopants to be added. This means that semiconductor-grade silicon must be hyperpure (the residual impurities are measured in parts per billion).

The most common way to produce silicon of very high quality is by the thermal decomposition of silane or some other gaseous silicon compound. A seed rod of ultrapure silicon is heated red-hot in a sealed chamber and the purified silicon compound is admitted. When the molecules of this compound strike the rod, they break down to form elemental silicon which then builds up on the rod. When the rod has grown to the desired thickness, it is removed; the rod is now ready to be made into a single crystal.

An alternative process for purifying silicon is **zone refining**. In this process, a rod of metallurgical-grade silicon is clamped in a machine with a moving induction heater coil. The coil first melts a zone through the entire rod near the bottom and then slowly travels upward. The silicon then melts at the top edge of the zone and solidifies at the bottom edge. When the liquid solidifies, impurities in the melt are excluded from the new crystal lattice so that the molten zone picks up the impurities and sweeps them to the top of the rod, which is then discarded.



Figure 2.1. Semiconductor-grade silicon. This highly refined material is purer than fine gold and is becoming more expensive as supplies fail to keep up with demand. (Siemens Solar Industries, Camarillo, CA)

Both methods of purifying silicon are expensive and energy-consuming. The resulting semiconductor-grade silicon presently costs \$25 per kilogram; this is down from the \$80 per kilogram cost fifteen years ago. Single-crystal solar cells are currently made from this type of silicon, but polycrystalline and amorphous silicon cells use lesser-grade materials. The latter part of this chapter describes these manufacturing processes.

GROWING SINGLE CRYSTALS

The boundaries between crystals in silicon act as traps for the electrical current carriers. To avoid these traps and to ensure the best performance, all semiconductor devices and some solar cells are made from single crystals of silicon. The techniques for growing silicon crystals have developed to the point that crystals six inches in diameter and six feet long are routinely grown by the **Czochralski process**. In this method, a seed crystal is dipped into a crucible of molten

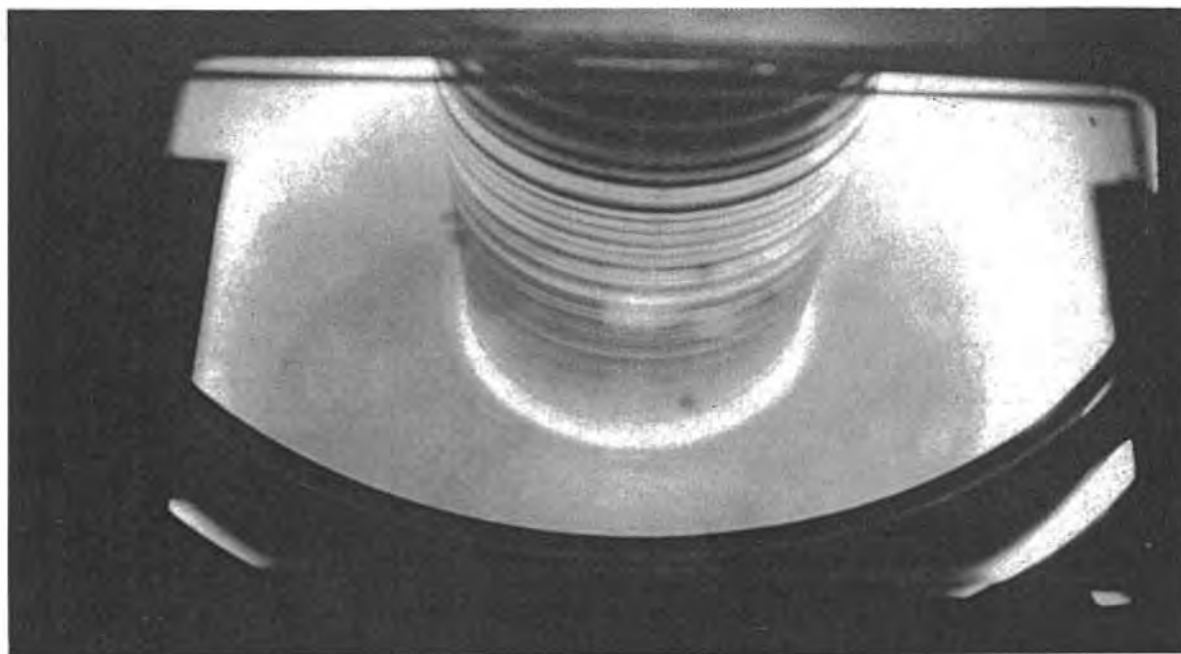


Figure 2.2. A single crystal of pure silicon being pulled from a crucible of molten material. Virtually all solar cells commercially produced are made by the Czochralski process. (Siemens Solar Industries, Camarillo, CA)

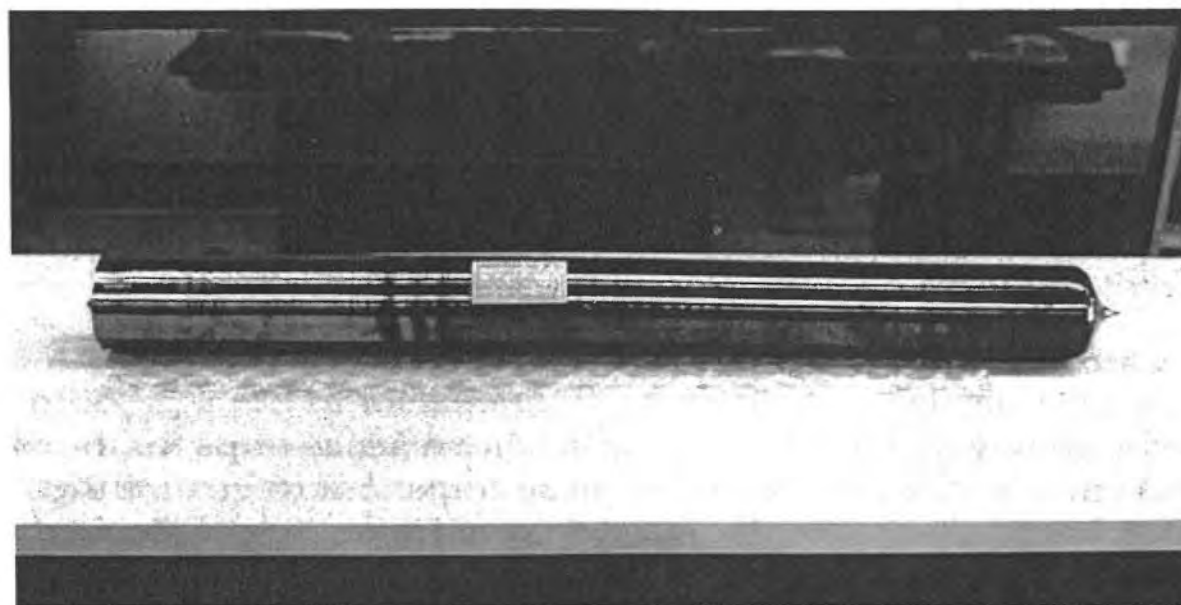


Figure 2.3. An ingot produced by the Czochralski process. The standard diameter of ingots has increased from 2.25 and 3 inches to 4.25 and even 6 inches as the technology has improved. (Siemens Solar Industries, Camarillo, CA)

silicon and slowly withdrawn, pulling a large round crystal as the molten material solidifies on the bottom of the seed. Feedback controls adjust the pulling speed and the temperature of the melt to produce a crystal of a given size. The total mass of the crystal is determined by the size of the pulling machine and the amount of material the crucible can hold. A small amount of dopant is usually added to the silicon during this step to produce the desired electronic properties.

SLICING THE CRYSTAL INTO WAFERS

Because most semiconductor devices, including photovoltaic cells, must be extremely thin, the silicon crystal has to be sliced into thin wafers. The thickness of the wafer—on the order of 300 microns (about 0.012 inch)—is determined chiefly by the fragility of the material; thinner wafers would be too difficult to handle. Slicing or “wafering” is usually done with a single thin-metal blade coated with diamonds. On most of these saws, the cutting edge is the inside edge of a washer-shaped blade. The outer edge of the disc of these “i.d.” saws is rigidly supported in a heavy ring to reduce flexing and to give a straight, smooth cut. A liquid lubricant is pumped continuously into the saw cut to cool the materials and wash away sawdust. Although the process is automated, it is time-consuming: one crystal will yield thousands of wafers—each cut one at a time. It is also wasteful because half of the high-purity silicon is lost as sawdust. Some manufacturers, notably Solarex (now part of BP Solar), have developed cutting techniques that use multiple wires and a diamond slurry cutting fluid which yield thinner wafers and less waste.

POLISHING AND ETCHING THE WAFER

The surfaces of a solar cell must be specially prepared to ensure the proper electrical and optical properties. Originally, solar cells were highly polished by using fine abrasives and chemical polishing etchants. A number of these mixtures, first developed for the microelectronics industry, leave a mirror-like surface that forms a good junction with the metals used for electrical contacts. Texturized surfaces, which

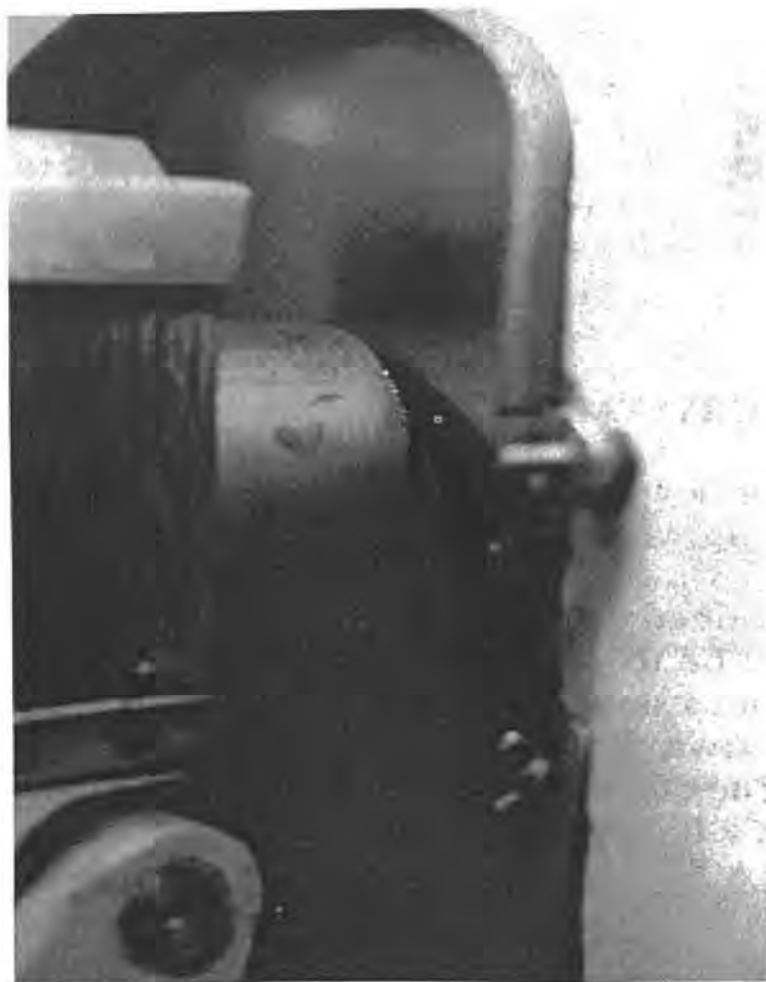


Figure 2.4. Slicing a silicon single crystal with a diamond i.d. saw. This process is time-consuming and wasteful: the saw cuts are as wide as the wafers produced. (Siemens Solar Industries, Camarillo, CA)

look like mountain ranges under the high magnification of an electron microscope, have recently been found to be more effective absorbers of light. Some manufacturers, such as Kyocera, have dispensed with grinding and polishing completely, relying on a simple etching procedure to produce the desired surface. Other surface treatments, such as ion milling, are being examined by manufacturers.

FORMING THE p-n JUNCTION

The starting material for most photovoltaic cells is p-type silicon. During crystal growth, a small amount of boron is incorporated into the crystal lattice. To make a p-n homojunction cell, the top few microns of the wafer must be made n-type. This is achieved by incor-

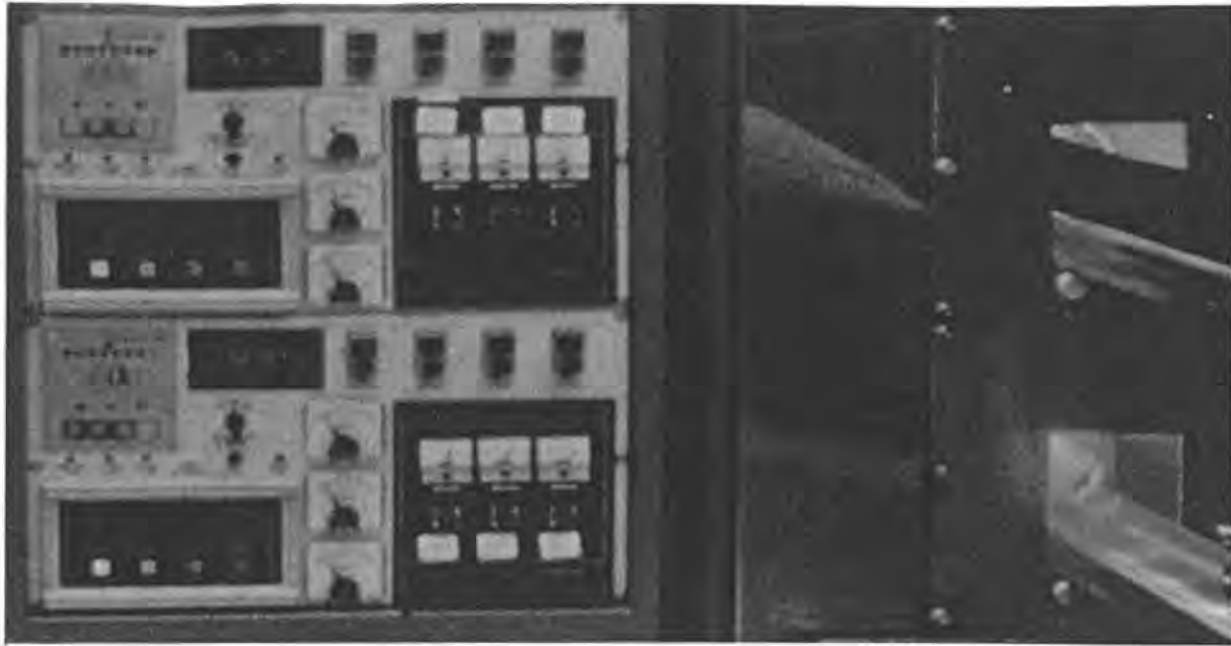


Figure 2.5. A diffusion furnace in which the p-n junction is formed. One furnace can process over 1,000 cells at a time. (Motorola Semiconductor Group, Phoenix, Arizona)

porating more phosphorus atoms into the top layer of material than boron atoms. The excess phosphorus, being an electron donor, makes the layer n-type. To do this, a rack of wafers is heated to a high temperature in a **diffusion furnace** in the presence of a phosphorus-containing gas. At a high temperature, but one that is still well below the melting point of silicon, the individual atoms will move and vibrate wildly within the crystal lattice and foreign atoms striking the surface will diffuse slowly into the bulk of the material. If the temperature and time of the exposure to the gas are properly controlled, a uniform junction can be formed a known distance into the wafer.

The surface that is to be the back of the cell must be protected to keep a junction from forming there also. Something as simple as sealing two wafers back to back can accomplish this. Sometimes a p⁺-p junction is diffused into the back of the cell to create a back surface field and improve the collection efficiency for the light-generated electrons.

A newer method of forming the front junction is **ion implantation**. This method has been used to make integrated circuits for a number of years, but has been applied to solar cells only recently. The ion implanter, a machine similar to a small particle accelerator, shoots individual ions at the surface of the wafer. (In this case the ions are atoms with one electron missing.) The depth to which the ions penetrate the front of the silicon can be controlled by changing the speed at which the ions hit the surface, so that the thickness and characteristics of the top layer of the cell can be carefully tailored. As automated ion implanters become more common, this junction formation technique will become an important one, especially for high-quality cells.

APPLYING THE FINGERS AND BACK CONTACT

Once the junction is formed, you have a working solar cell. To make the cell usable, however, contacts must be placed on the wafer so that the device can be connected to an external circuit. Both the front and back contacts must be ohmic contacts with as low a resistance to electric current as possible. The contact material must also adhere very well to the silicon and must be able to withstand soldering (or, in some cases, spot-welding). The back contact can be a solid metal coating since light does not have to pass through this area. In fact, a shiny metal contact will reflect back through the silicon any light that is not absorbed in the first pass through the cell; this allows a thinner wafer of silicon to be used.

A great deal of work has been done in contact design and fabrication. Each manufacturer has its own technique for producing inexpensive, reliable, rugged contacts. The most reliable seem to be those made from palladium/silver layers that are vacuum-evaporated through a mask or photoresist to make the initial thin layer. Once the pattern is established, a thicker metal layer is electroplated on top. Fingers made in this way can be very narrow and close together so that they block little light while maintaining a small resistance.

Another contact system incorporates electrodeless nickel plating. The solar cell is covered with wax using a silkscreen that exposes the silicon where the fingers are to be placed. Then the cell is dunked into a bath containing nickel compounds. A chemical reac-

tion deposits pure nickel on the uncovered silicon, producing the fingers. After the wax is removed, the fingers are tinned with solder. While simple and relatively inexpensive, the contacts this method produces do not always adhere to the silicon as well as would be desired.

Other methods of applying contacts include silkscreening a metal-containing paint onto the wafer and then baking to drive off the organic components which leaves a metal frit. Although present day cells have much finer fingers and much better tab adherence than solar cells made only a few years ago, extensive research continues to be devoted to improving contact systems.

THE ANTIREFLECTION COATING

Silicon is a very shiny material with a grey metallic appearance. It reflects 35% or so of the light that falls on it. To the solar cell, this is lost light that could have generated electricity. To lessen this waste, all solar cells are coated with an antireflection coating, the same type of coating that has been used for decades on the lenses of good cameras, binoculars, and other high-precision optics. These coatings are transparent layers with a thickness of about one-fourth the wavelength of light; a typical thickness is less than 100 nanometers or 0.1 micron. The coating could be made of any hard transparent material but the preferred optical coatings adhere well to silicon, have the right **refractive index** (they bend light properly), and are relatively easy to apply in accurately controlled layers.

Silicon monoxide, titanium dioxide, and some other optical coatings can be applied to the silicon in a vacuum coating process, such as **vacuum evaporation** or **sputtering**. In vacuum evaporation, a substance is heated to a high temperature in a vacuum system. The molecules of the substance "boil" off the surface and travel in straight lines until they encounter a cool surface upon which to adhere and build up a thin layer. Thin coatings of metals and many ceramic substances can be made in this fashion. Sputtering is a similar process, but it uses a high voltage and a radio frequency field to knock molecules from a target material and deposit them onto a material placed at the opposite electrode. This technique is used to deposit refractive materials that cannot be evaporated in a vacuum system.

Another way to form an antireflection coating is to make it out of the top layer of silicon. Silicon can react with oxygen- or nitrogen-containing gases to create silicon dioxide or silicon nitride. Although it is difficult to obtain a sufficiently thick layer of silicon dioxide by this process, silicon nitride antireflection coatings are used on commercial solar cells.

A final refinement common in space-quality cells, and used by at least one manufacturer of terrestrial cells, is the multilayer antireflection coating. Three or more layers of a set of two different transparent substances cancels reflected light almost completely, giving a reflection loss of less than 3%. The loss to bare silicon is 35%.

ASSEMBLY INTO MODULES

The cell is now completed and ready to use. Most modules are assembled by the individual cell manufacturers; the design of the cell's finger pattern is based on the company's particular module configuration. Chapter 3 describes module characteristics in some detail.



Figure 2.6. Automatic machinery soldering leads onto individual solar cells. These machines can replace tedious hand-soldering and produce a better joint. (Siemens Solar Industries, Camarillo, CA)



Figure 2.7. Assembling solar cells into strings.
(AstroPower, Newark, DE)

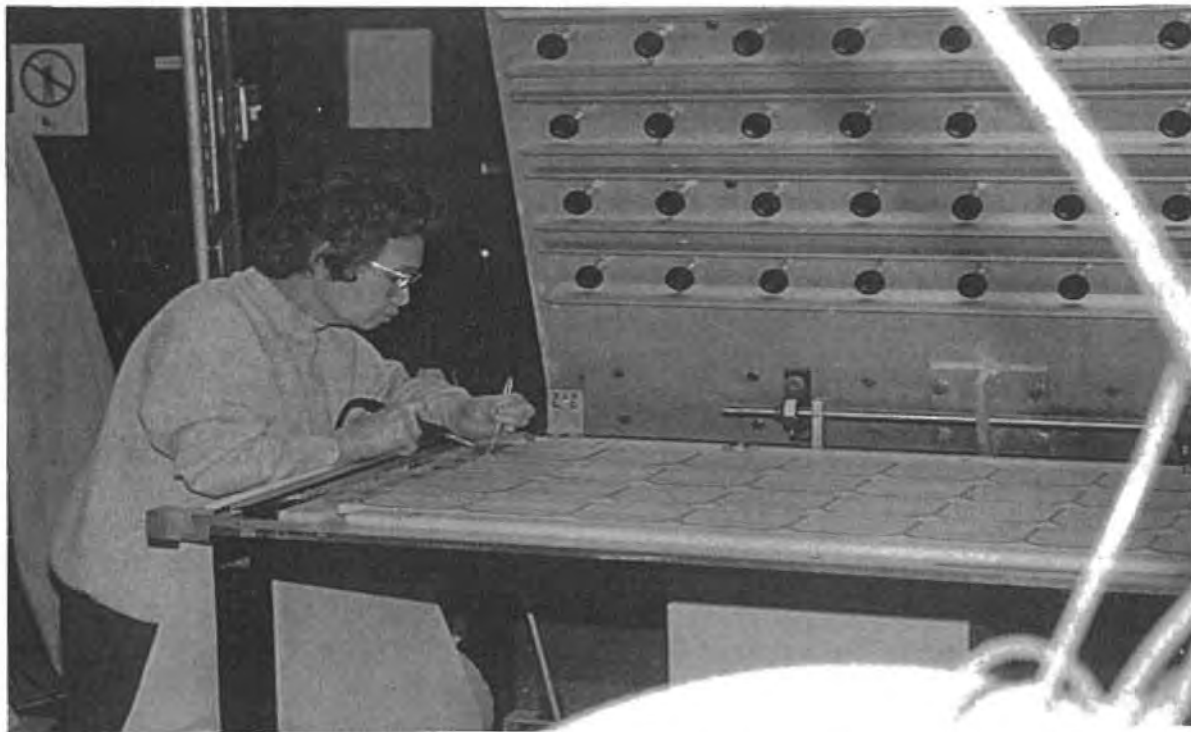


Figure 2.8. Soldering the final connections on a solar cell module. Even in the most automated systems, some handwork is still necessary. (AstroPower, Newark, DE)

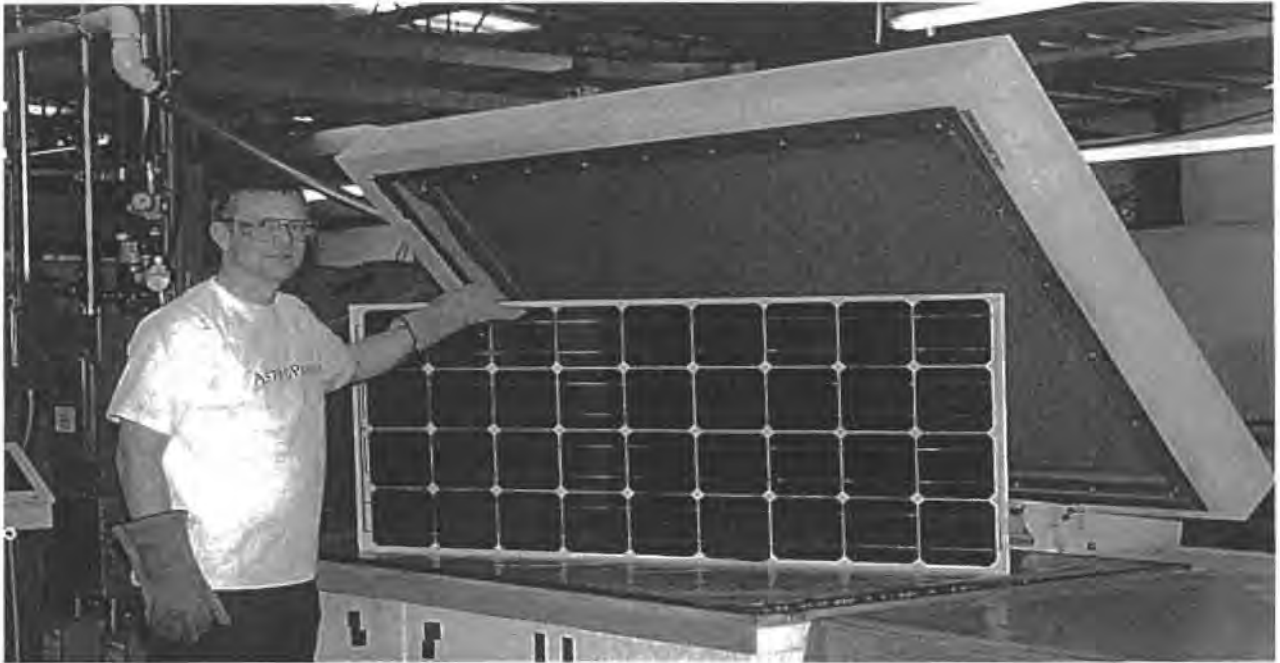


Figure 2.9. Sealing the finished module. The best systems are hermetically sealed in a process similar to that used to make safety glass for car windshields. (AstroPower, Newark, DE)

In general, solar cell manufacturers are attempting to institute more and more automation into the module assembly process, which consumes some 40% of the cost of the finished product. Automatic soldering and spot-welding machines are replacing crews that solder cells together by hand. Encapsulant systems with heat-curing plastics have almost completely replaced silicone resins. New simplified wire connectors are replacing expensive junction boxes. The final product is a less expensive but more rugged and reliable device to generate electricity from the sun's energy. The typical PV module has a warranty of twenty years or more.

NEW PRODUCTION TECHNIQUES FOR SILICON

Solar-Grade Silicon

The technology for manufacturing silicon solid-state devices has been so well developed, and so much research effort has been invested in the silicon solar cell, that the most logical way to cut costs is to

devise new ways to make this cell. A number of people have been doing just that.

Most solar cell manufacturers have automated the assembly lines that manufacture the cells and assemble them into modules. These lines have greatly increased production capabilities and have lowered module costs to the point that distributors are selling complete modules to small users for \$5.50 per watt. Manufacturer-direct sales to large projects have had prices as low as \$4 per watt.

The ultrapure semiconductor-grade silicon currently used in the manufacture of single-crystal cells is getting more expensive and more scarce as the electronics industry competes with the cell industry for the limited output of the few producers. The question is, do solar cells require starting material of such high quality? The answer is, not really. **Solar-grade silicon** produces 15 to 16% efficiency solar cells, but costs only a fraction of the current \$25 per kilogram paid for the **electronic-grade** used in integrated circuits. Wacker Chemitronic has set up a production facility in the United States to produce nothing but solar cell-grade silicon. Also, Jet Propulsion Laboratories, under contract with the Department of Energy, initiated a research program aimed at developing new processes to produce this grade of silicon in a cost- and energy-efficient manner. This program has attained the objective of encouraging some manufacturers to implement new processes.

Polycrystalline Silicon

One of the most expensive, energy-intensive steps in making a solar cell is pulling the large single crystal that serves as the starting material. If a perfect single crystal were not needed, a great deal of cost could be eliminated. Some researchers who have tested polycrystalline silicon believe that the loss of efficiency caused by the grain boundaries is just too great, but several methods of casting cubes of polycrystalline silicon with large crystal grain sizes have led to polycrystalline solar cells with efficiencies as high as those of the commercial single-crystal cells.

Joe Lindmayer of Solarex started a companion company called Semix, in joint venture with Amoco, to manufacture "semicrystalline" solar cells from large blocks of silicon cast using a proprietary process. The cooling of the molten silicon is controlled so that the impu-

urities in the starting material are swept to one end of the block and then discarded. This process utilizes **metallurgical-grade silicon**, which is much cheaper than electronic-grade. The resulting crystal grains in the blocks are so large that the cells produced behave almost like single-crystal cells. If the grain boundaries are perpendicular to the face of the device, the cell acts like a group of small cells in parallel. In 1983, Semix constructed its "Solar Breeder" plant in Gaithersburg, Maryland, to make this new type of cell directly from high-quality sand. Solar cells on the roof of the Breeder supply some of the power needed to run the operation, which is capable of producing enough cells each year to generate 25 peak megawatts of electric power. Since the takeover of Solarex by Amoco in 1984, the Breeder has been put into operation and is Solarex's main production facility.

Crystal Systems has perfected a similar system in which they can produce a cube of single-crystal silicon 12 inches by 8 inches, weighing 90 pounds (Figure 2.10). Ironically, this brings us back to single-crystal cells, but this crystal-growing process is very energy-efficient and produces high-quality cells from a metallurgical-grade starting material. The process, which involves a helium gas heat exchanger, casts the ingot in a silica crucible which breaks apart upon



Figure 2.10. Heat exchanger method (HEM) single-crystal silicon ingot.
(Crystal Systems, Salem, MA)

cooling and leaves the cube intact. Other organizations, including Wacker Chemitronic, are casting polycrystalline cubes also, but with smaller grain sizes. Kyocera sells polycrystalline cell modules made by a proprietary casting process.

Ribbon Growth Systems

The cubes of silicon described above still must be sliced. Although several multiple-wire slicing devices have been developed, the process remains very time-consuming and wasteful. Another approach would be to grow ribbons of single-crystal silicon and cut them to size. The cells would be produced without any further surface treatment. This method saves several steps and is a much more efficient use of expensive pure silicon.

Mobil has been working on ribbon growth systems for some time. Their process involves pulling a vertical ribbon of silicon from a carbon die set in a bath of molten silicon, but there is the problem of inclusions of silicon carbide forming when the hot silicon reacts with the die. The Japanese use boron nitride dies to eliminate this situation.

Mobil's ribbon puller produces a nine-sided cylinder rather than a flat ribbon. The continuous molten circumference allows more careful control over the solidification process and produces high-quality sheets with very few silicon carbide inclusions. The cylinder is sliced into 2-x 4-inch plates using a high-powered laser; solar cells are then produced from these plates through a set of proprietary steps. Mobil sold Mobil Solar to a consortium that includes Germany's Deutsch Aerospace. The new company, ASE Americas, has attained full production. Three members of the old Mobil Solar have started a venture called Evergreen Solar. They have developed a ribbon-growth process that uses a pair of strings to define the edge of the silicon ribbon during the low angle pull of the crystalline ribbon from the silicon melt. Evergreen Solar is in full production also and recently had a public stock offering.

In other ribbon growth methods, the ribbon is pulled horizontally or even downward or no die is used at all. D. N. Jewett of Energy Materials Corporation developed a process that pulls the silicon sheet almost horizontally from a quartz crucible. This system (Figure 2.11) has the advantage of operating at high pulling speeds while producing high-quality, defect-free ribbons. It is not currently in use.

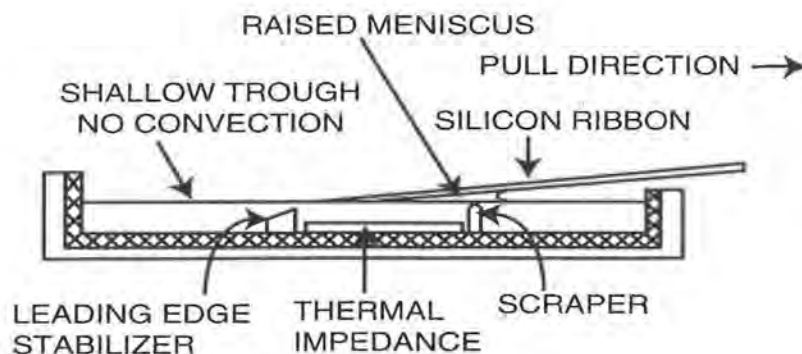


Figure 2.11. Silicon ribbon-pulling process developed by D. N. Jewett.
(Energy Materials Corporation, Harvard, MA)

A Westinghouse process exploits the dendritic growth of a pair of crystals at the edges of the ribbon to control the shape; Solavolt International developed a process in which a polycrystalline sheet, produced by chemical vapor deposition from silicon compounds, is melted very quickly by a scanning laser to produce a single-crystal ribbon. This process, shown in Figure 2.12, has an uncertain fate at the moment since Solavolt production facilities have been shut down. In 1982, Honeywell and Coors, in a joint project financed by the Department of Energy, experimented with ribbons of silicon cast onto ceramic substrates, but all work stopped when government funding ran out. In contrast, a group in France continues similar work with a graphite supporting matrix. The silicon layer can be very thin and if the substrates can be produced cheaply enough, the cell could meet DOE's cost objective of \$0.70 per peak watt.

AstroPower, a photovoltaic manufacturer in Delaware, has set up a pilot plant making cells from thin films of crystalline silicon coated onto a low-cost proprietary substrate. Although AstroPower has shipped special-project PV modules made by this process, which promises to be inexpensive, they still make commercial solar cells from single-crystal wafers recycled from the electronics industry.

AMORPHOUS SILICON

One of the most surprising industrial developments has been the rapid growth of the amorphous solar cell. From a laboratory curiosity in the



Figure 2.12. A thin film of crystalline silicon is grown on a proprietary substrate to make low-cost solar cells. (AstroPower, Newark, DE)

early 1980s, the cell has become a standard part of pocket calculators and watches. (Industry sales amounted to 100 million calculators in 1994, a substantial segment of the total Japanese cell output.) An extremely sophisticated automated manufacturing process has reduced the price of a set of four or five small cells to less than the cost of the batteries they replace. Even though the cost per watt of small amorphous cells is around \$4, the milliwatt power cells in use are only a few cents each.

The two main obstacles to immediate large-scale utilization and production of amorphous power modules are (1) light-induced degradation and (2) poor yield in large-area cell production. To understand this, we need to know more about **amorphous semiconductors**.

An amorphous material is one that appears to be solid but has no long-range crystal structure. Glass is a good example of this. Amorphous

selenium has been known as a photovoltaic cell material for over a century and has been used in Xerox photocopiers since the late 1940s. The semiconducting properties and the band structure of this material have been examined, and the photovoltaic cells made from selenium have been used commercially for decades even though they have an efficiency of only about 0.1%.

In 1966 Yoshihiro Hamakawa of Osaka University in Japan discovered a way to make **amorphous silicon** solar cells. His work was ignored until the mid-1970s when RCA began investigating amorphous silicon as a potential solar cell material. The material had been known for some time but had been dismissed as a solar electric converter because it normally has a high resistance. Actually, if the amorphous silicon thin film is deposited in such a way as to incorporate a small percentage of hydrogen and other elements trapped in the layer, the high dark resistance is immaterial and the solar cell will have a relatively high short-circuit current. It is believed that the hydrogen atoms form Si-H bonds to tie up some of the dangling bonds caused by the somewhat random arrangement of the silicon atoms in the amorphous layer.

The usual way to deposit the amorphous silicon layer is by **sputtering** silane (SiH_4) or some other silicon compound in a vacuum system. The reactive sputtering is achieved by producing a glow discharge in a low-pressure gas mixture using a high-voltage DC or radio-frequency AC power applied between two electrodes. One of the electrodes or a substrate placed between the electrodes will become coated with the amorphous film.

The amorphous silicon cell has developed commercially over the past decade and now constitutes an important branch of the photovoltaics industry.

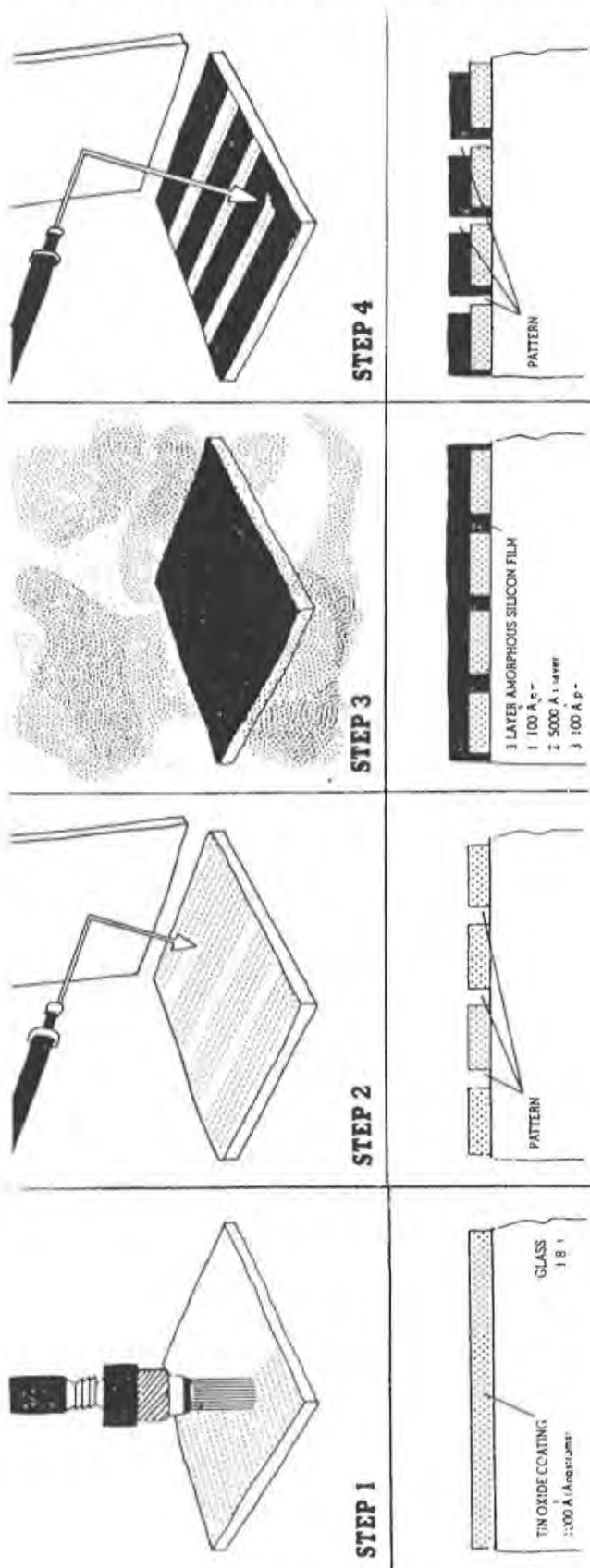
Amorphous silicon has a band gap somewhat larger than crystalline silicon and absorbs light more strongly in the visible part of the spectrum, which means that the theoretical efficiency of solar cells made of this material is actually higher than that for single-crystal silicon cells. A great deal of work remains to be done to clarify semiconducting properties and efficiency loss mechanisms before this efficiency can be realized. However, the simple fabrication steps and the thin films that can be used in making the solar cells should produce a practical, inexpensive cell even if the production-line efficiency is no more than 8%, although 15% has been

achieved already in the laboratory. Questions about the long-term stability of amorphous films under sunlight conditions are beginning to be answered, as the Stabler Wronski effect (named after its discoverers) is becoming understood and thinner multilayer cells diminish its importance.

Researchers at Osaka University in Japan and elsewhere have been working on a heterojunction solar cell combining amorphous silicon carbide with amorphous silicon. It is made by a sputtering system also, but uses a mixture of silane and methane as the reacting gas. This device has achieved 7.5% efficiency.

The first problem, the deterioration of the cell after exposure to direct sunlight for as little as one day, is poorly understood, even though considerable research effort has been directed toward the phenomenon. The extent of decline has been reduced by changing the formula of the complex mixture of gases used in the sputtering deposition of the amorphous layer, but the effect is still present and, for now, simply accepted. Some manufacturers refer to this as the "burning-in period" and rate performance after degradation. The relatively free movement of small atomic species such as hydrogen and fluorine in the loosely linked silicon atom matrix could be responsible for this Stabler Wronski effect; a good deal of research is aimed at replacing the fluorine and "locking up" the matrix with larger atoms, such as other halogens and boron. Boron, of course, also acts as a p-type dopant, giving the amorphous film the proper electronic characteristics for a solar cell. The research currently underway worldwide will certainly pay off in the near future and we will soon see commercially available amorphous solar cells of 8 to 10% efficiency. In fact in 1994, the National Energy Research Laboratory (NERL) announced a record performance of 10.8% after "stabilization" of an amorphous silicon multilayer solar cell manufactured by United Solar Systems (a division of Energy Conversion Devices) of Troy, Michigan. The company is now producing inexpensive "solar roof shingles" using this technology.

The second problem, poor yield in large-scale manufacture, could simply be one of quality control, similar to the problems that plague all semiconductor manufacturers when they enter a new product area. It is possible, though, that the point defects that could short out an entire cell will prove impossible to eliminate. In this case, the best strategy might be to institute an "integrated circuit" approach—large

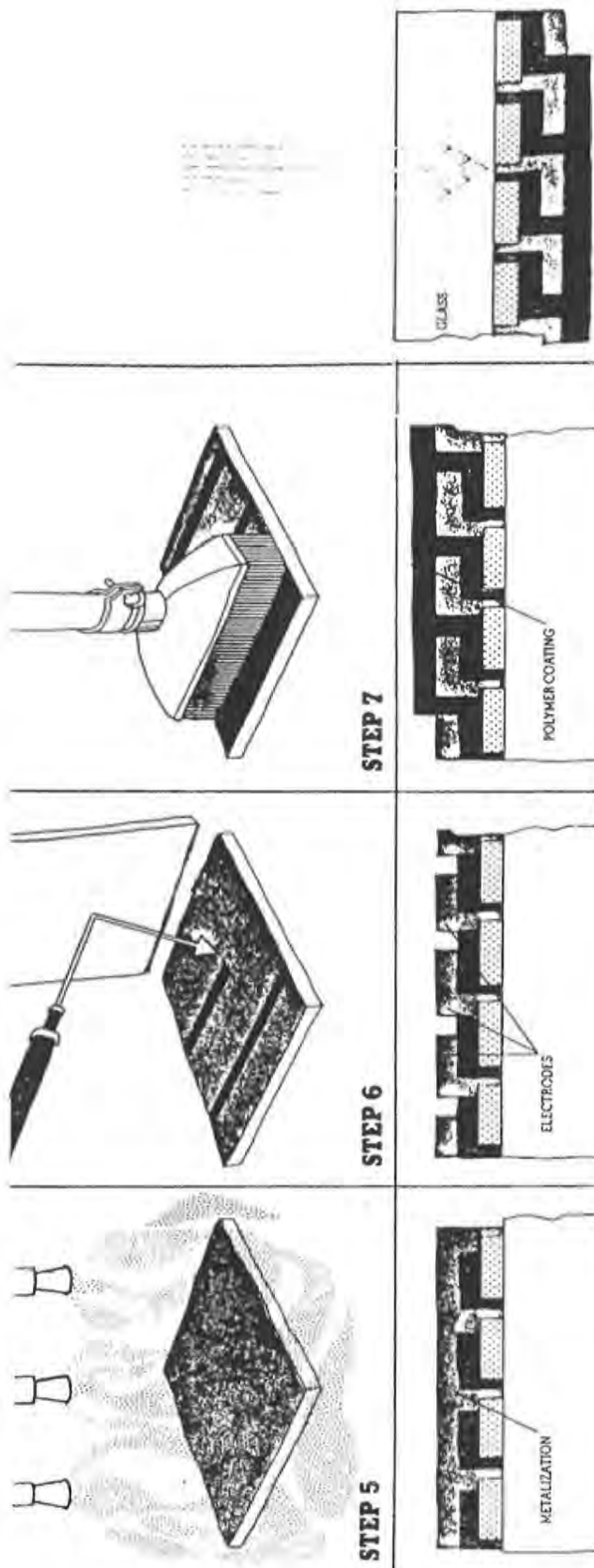


The glass substrate is coated with a transparent conductive coating. Tin oxide is deposited by a chemical spray deposition process from organometallic tin compounds.

The transparent conductor is patterned into regions of conductive and nonconductive areas by removing the tin oxide coating with a scanned high power laser.

A deposition chamber lays a film of amorphous silicon on top of the patterned tin oxide. Three different layers of amorphous silicon are deposited: one layer with p-type conductivity, a middle intrinsic layer, and a top layer with n-type conductivity. This configuration converts sunlight into electricity.

Strips of the amorphous silicon films are removed, using laser techniques similar to Step 2.



The second electrode, composed of a double metal layer (one is aluminum), is deposited in an evaporation chamber. The evaporated metals are deposited in a thin film onto the scribed amorphous silicon.

A laser cuts thin strips from the metal electrode.

A protective layer of organic polymer is deposited on the back of the panel, using a combined dip/spray process.

The completed panel: a number of cells connected in series and parallel. The two output conductors are strips of copper tape on opposing edges. The supporting frame of the array contains the inter-panel connectors.

Figure 2.13. The step-by-step process of amorphous silicon photovoltaic panel manufacture. This process is capable of handling glass up to one foot by three feet. By varying the laser scribing pattern of the various layers, different combinations of voltage and current can be obtained. (Advanced Photovoltaic Systems, Princeton, NJ)

amorphous photovoltaic modules composed of thousands of tiny cells all made at one time on a single substrate, connected only after testing has revealed the defects.

It is becoming difficult to keep track of the corporations that have announced new or expanded efforts in the amorphous solar cell area. The Japanese are still slightly in the lead in production output and, either directly or through joint ventures with American companies, such as United Solar Systems, are responsible for most current commercial sales (although U.S. researchers are leading in new developments). Japan has built demonstration homes with amorphous power panel roofs and several companies have shown prototype power panels in the 30- to 40-watt size. None of these companies accept orders for immediate delivery; schedules are vague and have a tendency to slip. Actual full-scale production will have to wait until these problems are solved.

In the United States, United Solar Systems and Advanced Photovoltaic Systems, Inc. (formerly Chronar), of Princeton, New Jersey, depend on amorphous cells for their entire product line. United Solar Systems, in conjunction with Sharp, maintains a full-scale automated production line in Japan to fabricate a wide ribbon of cells on a continuous basis; two more lines will be operable soon in the U.S. and the technology has been exported on a turn-key basis to Egypt. While United Solar Systems has demonstrated large-sized, flexible amorphous modules, their production modules are small units for calculators and consumer devices that are not exposed to long hours in the direct sun.

Chronar, on the other hand, concentrated on large-wattage power modules from the start and consequently was slow to sell solar products on the open market. Chronar's profits had been produced by selling technology—arranging joint ventures in Egypt and elsewhere to set up amorphous assembly plants. Their own plant, built in conjunction with AFG Industries, Inc., used automated technology to build amorphous modules onto tin oxide-coated glass (see Figure 2.13). These small cells, produced for use in calculators, run at about 3% efficiency. Chronar also introduced an innovative solar patio light which used a 2-watt amorphous silicon panel to charge a battery that operates a small (0.8 watt) light. Although these inexpensive outdoor lights sold very well, losses soon forced a reorganization of the corporation a few years later, with Advanced Photovoltaic Systems assuming the photovoltaic business.

Most major solar cell manufacturers have announced amorphous silicon research and development efforts. Some companies, like Exxon and Photowatt SA, have closed their crystalline silicon operations, pinning all their hopes on a future amorphous solar cell line. Others, like Siemens Solar (formerly Arco Solar) and Solarex (now part of BP Solar) are phasing in amorphous products as they are ready, but are not decreasing conventional solar module production. Solarex, for example, bought RCA's amorphous silicon research and development section, as well as the U.S. patents for amorphous silicon cells. In fact, it was the pioneering work at RCA, the first American company to work on amorphous silicon cells, that led to this recently developed industry. Even though the basic cell was discovered in a Japanese university laboratory, Japanese companies paid no attention to the work until RCA announced its amorphous program at the 1976 IEEE Photovoltaic Specialists Conference.

The boom in amorphous silicon solar cells will continue. It is only a matter of time before the technical problems will be solved and large power modules become generally available. The price per watt for these devices, however, will not drop precipitously. The cost of manufacture and the high reject rate will make it difficult, at first, to profit, especially in competition with the present price per watt of crystalline silicon cells. The price will start to decline only after large-volume deliveries have given production people the time and experience to take advantage of the inherent economics of amorphous devices. As this happens, new markets will open up, and amorphous photovoltaics will begin to produce a significant amount of our electric power.

RECOMMENDED READINGS

- Chalmers, Bruce. "The Photovoltaic Generation of Electricity." *Scientific American* 235:34-43 (October 1976).
- Hubbard, H. M. "Photovoltaics Today and Tomorrow." *Science* 244: 297-304 (April 21, 1989).
- Perez-Albuerné, E. A., and Y.-S. Tyan. "Photovoltaic Materials." *Science* 208:902-7 (May 23, 1980).

Chapter 3

Solar Cells and Modules

SERIES AND PARALLEL STRINGS

The maximum useful voltage generated by a solar cell is on the order of 0.5 volt. This is not a very high potential and not many devices can operate on such a small voltage. However, solar cells can be connected in **series** (the back contact of one cell connected to the front contact of the next) to obtain a higher voltage. Figure 3.1 (top) shows such a series string, which is called a **solar module**. (Although the terms **solar array** and solar module are sometimes used interchangeably, an array is a set of one or more modules.) A typical solar module will have 33 cells in series, producing an open-circuit voltage in bright sunlight of around 20 volts, or 16 volts when producing its maximum power. Such a module is designed to charge a 12-volt storage battery. It is important to remember that the total current output of a series string of cells is the same as that of a single cell.

To increase the current output, solar cells are wired in **parallel** (the back contact of one cell connected to the back contact of the next, with the front contacts similarly connected). In a parallel sys-

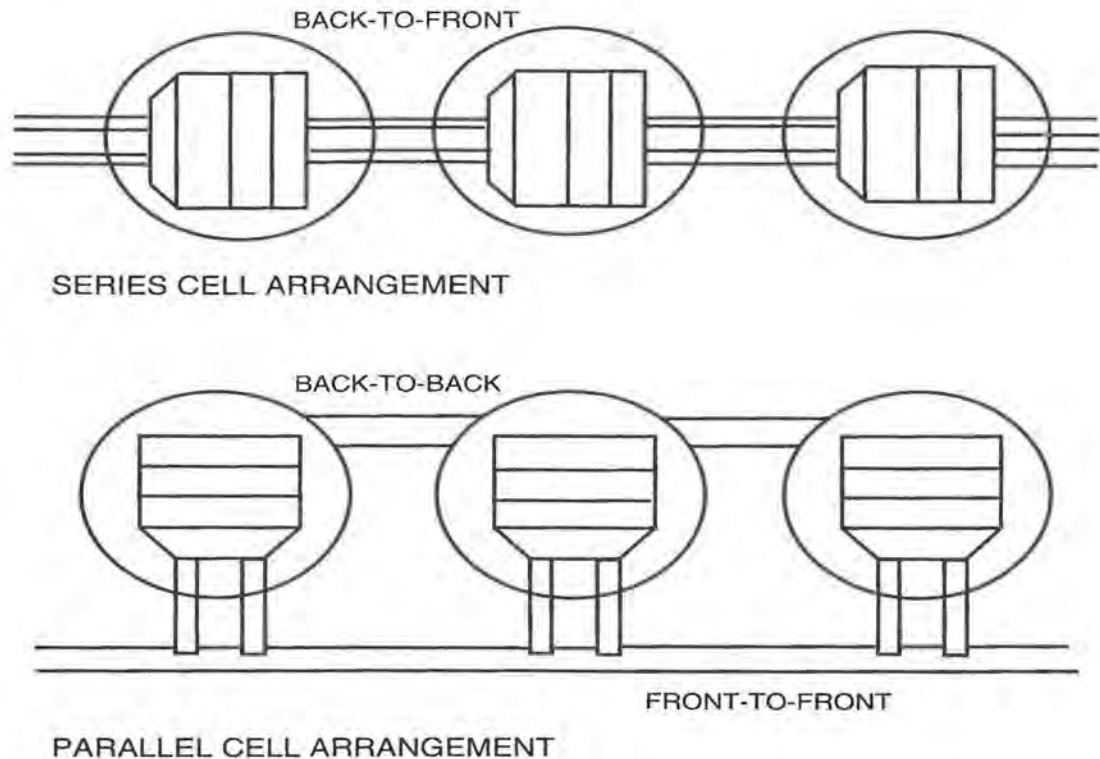


Figure 3.1. *Top:* Series string of solar cells increases voltage.
Bottom: Parallel string of solar cells increases current.

tem, such as shown in Figure 3.1 (bottom), the total current is the sum of the individual current outputs of the cells, but the total voltage is the same as the voltage of a single cell. Usually, individual cells are wired in series, forming a module, to obtain the desired output voltage; modules are wired in parallel in an array to obtain the desired current. Chapter 4 details this procedure.

Solar cell manufacturers produce a variety of modules that can be combined into an array to meet just about any voltage and current need (see Figure 3.2).



Figure 3.2. Finished AstroPower solar cells exiting the furnace where the top finger contacts were fused onto the single crystal silicon.

(AstroPower, Newark, DE)

MODULE CONSTRUCTION TECHNIQUES

Since silicon solar cells and arrays were first developed for the space program, the construction techniques emphasized reliability. In most cells the front contact finger patterns are designed with some redundancy so that a break in the pattern or a bad solder joint will not shut down the entire cell. The AstroPower cells, shown in Figure 3.3, illustrate this design technique. The cells are fastened into series strings by sweat-soldering thin, tin-plated copper ribbons over the three main crossbars. Then the ribbons are sweat-soldered onto the back of the next cell. Even if a



Figure 3.3. These single crystal silicon solar cells have efficiencies as high as 18%. (AstroPower, Newark, DE)

cell cracks, the two pieces are still fastened in parallel and electrical performance is virtually unchanged.

The cell pictured here illustrates the older technique of nickel fingers tinned by an industrial wave-soldering machine. Other cells, primarily used for space applications, are made with silver-plated and palladium-silver fingers. Silkscreening techniques are now almost universally used for large production terrestrial cells. Corrosion and mechanical failure of the finger contacts and interconnects are the most common causes of cell failure, so noncorrosive metals must be used. However, the metals must have the proper electronic behavior in contact with silicon. Most cells are soldered together to make modules, but some manufacturers now spot-weld the interconnections. Many small solar modules come equipped with a built-in **blocking diode**. This diode protects a storage battery against drainage by preventing the current from running backward through the solar cell array. Blocking diodes will be discussed further in the next chapter.

ENCAPSULATION

Cells must be sealed to protect them from the environment and to support them in the module. The two most common encapsulants are transparent silicone rubber and an ethylene vinyl acetate (EVA) plastic similar to the plastic layer used in automobile safety glass. Usually a top cover of plastic or tempered glass is added to offer better protection against the elements. Glass covers are more scratch-resistant and remain transparent longer, but they do not flex as much as plastic covers. This flexibility makes plastic modules more suitable for use on sailboats and camping vehicles. Of the two plastics most commonly used, polycarbonate is the more damage-resistant and can withstand higher temperatures, but acrylic is more flexible and less expensive.

Bringing the electrical wires out of the panel requires careful design. The electrical connectors are a pair of contacts that protrude from the back of the panel and are sometimes encased in a small junction box. Some modules are designed so that the wires project from the side, which allows the panel to rest flat on a support surface (for example, a roof or sailboat cabin top). These connectors must be very well sealed, so that water cannot seep in along the wires and corrode the interior contacts. They also must be very secure so that the wires cannot be pulled out or put strain on the cells.

MODULE FAILURE MECHANISMS

Joints Between Cells

The silicon solar cell is a remarkably rugged device. The cell itself can withstand a great deal of abuse and extreme temperatures, both high and low. It is also impervious to most corrosive chemicals. When a solar module fails, the problem usually lies with something other than the cells.

The first solar module I constructed failed prematurely after four years of operation on the deck of a small sailboat. The main problem was the corrosion caused by saltwater that had leaked into the case. Some of the joints between cells had failed mechanically, as well. The cells had been fastened in series by a technique called **shin-**

gling. The front edge of one cell is overlapped by the back edge of the next, similar to roof shingles, and the edges soldered directly together. No copper jumpers are used to interconnect the cells except from one row to the next. Since the entire row is one rigidly fastened unit, any flexing or thermal expansion puts a great strain on the adjoining edges, pulling the top contact loose from the underlying cell.

Producing a good mechanical bond between the silicon cell material and the nickel or silver top finger contact is difficult, and it is surprisingly easy to pull the fingers right off the cell surface by jerking on the jumper strip soldered to the fingers. However, because the newer silk-screened fingers adhere very well, these cells will break before the tabs can be pulled off. The back contact covers the entire back of the cell and, while it is not actually any stronger, the greater surface area helps make the cell more durable.

Too high a temperature during the process of soldering contacts to the cells may also loosen the fingers from the silicon; too low a temperature will cause a "cold" solder joint that will quickly fail. The exact composition of the solder and the flux, and the cleanliness of the operation, greatly influence the reliability of the joints.

Encapsulant Problems

If the thermal expansion of a rigid encapsulant differs sufficiently from that of the cells, the encapsulant can pull loose or the cells can crack. This has been a problem with cells embedded in polyester resins.

Direct sunlight creates a very harsh environment and can cause chemical reactions in encapsulants and cover materials, turning them cloudy or yellow. While this may have no effect on the cell itself, it will cut down on the amount of light that reaches the cells and this will lower system efficiency. These reactions are accelerated by the high temperatures modules can attain under full sun in the summer. The cells can withstand much higher temperatures than any other part of the module, although cell efficiency drops when the temperature rises. It is best to keep the cell temperature below 60°C.

Recently, some problems have come to light with older PV modules that used EVA encapsulants. After long exposure to high temperatures, the material turns brown and begins to decompose,

forming acetic acid that corrodes the interconnect ribbons between cells. This problem occurs most often when reflectors have been added to the system to increase light intensity and power output, but without adequate provision for cooling. Even then, it takes years for this condition to appear.

Shunt Diodes

A cell can be permanently damaged if a large reverse voltage is applied to the electrodes. A solar cell is an electrical rectifier which means that it passes current in one direction only. In the dark, the silicon solar cell acts just like any other silicon diode rectifier. However, in the manufacture of solar cells, no real attempt is made to build in an ability to withstand a large reverse bias since the cell is not usually used in this way. There is one circumstance under which this reverse voltage condition can occur: when one cell is shaded while the rest of the cells in a series string are in sunlight. When this happens, the current through the string immediately stops and the sum of all the open-circuit voltages of all the other cells shows up across the shaded cell. If the cell cannot withstand this voltage, it will break down electrically and begin to conduct. The resistance heating effect of the current can make a cell hot enough to melt the solder connections and destroy the fingers.

Sooner or later, such shading will occur: for example, a leaf falls on one cell or a tree casts a shadow on a module. Since it is impossible to prevent such occurrences, it is necessary to take precautions so that shading will not destroy a cell. With 33-cell modules, reverse bias breakdown is rarely a problem as virtually all cells will take 30 volts or more in reverse bias. But if higher voltage strings are needed, shunt diodes should be installed. Chapter 4 describes how to wire shunt diodes, as well as other practical details of connecting solar modules. Some manufacturers have constructed experimental cells with the shunt diode built into the cell structure and some amorphous silicon modules have shunt diodes built into each long row. With these cells and modules, no external shunt diode is necessary.

In spite of the potential troubles described above, solar cell modules, if properly designed and installed, can last a remarkably long time. The first solar modules made by Bell Laboratories and originally installed in Americus, Georgia, in 1957, are still in opera-

tion. A minimum of 25 years of reliable operation can be expected from a solar electric installation.

CONCENTRATOR SYSTEMS

One way to use expensive solar cells more efficiently is to concentrate more light onto them. A detailed description of the numerous schemes that have been devised to accomplish this is beyond the scope of this work. Instead, we will discuss the general principles and give examples of each type.

The first parameter that can be used to characterize a concentrator system is the **concentration ratio**. This is simply the ratio between the area of the clear aperture, or opening through which the sunlight enters, and the area of the illuminated cell. Figure 3.4 shows a simple lens-type concentrator similar to a magnifying glass used to start fires. The concentration ratio is the area of the lens divided by the area of the cell. If the lens is 200 mm in diameter, its area is 314 cm^2 ; if the cell is 50 mm in diameter, its area is 20 cm^2 (for a circle, the area $A = \pi r^2$). The concentration ratio is $314/20 = 16$ to 1 (sometimes expressed as a concentration ratio of 16 suns). This means that the cell receives 16 times the light (minus the reflection and absorption losses in the lens, which can be very small for a coated lens) and should put out 16 times the power of a similar cell used without the lens. Because the lens does not have to be of fine optical quality (it could be molded plastic), it would seem that this system would be much cheaper than the 16 cells it replaces. The reality is not quite so simple.

First, with all the extra sunlight pouring onto it, the cell will heat up. With a concentration ratio of three suns or more, some way must be found to cool the cell. Simple cooling fins mounted to the back of the cell may suffice, but in hot climates or with higher concentration ratios, water or forced-air cooling becomes necessary. The usual EVA encapsulant is unsuitable for concentrator systems because it degrades at the higher temperatures and light intensities, so the more expensive silicone encapsulant is generally used. Silicone RTV has an unusual combination of properties in that it is an excellent electrical insulator while it conducts heat reasonably well and it can withstand high temperatures without yellowing; the excess heat removed

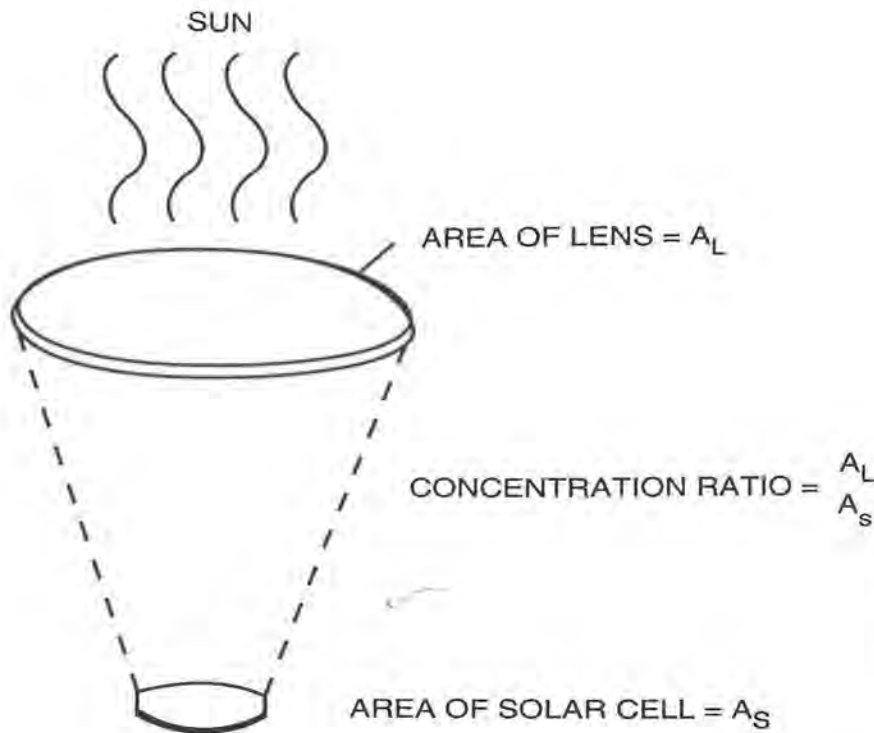


Figure 3.4. Diagram of a simple lens-type concentrator.

from the cells can be saved and used. A system that produces usable heat as well as electricity is a **hybrid system**. Hybrid systems can be very cost-effective when neither the heat nor the electricity generated separately would justify a solar system. Hybrid systems are discussed later in this chapter and again in Appendix A, which contains step-by-step instructions for hybrid module construction.

Second, the currents produced by the photovoltaic cells in concentrator systems can become quite large. (Currents in excess of 100 amps have been produced by a single cell.) In order to handle these massive currents, special cells have to be constructed. Usually these cells are thinner than the normal cell and have a much smaller cell resistance. The finger pattern and top contact for the cell must be carefully designed to carry these currents without blocking too much of the cell's surface area. Figure 3.5 shows a concentrator cell capable of handling a concentration ratio of up to 200 suns. Naturally, such cells are more expensive than the standard solar cell, but each one produces so much power that the extra cost is justified. Ordinary solar cells can handle a concentration ratio of 3 or 4 suns, provided they are cooled adequately.

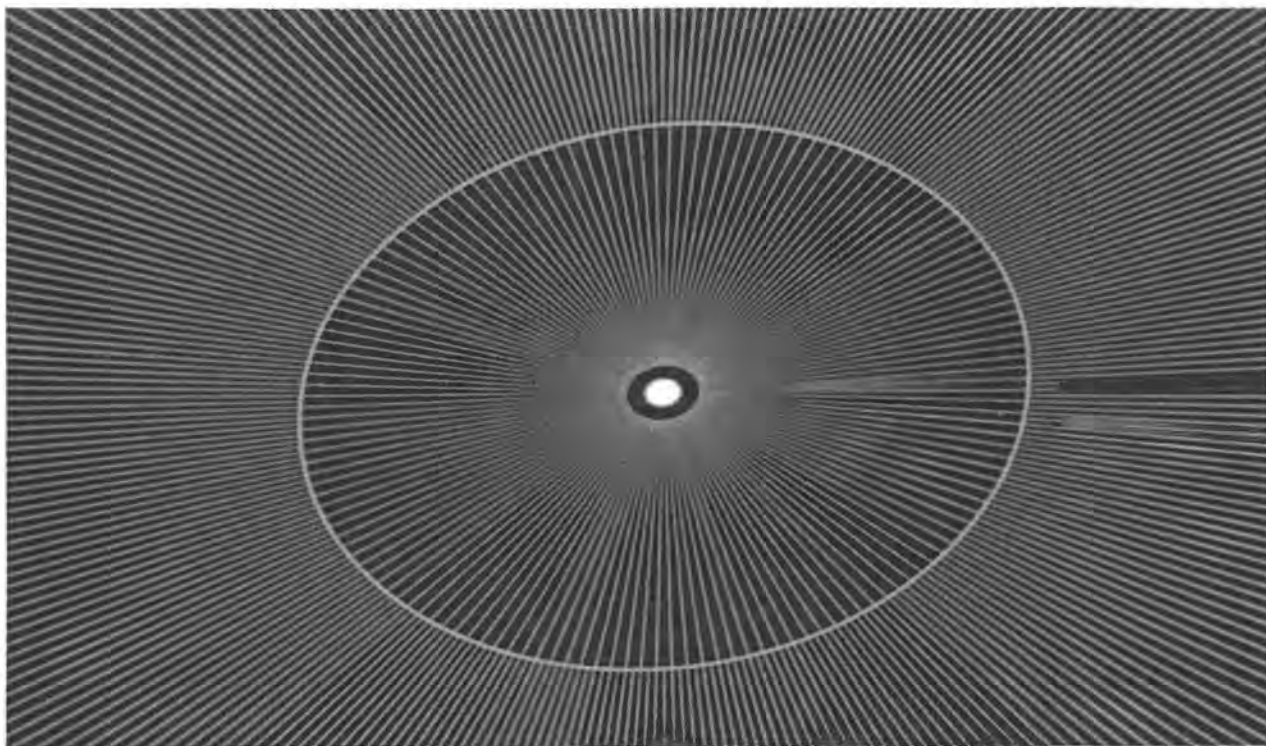


Figure 3.5. Concentrator cell capable of handling ratios of 200 suns.
(Applied Solar Energy Corporation, City of Industry, CA)

Third, for a concentrator system to work best, it must point directly at the sun at all times. Therefore, a tracking system must be devised to pivot and follow the sun as it travels daily from east to west. The pivot must also raise and lower the angle to allow for the seasonal change in the sun's path in the sky—high in the summer and low in the winter. The simple concentrator shown in Figure 3.4 now has a complex tracking mount. The mount could be moved by hand, which would require constant adjustment, or it could have a clockwork mechanism that tracks the sun automatically. The most sophisticated systems have photocell detectors and feedback mechanisms to constantly correct the system and keep it directed correctly.

Two-Axis Tracking

A mount that is capable of pivoting both daily and seasonally to follow the sun's path is called a **two-axis tracking system**. Many two-axis tracking systems have been built experimentally and sever-

al are available commercially. Some units use a small concentration ratio of 3 to 1, so a simple cone reflector is sufficient and large tracking errors can be tolerated. If the unit also has forced-air cooling of the cells, the hot air produced can be put to some useful purpose. Such modules were commercially available back in the 1980s.

Figure 3.6 shows another two-axis tracking system that uses **Fresnel lenses** as the concentrator elements. Fresnel lenses work as well for light concentration as the thick lenses they replace, but they use only a fraction of the material and can be molded out of plastic. It is also possible to have a greater optical correction in the outer edge of a Fresnel lens so that the distance from the lens to the cell can be shorter for the same concentration ratio. This particular Fresnel lens concentrator system, produced by Martin Marietta Corporation, was installed in a village in Saudi Arabia and has a 350-kW capacity, enough to supply the power needed by two villages. (It replaced a set of diesel generators.) With a concentration ratio of 33 suns, the system has a particularly sophisticated tracking controller using coarse and fine sun sensors and a small computer. The system is passively cooled and no provisions were made to collect the waste heat.

Another commercially available two-axis concentrator is being manufactured by Midway Labs in Chicago. This system, developed by Roland Winston of the University of Chicago, uses two-stage concentrator optics to reach a concentration ratio of 335 to 1. Complete with tracking mount, it is cost-competitive with a fixed array of flat PV modules of equivalent electrical output.

One-Axis Tracking

The purpose of a solar concentrator is not to give a clear image of the sun, but rather to collect the sunlight that falls over a large area and project it onto the smaller area of the collector or array. The quality of the image does not matter as long as most of the sunlight falls onto the cells. Figure 3.7 shows a trough-type parabolic collector that does this in one dimension. This particular embodiment of the trough collector is called a **Winston Concentrator** as it was also developed by Roland Winston. Its great advantage for smaller concentration ratios is that it does not have to track the sun daily for the seasonal variation in the sun's position. Table 3.1 gives the acceptance angle and frequency of adjustment for different concentration

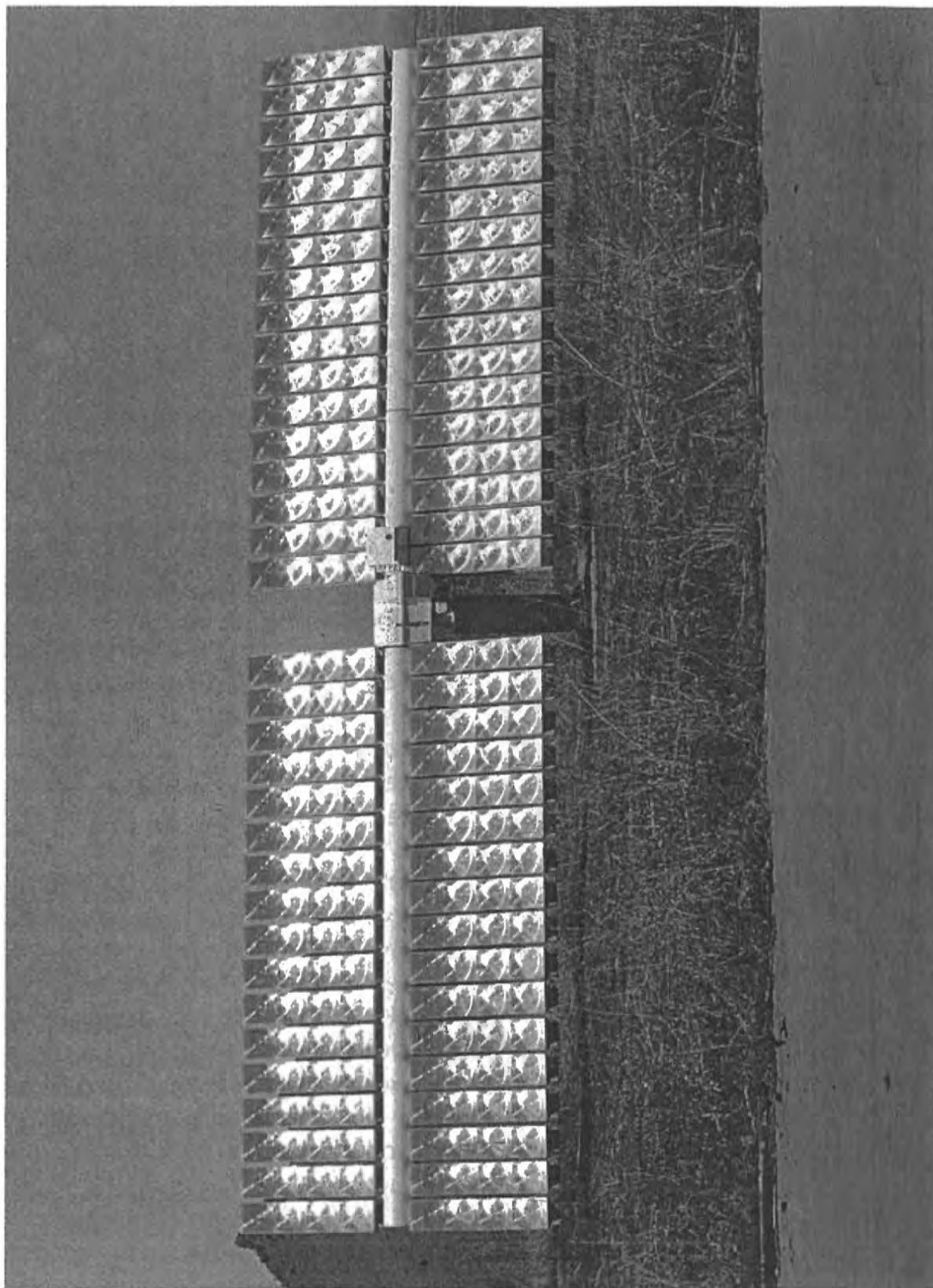


Figure 3.6. Fresnel lens two-axis tracking system array. (Martin Marietta Aerospace, Denver, CO)

ratios. The **acceptance angle** is the total range of sun positions over which the sunlight will still be collected by the mirror system and focused onto the solar cells. This table assumes that the axis of the trough collector is horizontal and pointing east and west.

This simple system does not effectively collect sunlight early in the morning or just before sundown when the sun is shining more or less lengthwise down the collector. Another version of the linear concentrator is oriented north and south and tilted south at an angle equal to the latitude of the installation. The system tracks the sun during the course of a day but needs no adjustment for seasons and so the mount and tracking mechanism can be quite simple. Also, connecting the cooling fluid pipes or air ducts to the system is greatly simplified if a hybrid or **total energy system** is desired.



Figure 3.7. Trough-type parabolic collector, similar to that developed by Winston, mounted on the roof of the Raymond Frady residence near Miff-
lin, Indiana. This type of hybrid concentrator photovoltaic system is particularly suitable for remote residential applications.

Table 3.1
Acceptance Angle and Adjustments Needed per Year for Different
Concentration Ratios for a Winston Concentrator

Concentration Ratio	Acceptance Angle (degrees)	Number of Adjustments per Year	Shortest Period between Adjustments (days)
2	30.0	0	—
3	20.0	2	180
4	14.5	4	35
6	9.6	10	26
10	5.8	82	1

Whatever configuration is used, flat plate or concentrator, hybrid or electricity-collecting only, the inherent simplicity of operation makes a PV system easy to install and maintain. The only connections to the solar module are a pair of wires, giving the user a great deal of design flexibility. The next chapter explains exactly how solar cells are used.

RECOMMENDED READINGS

- Backus, Charles E., Ed. *Solar Cells* (New York: Institute of Electrical and Electronics Engineers, 1976).
- Commoner, Barry. "The Solar Transition." *The New Yorker* 55:53–54, Part I (April 23, 1979); 55:46–48, Part II (April 30, 1979)
- Fan, John. "Solar Cells: Plugging into the Sun." *MIT Technology Review* 80:14–15 (August 1980).
- Institute of Electrical and Electronics Engineers. *Spectrum* 17:(February 1980). A special issue devoted to photovoltaics.
- Merrigan, Joseph A. *Sunlight into Electricity* (Cambridge, MA: The MIT Press, 1975).
- Perez, Richard. "The Fire Within." *Home Power* 40:28–31 (April/May 1994).
- Pulfrey, David, Ed. *Photovoltaic Power Generation* (New York: Van Nostrand Reinhold Co., 1978).

Chapter 6

New Developments in Photovoltaic Technology

The standard method of making silicon solar cells is both expensive and energy-consuming. If solar cells are going to compete with the nonrenewable resources now used to generate electricity, new types of cells and new manufacturing processes will have to be developed. The present price of about \$4 to \$5 per watt for crystalline silicon modules is too high to compete with central utilities. The Department of Energy has an ongoing research program aimed at reducing this cost and this program, together with the photovoltaic part of the Small Business Innovation Research (SBIR) Program, is succeeding in lowering cost as well as increasing module longevity. In addition, a number of private companies and research groups are still working on a great many alternative approaches to photovoltaic production of electricity. These include new ways of using silicon, other materials and combinations for solar cells, and clever optical systems to more effectively exploit the photovoltaic process. This chapter will review a number of these systems and will attempt to assess their prospects.

OTHER JUNCTION STRUCTURES

Many of the new developments start with silicon, the best understood semiconductor material. Once the thin flat piece of silicon is produced, a junction has to be formed at the top surface to make a photovoltaic cell. A number of alternatives to the diffused p-n junction are being investigated, both to increase cell efficiency and to cut manufacturing costs.

Martin Green and his co-workers at the University of New South Wales in Australia have been working on entirely new configurations for the PV junction in silicon. Their latest work uses thin layers of alternating p- and n-type silicon deposited onto glass substrates. Vertical grooves are etched by laser beam through these layers all the way to the glass substrate and then metal contacts are added to fill the grooves. By making alternating buried metal strip contacts either p- or n-type silicon, a large number of tiny p-n junctions are created in one cell. With its extremely short minority-carrier path lengths, this configuration is very tolerant of defects and acts almost like the theoretically ideal silicon solar cell. The grooved, clear top coating bends light that would have fallen onto the metal fingers away to the active cell area, utilizing almost every photon and producing a record silicon-cell efficiency of over 24%. The process is licensed to BP Solar, which has simpler buried-contact configuration modules already in production in Australia.

Tin Oxide and Indium Oxide

Two successful heterojunctions with p-type silicon are **tin oxide** and **indium oxide** doped with tin oxide (called **ITO** by the engineers working on the material). Both are n-type semiconductor materials which are transparent to visible light but which are good conductors of electricity. Tin oxide can be easily deposited onto glass or other substrates by spraying tin chloride in water onto the heated substrate. Tin oxide-coated glass (called NESA glass) is used as a transparent conductive surface for such applications as aircraft windows. The processes for producing it are well-developed and inexpensive. Indium oxide thin films, a more recent development, are easy to produce and are used in the "Low E" insulating glass used in modern house windows. However, indium is an extremely rare element and

there are those who question the advisability of making solar cells with indium compounds, since such a large quantity of cells would be required to meet a significant portion of our energy needs. In the laboratory, tin oxide and ITO heterojunctions with silicon have been produced which are as efficient as the normal p-n homojunction silicon cells.

Metal-Semiconductor Junctions

Another type of junction that can be used in a solar cell is the **Schottky barrier** or **metal-to-semiconductor junction (MS junction)**. This junction is produced when a low work-function metal like aluminum is deposited onto a p-type semiconductor or a high work-function metal like gold is deposited onto an n-type semiconductor. Becquerel's first photovoltaic cell was a Schottky barrier device. This barrier contact is in contrast to the low-resistance ohmic contacts usually required for metallic contacts to semiconductor devices. If an extremely thin (20 Å) insulating oxide layer is placed between the metal and the semiconductor, the device is called a **metal-insulator-semiconductor junction** or **MIS solar cell**. MS and MIS junctions have been made with silicon and nearly all the metals in the periodic table. In the laboratory, some of these devices have shown enhanced open-circuit voltages and efficiencies compared to the standard silicon p-n homojunction solar cell; however, the complexities involved in making the precisely controlled, extremely thin layers required for their successful operation would seem to rule them out as likely candidates for commercial devices in the near future. The research devoted to these junctions has greatly increased our knowledge of how semiconductor devices work and of some of the mechanisms that cut solar cell efficiency.

PHOTOELECTROCHEMICAL CELLS

A few years ago, Texas Instruments (TI) announced the development of a new type of silicon solar cell. Instead of an all solid-state device with the junction between two different solid materials, this cell has a silicon-liquid junction. The silicon electrode is not in the form of a flat surface at all, but rather tiny beads made in the same way as

buckshot. Molten silicon is poured through screens to make tiny droplets that solidify as they fall through the "shot tower." The simplified processing steps and the ability of the device to produce hydrogen as well as electricity had created quite a bit of excitement, given the interest in the **hydrogen economy**. More recently, Texas Instruments has developed a method of mounting the beads between a perforated aluminum sheet and a solid backing sheet to produce an inexpensive, flexible silicon solar cell. TI has joined with Southern California Edison to set up a manufacturing plant to exploit this process to produce PV modules for large-scale solar power farms.

The **liquid junction** photovoltaic cell is also being investigated in a number of laboratories. Most of these cells use a semiconductor material as the anode and have had problems with long-term stability, because the light-induced chemical reactions can irreversibly change the anode surface. But Bell Labs has developed a type of liquid junction cell that has the active semiconductor electrode as the cathode and the cell actually becomes more stable when exposed to sunlight. The device can be designed to produce either electricity or hydrogen, and steady-state efficiencies of 11.5% have been achieved. However, their current cell uses scarce indium phosphide as the photocathode material; any large-scale exploitation of this technique will necessitate the development of a more commonly available cathode material.

CADMIUM SULFIDE/CADMIUM TELLURIDE AND OTHER II-VI HETEROJUNCTION CELLS

In the 1960s, Clevite Corporation developed a thin-film solar cell to be used in the space program. The cadmium sulfide solar cell, as it was called, had been invented in the early 1950s by Reynolds. It was not until twenty years later, however, that scientists figured out that the active semiconductor in the cell is not cadmium sulfide, but rather the cuprous sulfide layer found when the cadmium sulfide layer is dipped into a copper chloride solution. The cell is another example of a heterojunction solar cell.

The Clevite cell was never very successful because of difficulties in reproducibility of good cells and long-term instabilities in the finished modules. In the early 1970s when interest in terrestrial uses

of solar energy made a low-cost solar cell attractive, major research on the $\text{CdS}/\text{Cu}_2\text{S}$ cell was again undertaken, mainly at the University of Delaware under Karl Böer. For several years, SES, a subsidiary of Shell Oil, sold a solar module that used vacuum-deposited CdS , but it was taken off the market in 1976 due to instability problems. Because this type of cell can react with the moisture in the air, it was found that traces of moist air entered the modules—even when sealed into glass-fronted enclosures—and destroyed the junctions. SES tried to market the devices several times but found the sealed modules required were too expensive to market competitively.

Ease of manufacture from relatively inexpensive starting materials has kept interest alive in this potentially low-cost solar cell. J. F. Jordan of the Baldwin Piano Company developed an inexpensive way to spray cadmium sulfide coatings onto glass substrates. His process was taken to the pilot-plant stage by Photon Power Corporation of El Paso, Texas, a joint venture between Total, a French oil company, and Libbey-Owens-Ford. Photon Power had expected to sell 4% to 5% efficiency modules at \$2 per watt of capacity when they went into full-scale production, but start-up problems caused them to drop the project.

Although the cadmium sulfide/cuprous sulfide solar cell turned out to be unstable and not commercially usable, cadmium sulfide is still an important photovoltaic material. Its best use at present is as the window material in heterojunction cells that have replaced the thin cuprous sulfide layer (that was the actual photovoltaically active material in the old "cadmium sulfide" solar cell) with other materials. There are a number of materials similar to cuprous sulfide that can be used to produce photovoltaic junctions. These II-VI compounds (named after the second and sixth columns of the periodic table) are being investigated and several promising materials such as cadmium selenide and cadmium telluride have been used in solar cells. These materials can be deposited as thin films by essentially the same processes that are used for cadmium sulfide films and also by electroplating. Ametek, Incorporated of Harleysville, Pennsylvania, and BP Solar in England have both electroplated N-I-P cadmium telluride solar cells, with BP's cells reaching 13% efficiency. Other processes such as silkscreen printing and spray coating have produced thin film CdTe cells of similar efficiencies, but new processes such as atomic layer epitaxy using close-spaced sublimation have successful-

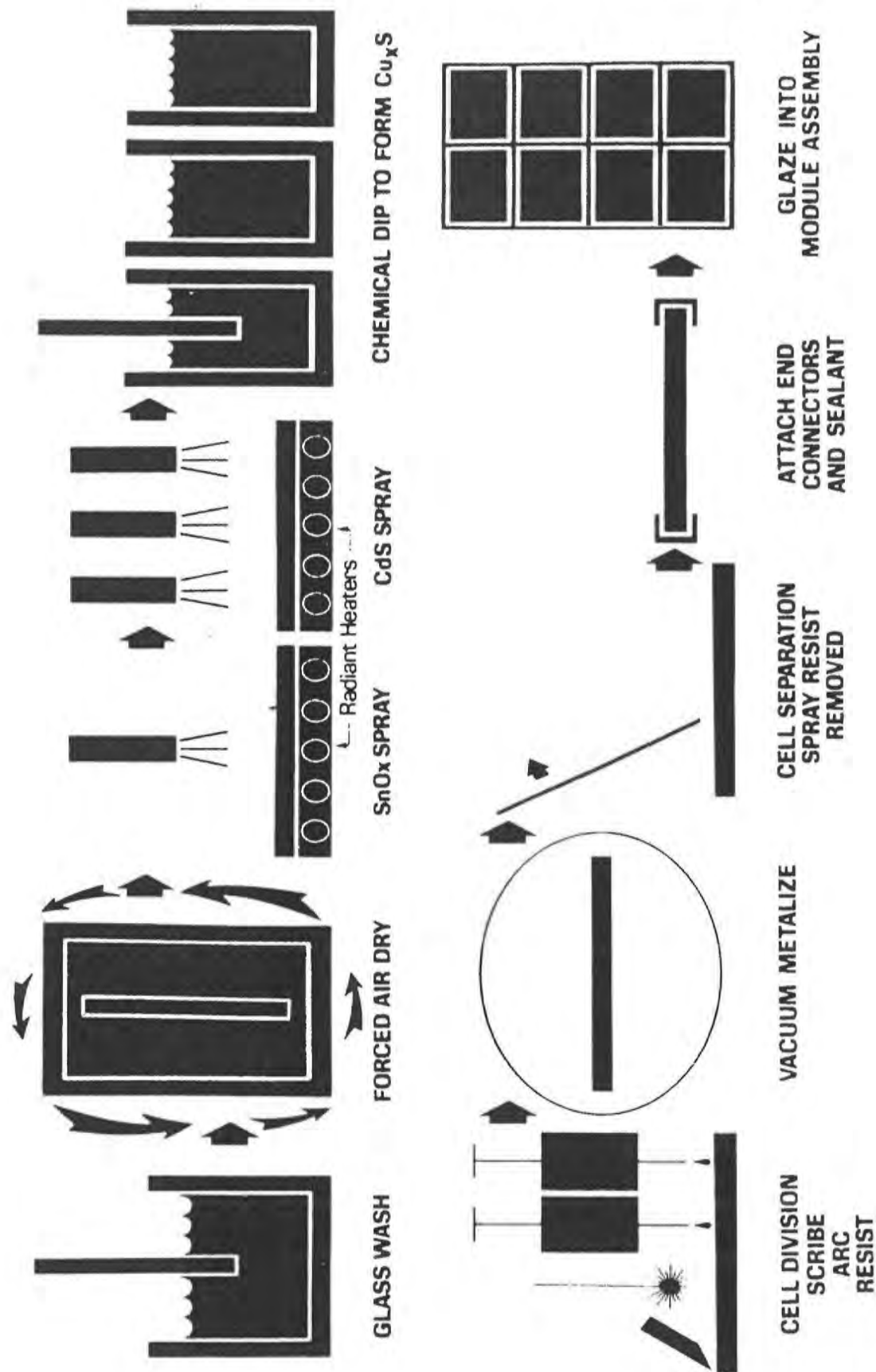


Figure 6.1. Process of producing thin-film photovoltaic cells. (Photon Power, Inc., El Paso, TX)

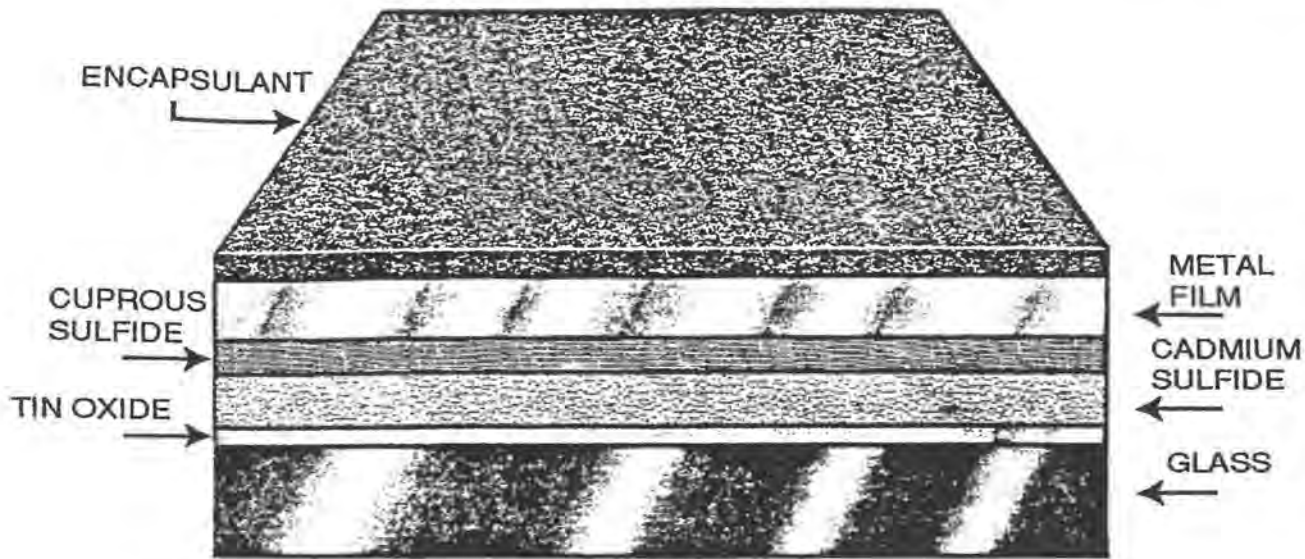


Figure 6.2. Diagram of a cadmium sulfide/cuprous sulfide cell.
(Photon Power, Inc., El Paso, TX)

ly produced CdS/CdTe cells with a verified efficiency of almost 16%, a new record for this material. Boeing Corporation and others have replaced the cuprous sulfide layer with one of copper indium disulfide and have achieved a thin-film cell with over 13% efficiency. A great number of combinations are possible and the development of these semiconductor materials is now the focus of a great deal of research at the National Energy Research Labs (NERL) and a number of semiconductor manufacturers. In fact, Matsushita in Japan is now delivering small silk-screened cadmium telluride modules for use in pocket calculators; manufacturers in Europe will soon follow suit.

Some questions have been raised about the safety of solar cells containing cadmium because it is a poisonous heavy metal. Of course it is extremely important that introduction of a new technology not be a cause of new environmental problems when applied on a large scale. It is ironic, however, to compare the accessibility of cadmium in solar cells to that used to plate refrigerator racks and the bolts on children's toys. Recently, the DOE has begun to research methods of recycling thin-film PV modules containing cadmium to recover the heavy metals, both to protect the environment and to reuse the relatively scarce cadmium, tellurium, and indium.

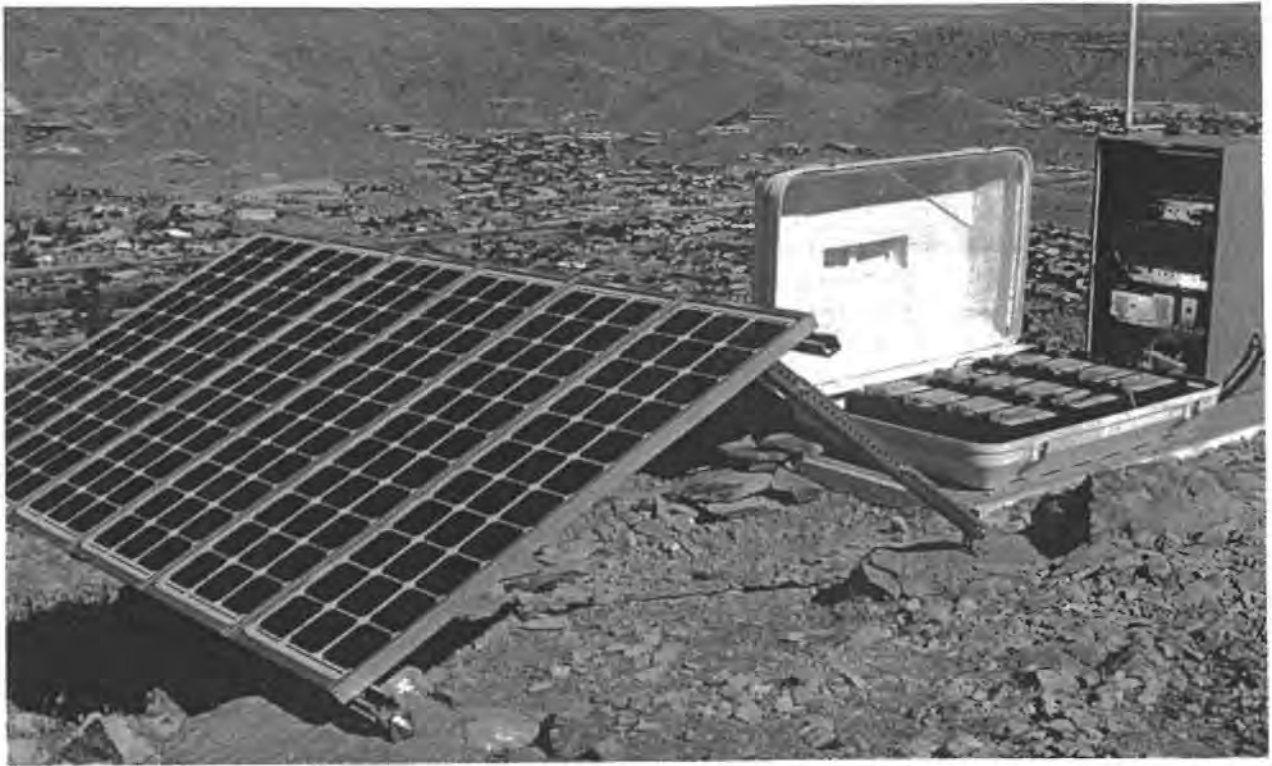


Figure 6.3. Town of Paradise Valley, Arizona, police repeater on Mummy Mountain. (Solavolt International, Phoenix, AZ)

III–V SEMICONDUCTOR COMBINATIONS

The III–V group, a whole class of compound semiconductor materials, derives its name from the third and fifth columns of the periodic table. The compound semiconductors are made by choosing one (or more) element from each column. Gallium arsenide is the best known of these substances, but the list also includes gallium phosphide, indium phosphide, and more complex mixtures such as aluminum gallium arsenide. The III–V compounds are important commercially; for example, they are used in making those light-emitting diodes (LEDs) lighting up all over new appliances.

The III–V semiconductors have been studied extensively; their properties are well understood and they can be tailored to specific applications. The band gap of gallium arsenide is almost ideal for the construction of high-efficiency solar cells; the high-quality crystals made of these materials allow most of the light-generated current to

be collected by the contacts. The material will also withstand surprisingly high temperatures without damage. Consequently, the ~28% efficiency attainable with these solar cells represents the greatest efficiency of any solar-cell single junction produced so far. Several groups are working on extremely high-quality III-V compound solar cells for use at the focus of high-power concentrating systems. Boeing has achieved a record 33% efficiency with a multijunction gallium arsenide/gallium antimonide concentrator cell. The only problems with these cells are cost and availability.

All the III-V compound solar cells developed so far use gallium and/or indium. Both elements are extremely rare, much more so than gold, and the only reason the prices of these metals are not astronomical is that until recently there was essentially no commercial use for them. They are produced as by-products in the smelting of other metals, notably aluminum and zinc. Also, the processes presently used to produce the single-crystal materials, such as epitaxial growth, are expensive and energy-intensive. The only reasonable way to generate large amounts of solar power with such cells is to use very small amounts of these scarce elements per watt of capacity. Two possibilities are thin-film cells and concentrator systems, such as the Boeing development mentioned above. It is impossible to tell if these cells will make a major contribution to the solar cell industry, but they will certainly be used in those situations where considerations of high efficiency or good thermal stability outweigh those of cost.

One use of photovoltaics in which cost is no object is military and space hardware. Gallium arsenide cells are now routinely used in space satellites and the Department of Defense is sponsoring research to investigate promising III-V compound solar cells. These grants, small by military standards, have become an important portion of the support that the U.S. government is giving to solar cell research.

ELECTROPLATED CELLS

Many of the new semiconductor materials are extremely strong absorbers of light. They are called **direct band gap semiconductors** and the light that is absorbed to create the charge carrier is absorbed

in the first micron or so of the material. This means that the entire solar cell can be extremely thin and can be made of polycrystalline material if the average grain size is larger than the micron or less that the charge carriers have to travel. If the grain boundaries can be **passivated** so that they won't act as carrier recombination centers, the crystal grains can be even smaller. (A **recombination center** is a point at which a hole-electron pair created by the absorbed light can recombine before the electron passes through the external circuit. It acts as an internal short circuit.) With thin layers of small grain size, electroplating is an excellent way to build a thin-film solar cell. Electroplated cells have been made with cuprous oxide, zinc phosphide, and cadmium telluride.

Cuprous oxide is called an "emerging material" by the planners in the Department of Energy even though it was the first known photovoltaic cell material and was studied in the early part of this century. It is a p-type semiconductor and simple Schottky barrier solar cells can be made by heating a sheet of copper in air for 15 minutes to 1000°C, followed by annealing at 500°C for another 15 minutes. This solar cell is extremely inefficient because the active junction is between the thin cuprous oxide layer formed and the underlying copper; the light must pass through the entire cuprous oxide layer to get to the junction. Several years ago, Dr. Dan Trivich and I developed a method of making front-wall Schottky barrier solar cells in which the active junction is between cuprous oxide and a thin semitransparent metal layer covering its surface. These cells display an efficiency of only 2%, but our theoretical studies indicate that an efficiency of over 13% may be possible, if the right combinations of materials and processing steps could be found. It is possible to electrodeposit cuprous oxide thin films in a process that would cost pennies per square foot; if cells of only 5% efficiency could be thus manufactured, costs of \$0.25 or less per watt of capacity would be achievable. The supporting substrate would be the most expensive item in the finished product.

Similar costs per watt would be possible for electroplated cadmium telluride and copper indium diselenide solar cells. With electroplating, it is possible to have precise control of the materials used so that alloy depositions are possible. This control also means that electroplated solar cells can use heavy metals efficiently and safely with no toxic waste disposal problems in a well-run plant. Although

several groups are hard at work on electroplated solar cells and laboratory results look very promising, we should not expect commercialization of the process for several years.

Many combinations are possible and a number are already under investigation on a small scale. The main barrier to developing inexpensive, efficient solar cells is a lack of knowledge of the semiconducting properties of these promising materials.

ORGANIC SEMICONDUCTORS

Among the little-explored potential solar cell materials are organic semiconductors. These materials have been used in experimental photovoltaic cells in two ways—as photosensitizers and directly as the semiconductor element in a cell structure. It has been known for a long time that certain classes of dyes can, if deposited in a thin layer onto a base material, make that material photosensitive to the light the dye absorbs. This technique has been used for nearly a century now by the photographic industry to make orthochromatic and, later, panchromatic film. The silver halides used in photographic film (silver chloride, bromide, or iodide) are only sensitive to blue or ultraviolet light, but the dyes used to coat the tiny crystals of silver halides can absorb the rest of the visible spectrum and somehow transfer the energy of the absorbed light to the underlying crystal. It is now generally believed that this transfer involves the actual transfer of a charge carrier (either a hole or an electron) to the substrate material. The same technique has been commercially used in copying machines. Amal Ghosh at Exxon, and others, succeeded in making photoelectrochemical cells that can produce both hydrogen and electricity by dyeing titanium dioxide-coated electrodes with the organic dye phthalocyanine, thus rendering them sensitive to the visible sunlight that titanium dioxide (the main constituent of good quality white paint) normally reflects. The efficiency of such cells is still low, but they appear to be quite stable and would be very inexpensive to produce.

Organic semiconductors have also been used directly in Schottky barrier photovoltaic cells. About twenty years ago, while experimenting at Xerox Corporation with layers of phthalocyanine and other organic dyes in an attempt to determine the mechanism of energy

transfer between the dyes and various substrates, I accidentally discovered that some of the devices exhibited a photovoltaic effect. We studied this effect for a while since it looked promising as a photo-detector for Xerox's high-speed facsimile system then under development, but nothing was done at that time to exploit the system for solar energy conversion. Xerox of Canada has taken up the idea as a potential solar cell, but the efficiency achieved so far is still low because of the poor conductivity of the material. But this class of organic pigments, all similar to chlorophyll in chemical structure, could produce an extremely cheap solar cell that could be literally painted onto the substrate.

A new way to use dye-sensitized inorganic oxides has been discovered by Michael Gratzel of the Swiss Federal Institute of Technology. He produces a photoelectrochemical cell by coating titanium dioxide with special ruthenium containing organic dyes. These dyes bind extremely well to the colloidal titanium oxide, allowing him to prepare very thin, highly absorbing films onto the surface of tin oxide-coated glass. The layers are very stable and allow the conductively coated glass to be used as a window electrode in a liquid cell. A thin opaque platinum counter-electrode forms the back contact. The electrons excited in the dye molecules by the energy of the absorbed photons have only a very short path through the titanium dioxide to the degenerate n-type tin oxide which becomes the negative electrode of the cell in the light. Electrons then flow through the load and are reinjected into the ionic liquid electrolyte from the back contact. The active dye molecules take up the electrons to complete the circuit.

Gratzel and his associates recently devised a totally solid-state version of this photovoltaic process, and a newly formed company, Sustainable Technologies Australia (STA), is manufacturing pilot quantities of thin film cells on a glass substrate. The PV cells now produced are below 6% efficiency, but company scientists hope to achieve above 10% efficiency when in full production. These elegant, transparent, burgundy-red PV modules are well-suited for building-integrated PV walls and skylights.

Recently, Alvin Marks, the inventor of 3-D movies, has been working on a new concept for an organic solar cell. He has been taking the thin polarizing plastic films used in those cheap paper glasses we wore to watch the movies and changing the formulation of the linear polymers to make the films electrically conducting. The idea is that the films absorb virtually all of the light of a particular polarization and produce

free electrons that will be captured at an electrode strip on the film. Two films with crossed polarization will absorb all the incoming light, leading to a high quantum efficiency.

Alvin Marks started Phototherm Inc., a company in western Massachusetts, to work on this idea. His basic idea is feasible from a scientific point of view. With the help of a couple of small grants and some research assistance from Argonne National Laboratories, he has produced the conductive polarizing polymer films and has produced a small voltage under illumination, but the cell resistance is still too high for a commercial device. The tricky steps seem to be those of incorporating the necessary diode junction into the polymer chains using charge transfer dyes and arranging a path for the electrons to get to the collecting electrodes without shorting out the microcells.

Another embodiment of his idea, using microelectronic techniques to fabricate the multitude of submicron-sized dipoles onto an inorganic substrate, is being tried at the nearby University of Lowell (Massachusetts). This system should produce a working device but will probably be too expensive for ordinary use.

Alvin Marks has been claiming very low cost and high efficiency for his Lumiloid polymer solar cell. While the plastic film cells will probably be inexpensive to produce, quantum efficiency (which can be very high for organic dye molecules) differs from device energy efficiency (which will probably remain low). However, an efficiency of only 5% would be commercially useful in a simple device.

There are a number of other dark horse solar cell possibilities that have been given only cursory research efforts. Any one of these, if proven to be commercially usable, could suddenly change photovoltaics from a rarity used only at remote sites and for special situations to the system that replaces all conventional utilities. Chlorophyll membrane systems, photosensitized zinc oxide, and little understood compound semiconductor systems fall in this category.

CLEVER OPTICAL SYSTEMS

In addition to exploring new solar cell materials, researchers are also looking hard at ways to make existing solar cells utilize sunlight more efficiently. Most of these systems employ clever optics to direct or focus the light before it is absorbed by the cell.

The simplest systems are the hybrid optical concentrator systems discussed in Chapter 3. New inexpensive Fresnel lens optical systems, nonfocusing concentrators that allow large tracking errors, and automated assembly systems promise to lower the final installed cost of concentrator systems and make them competitive with the cheapest flat plate photovoltaic collectors. Most of these designs incorporate methods to extract the heat generated in the solar cell and put it to use, making the system even more economically attractive. SunWatt has introduced an inexpensive hybrid concentrator based on an aluminum fin with a copper tube, similar to the design of a solar water heater.

CASCADE CELLS

The cascade cell, first proposed in 1953 by Dan Trivich, is simply a stack of different solar cells. Each one absorbs part of the solar spectrum and passes the rest of the light on through to the other cells in the stack. The cell made with the semiconductor that has the largest band gap has the shortest cutoff wavelength and transmits most of the light redder than this wavelength. This light can be utilized by a semiconductor with a narrower band gap placed behind the first cell. It is possible to stack even a third cell or more and efficiently use the entire spectrum of sunlight including the infrared. A single, narrow band gap cell would also absorb the entire solar spectrum, but would have a low output voltage, essentially wasting a good deal of the energy of the short-wavelength light. The cascade cell will have an output voltage that is the sum of the voltage of the individual cells. The output current of the device is less than that of the simple, narrow band gap cell, but the overall efficiency ends up much higher. Experimental two-cell devices have been constructed using gallium arsenide and aluminum gallium arsenide and various combinations with silicon, gallium arsenide, and germanium. In some of these systems all the various cell layers are constructed directly on top of each other; they utilize a **tunnel junction** or some other sort of shorting junction to make an electrical connection between the cells in the device. Actual efficiencies of over 33% have been measured and theoretical efficiencies of 60% or more have been predicted for these multijunction devices.

The Department of Defense is interested in these **tandem cells** because of the great amount of power delivered by a small package. A photovoltaics-powered unmanned airplane with two-layer tandem cells covering the wings is now a possibility. The cells would produce enough extra power, stored in the batteries, to keep the plane flying all night. The drone could circle for months at high altitude, taking surveillance pictures.

Most experimenters envision using the cascade cell at the focus of an optical concentrator system since the cost of the complex cell is expected to be high and the efficiency of the system actually increases with greater light intensity.

Another version of this is shown in Figure 6.4. Here the incoming light is split into various colors with selective filters and directed to several different cells, each is designed to use a particular band of wavelengths more efficiently. Varian Associates has also been working on a version that uses high concentration ratios and very efficient dielectric-coated filters as the beam splitter. A potentially cheaper

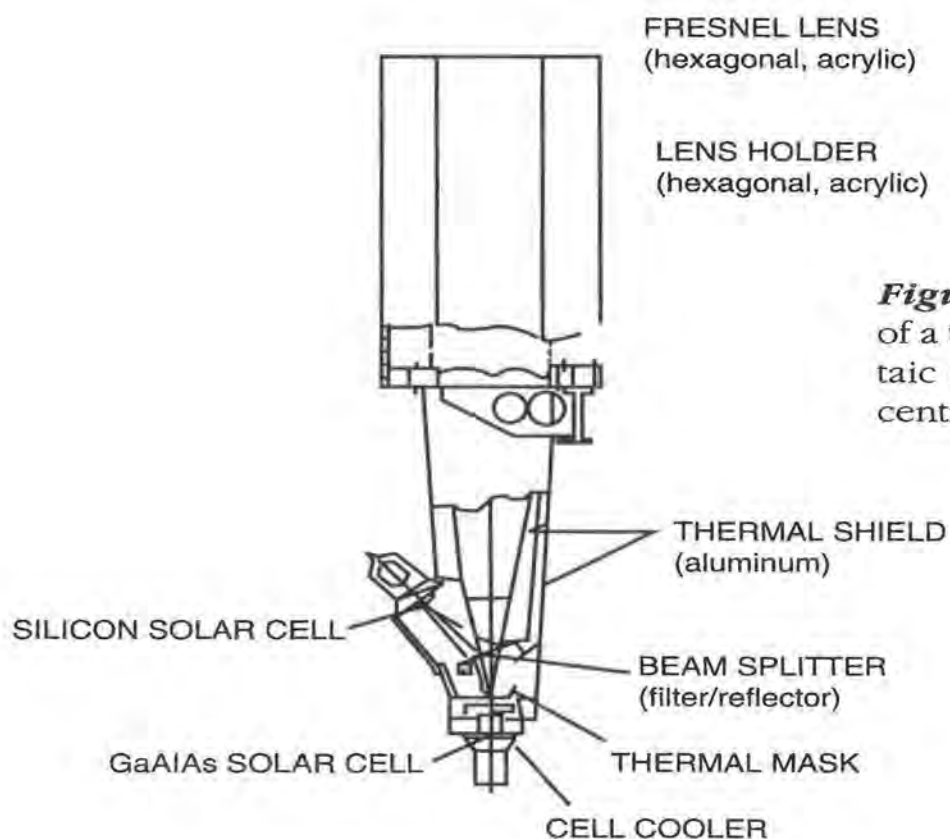


Figure 6.4. Diagram of a two-cell photovoltaic device using concentrated sunlight.

version is being developed by W. H. Bloss at the University of Stuttgart; it uses holograms developed in gelatin as the dispersive concentrating (DISCO) system. The DISCO system focuses the light and splits it into several bands of different wavelengths directed at the two or three different solar cells used.

LUMINESCENT CONCENTRATORS

One of the most exciting new concentrator systems is the luminescent solar concentrator which absorbs solar radiation in a flat plate by means of colored dyes. These dyes fluoresce in all directions at a longer wavelength than the incoming radiation. Most of this reradiated light is confined to the collector by total internal reflectance and transmitted to the edge of the sheet where small photovoltaic cells convert it into electricity. The basic concept has been known for years and, in fact, has been used in drafting triangles for illumination. The application to solar energy collection was first proposed in 1976 by Lambe and Weber of Ford Motor Co. Research Labs. Since then a number of groups have worked on the idea, using organic dyes in plastics or inorganic fluorescent compounds in glass. A rather complete theoretical treatment of the efficiencies and concentration ratios to be expected is given by Goetzberger and Greubel (see Recommended Readings).

Wood and Long experimented with liquid-filled flat plastic cases as luminescent concentrators in which a mixture of dissolved dyes absorbs most of the visible solar spectrum. A cascading of energy, which they envision as a series of fluorescences and reabsorption by the different species of dye molecules, produces a final fluorescent light which is transmitted at a long wavelength to the photocells at the edges of the case. In their experiments they found a rapid heat build-up in the liquid because all the incoming light energy that is not finally converted to electricity or that escapes from the case is trapped as heat. They also found that the dyes bleached rather quickly under their experimental conditions.

At Skyheat Associates, I have been working on a version of a luminescent concentrator that utilizes both the heat and the electricity developed from the sunlight. Dyes dissolved in a liquid absorb the solar radiation and transfer the light to solar cells fastened to the



Figure 6.5. A luminescent concentrator. This flat plastic tank contains a colored fluorescent liquid. The liquid concentrates light onto small solar cells glued to the edges of the tank. (Skyheat Workshop photo)

end of the flat tank. The liquid is heated and can be pumped through a heat exchanger to extract the heat generated. Cooler operating temperatures and a careful choice of dyes seem to greatly reduce the dye stability problem, but the system is still in early development and working models are too inefficient to be of practical interest.

THE SOLAR THERMOPHOTOVOLTAIC SYSTEM

This complicated-sounding name describes a system that combines some aspects of solar thermal concentrator devices with a method of converting the heat generated by focused sunlight directly into electricity. If a large parabolic mirror focuses sunlight through a small opening into a well-insulated black cavity, the interior of the cavity can become extremely hot (1500°C or more). This temperature causes the inside walls to radiate in the infrared, with the radiation bouncing back and forth in the cavity. If a germanium photovoltaic cell is placed in one wall of the cavity, the infrared absorbed can be converted into electricity because of germanium's narrow band gap.

Loferski and others at Brown University developed a special, high-efficiency germanium solar cell especially for this application and calculate that overall conversion efficiencies as high as 20% are possible with such a system. The germanium cell would actually stay cool, even in such a hot environment, since the incoming infrared energy is converted into electricity. However, if the cell were disconnected from the electric load, it would quickly heat up and destroy itself. The solar thermophotovoltaic system has the disadvantage (or advantage, depending on your viewpoint) of only being practical in a large centralized system like a **power tower** where economy-of-scale justifies the expense of the complex tracking system for a whole field of steerable mirrors. Recently, Applied Solar Energy started work under government contract to develop these high-efficiency thermophotovoltaic cells.

RECOMMENDED READINGS

- Bloss W., J. Loferski, et al., eds. *Progress in Photovoltaics*. 1:1 (January 1993) (Sussex, England: Wiley & Sons).
- Goetzberger, A., and W. Greubel. "Solar Energy Conversion with Fluorescent Collectors." *Applied Physics* 14:123-39 (1977).
- Hovel, Harold. "Photovoltaic Materials and Devices for Terrestrial Solar Energy Applications." *Solar Energy Materials* 2:277-312 (1980).
- Proceedings of the IEEE Photovoltaic Specialists Conferences* (New York: IEEE, January 1980 through May 1993).
- Zweibel, Kenneth. *Harnessing Solar Power: The Photovoltaic Challenge* (New York: Plenum Press, 1990).

Appendix A

Assembling Your Own Solar Modules

It is possible for you to assemble your own photovoltaic modules, starting with individual cells. Although it is difficult to match the reliability and durability of the standard laminated commercial PV module, there are a number of reasons why this might be worthwhile. You might need a custom module for a special purpose that requires an unusual voltage or even multiple voltage outputs. Or you may need a module with a special shape to fit a particular location. Perhaps you have acquired a very inexpensive set of solar cells, maybe surplus or from an electronic “flea market,” and you want to put them to work. Or you may simply want to learn more about solar cells and prefer the “hands-on” approach.

Over the years I have taught numerous workshops both in the U.S. and abroad where participants have assembled their own solar modules. Actually handling the solar cells helps to “demystify” the photovoltaic cell and to make it seem a more real, practical device. This provides a great learning experience for children also, and lately I have been working with the Maine Solar Energy Association (MSEA) and other groups to bring hands-on workshops into the class-

room. MSEA also offers summer weekend workshops where participants assemble large hybrid modules which some participants purchase and take home. It is an enjoyable and inexpensive way to enjoy a weekend in Maine.

TESTING SOLAR CELLS

There are a number of sources from which the average person may obtain individual solar cells. (Appendix B lists names and addresses of manufacturers; some, such as SunWatt and AstroPower, will sell to individuals.) These cells range from well-tested and calibrated devices guaranteed to perform to their given specifications through standard production-quality cells to untested or reject cells that can be purchased at a substantial discount. Even if you purchase a standard guaranteed cell, it is important to test each one thoroughly before using it. The amount of work entailed in removing one cell from a finished module and the danger of ruining the neighboring, good cells make testing individual cells a must.

Fortunately, testing solar cells is neither difficult nor complicated. The apparatus needed can be as simple as an inexpensive multimeter or voltmeter and ammeter of the proper range. Electronic supply houses sell these meters for \$10 and up. A fancy digital meter is not needed, but it is good to have one that has among its selection of ranges a voltage range as low as 1 volt or less and a current range above 10 amps. To test completed modules, we will be measuring voltages of 16 to 18 volts or more and short-circuit currents possibly as high as 2.5 amps, depending on the size of the module and the light conditions.

The simplest test which gives meaningful information measures a cell's short-circuit current and open-circuit voltage under bright sunlight conditions. If bright sunlight is not available, it is possible to perform the tests outside or with the light through a window on a cloudy day or even under artificial illumination. To get meaningful results under these conditions, it is necessary to have a standard cell of known output available to measure the actual light intensity. Even then, if the light used in testing the cells is very different in color from that of real sunlight, any difference between the spectral response of the cells to be tested and that of the standard cell will

produce an error. For example, on a cloudy day when the illumination is much bluer and “colder,” a blue-sensitive cell will respond more efficiently than it would to “warm” incandescent illumination of the same intensity. However, if the standard cell is made of the same material as the cells to be tested, these differences will be negligible. What we aim for is not a set of 32 perfect cells, but rather a matched set of cells of roughly equivalent quality—even if that quality is relatively poor compared to the best cells available.

A Simple Solar Simulator

To test solar cells indoors, you need a solar simulator. Usually, solar simulators are expensive devices with xenon lights and filters, but a very simple way to produce a reasonable simulation of AM1 and AM2 sunlight is to use a standard EHL projector lamp. These lamps, which are used in slide projectors, have special reflectors that are designed to let the infrared light escape from the bulb and that reflect only the visible light onto the slide to keep the slide cool. By coincidence, the spectral output of this lamp is very close to that of sunlight AM1 conditions if the lamp is operated at 117 AC. If the lamp voltage is reduced to 100 volts, the output becomes redder and nearly matches AM2 sunlight. The exact distance between the bulb and the solar cell will vary with each bulb, but it is about 35 cm. You can determine the exact distance with a solar cell that has been previously calibrated, but even without this the simulator will give a constant light output so that the cells can be checked relative to each other.

A Simple Sample Holder

To measure the electrical properties of solar cells, it is necessary to make good electrical contacts to both the back contact and the top fingers in such a way that the cell is not shadowed. Figure A.1 shows a simple sample holder that can be built to do this. The base is a 6- x 8-inch piece of plywood onto which a piece of thin copper or galvanized steel is glued with contact cement. The five-way binding posts, available at most electronic supply stores, serve to connect the wires from the multimeter or voltmeter and ammeter to the holder. After drilling a pair of small holes $\frac{3}{4}$ inch apart for the shafts of the binding posts, drill a larger hole from the back for each part so that

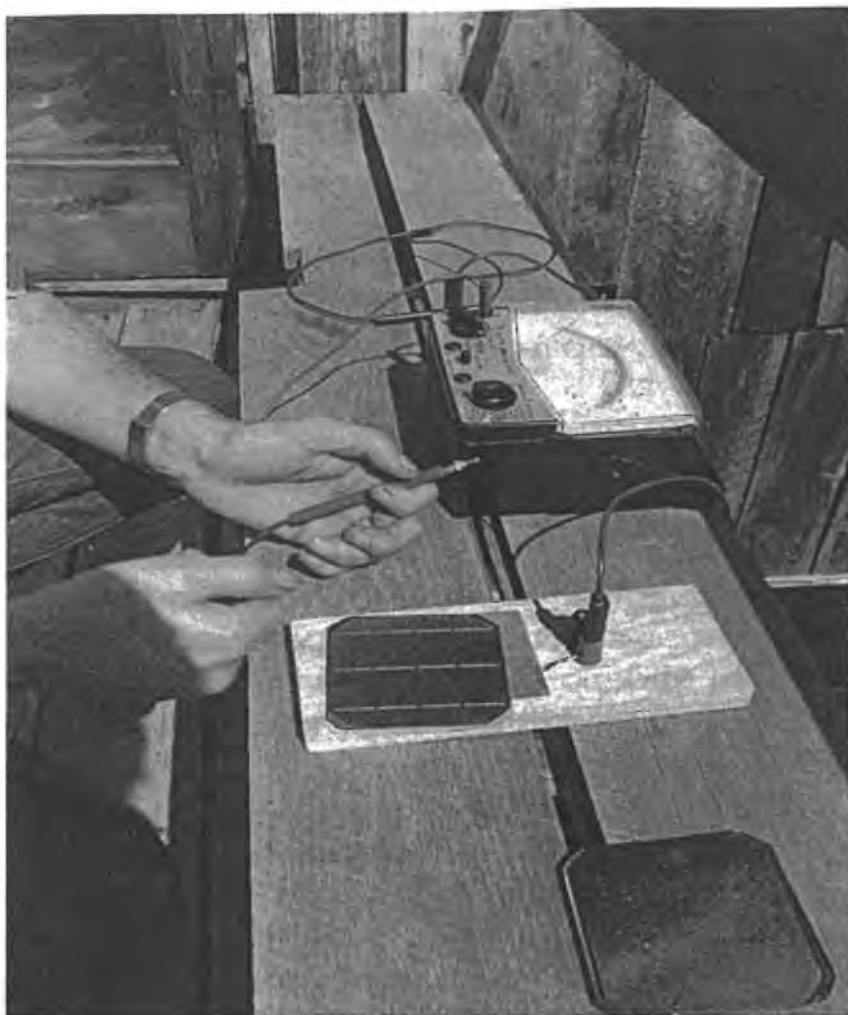


Figure A.1. A simple sample holder. (David Ross Stevens photo)

the nuts holding the posts in place can be recessed, allowing the plywood base to sit flat. When a cell is to be tested, the back contact is established by resting the cell on the metal plate. (It is important that the plate be kept clean and free of insulating oxides.) The slight pressure of the front contact against the fingers should be enough to make a good back contact.

Two types of front contacts are possible for this holder. The simplest is just one of the probes that comes with a multimeter. It is the easiest to use if the holder is kept flat and there are a lot of cells to test: a cell can simply be laid on the holder plate and touched with

the probe. A spring-style holder is easier to use for intensive testings of a single cell: it frees the hands and holds the cell securely in place so that the holder can be tipped to face the sun directly. Also, since the pressure is constant, variations in the measured short-circuit current caused by poor contact are minimized.

More elaborate sample holders with temperature-controlled bases and adjustable top contacts can be constructed for more advanced research into the properties of semiconductor solar cells. But for our testing purposes, the holder shown should be adequate.

CURRENT-VOLTAGE MEASUREMENTS

All commercially available silicon solar cells produce nearly the same voltage. Even for relatively inefficient cells, the open-circuit voltage should be over 0.5 volt and not exceed 0.6 volt under direct sunlight illumination. This voltage will change only slightly with changes in the brightness of the sunlight. Under reduced illumination, the open-circuit voltage will drop to 0.3 volt or so.

The occasional defective cell with little or no voltage output probably is shorted. If you examine the cell and find no obvious defect, like a spot where the front contact finger has accidentally been extended to the edge so it can touch the back contact, the short is internal and cannot be fixed. If you are positive that the measurements have been made correctly and the short persists, it is possible to rescue part of the cell by deliberately breaking the cell in half, retesting, and using the good half. If the short is a point defect, the rest of the cell area will be perfectly good. Of course, the bad half can also be broken further, since each part of a solar cell—no matter how small—is a complete solar cell. With some clever jumper wires between the fingers, broken pieces of cells can be assembled into usable modules.

The current output of a solar cell is directly related to the area of the cell and the intensity of the light falling onto it. It is also dependent on the quality of the cell and should be the main determinant of whether or not to use a particular cell in a module, since the maximum current output of a series string of cells will be essentially the output of the worst cell in the string. The rated or AM1 output of a cell is the current expected from sunlight coming from directly over-

head through a dry atmosphere (the Sahara Desert at high noon) and is the one most often used in literature and specifications. The AM2 output is closer to what would normally be expected from measurements made outdoors under normal weather conditions. For silicon cells not listed in the table, a figure of 27 mA/cm² for AM1 or 21 mA/cm² for AM2 conditions could be used. Simply calculate the surface area of the cells (including the fingers) in square centimeters and multiply by those figures to calculate the expected current output. If a standardized cell is available, it can be used to measure the exact light intensity at any given moment and will greatly simplify the checking process. You must be sure, though, that the standard cell and the cell to be tested are exposed to exactly the same light and are oriented at the same angle.

HOW CELLS ARE CONNECTED

Solar cells can be connected to an external circuit in a number of ways. They can be fitted into a holder with spring contacts that press onto the front and back; the connections can be spot-welded; or the circuit they power can even be built onto the same chip of silicon as the cell area. But the most common way to connect solar cells is by soldering jumpers onto them.

Solar cells can be purchased with a current rating of 2.5 amps, but the half-volt output of a cell is usually too little for practical systems. The whole purpose of assembling cells into modules is to increase the voltage or current available compared to the individual cell output. Usually, the cell is sized to deliver the required current, and these cells are connected in series to produce the required voltage. Even if the current output desired is that of two or more individual cells, it is probably better to make these up as a set of two or more separate modules and then connect the modules to the external circuit. A blocking diode should always be used in connecting an array to the battery to keep current from flowing backward through the array at night or any other time when the array is putting out less than the battery voltage. If a separate blocking diode is put in series with each module in an array, the failure of one module will not affect the other. Figure A.2 shows several methods that have been used to build a series string of solar cells.

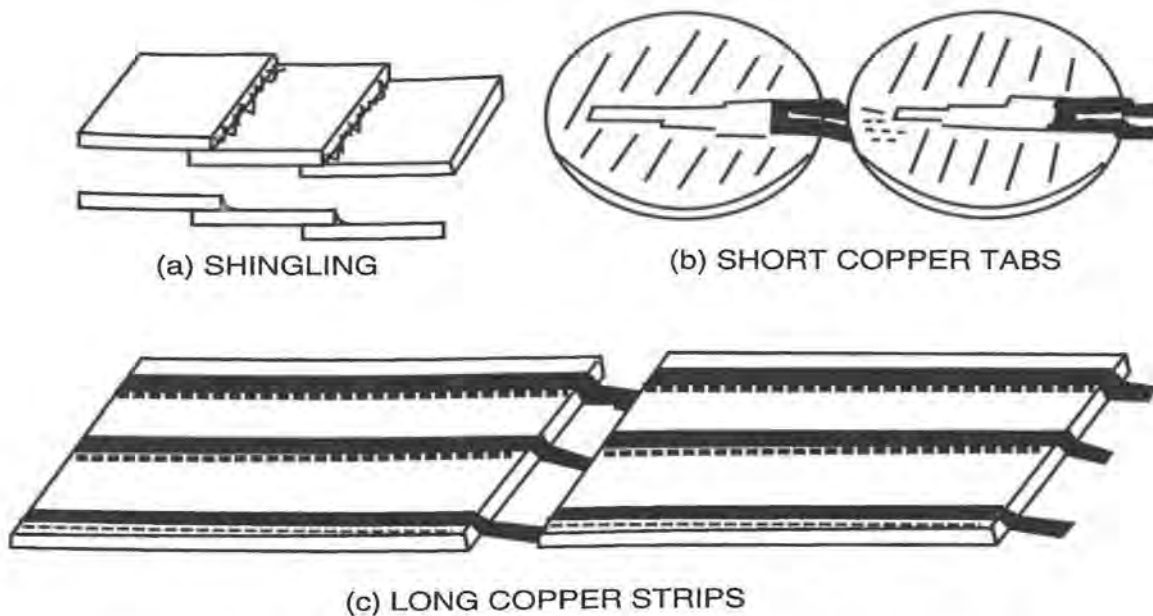


Figure A.2. Several ways of connecting solar cells in series.

Early in the space program, when solar cells were used to power the first satellites, the usual practice for assembling a series string of cells was called **shingling** (shown in Figure A.2a). The bottom edge of one cell overlapped the top edge of the next cell by about 1 mm and was soldered. The finger pattern was designed with a soldering strip on one edge. However, expansion and contraction with temperature, along with any flexing, places an enormous stress on the solder junction and premature failure was one result.

At the present time, the most common way to interconnect solar cells is to use jumpers made of copper foil. Commercial solar modules have specially shaped foil pieces preplated with tin or solder, but straight strips can be used with most finger patterns.

It is quite easy to prepare jumper strips out of copper foil; the series connection methods are illustrated in Figure A.2 b & c. The copper foil should be quite thin (0.002 inch or 50 microns) in order to allow flexible connections that will put little stress on the cells themselves. These strips are very easy to cut from a wide piece of copper foil (see Figure A.3) or the foil used to assemble stained glass pieces can also be used. (This foil is available at many hobby shops or stained-glass supply dealers.) The exact size and shape of the strips will depend on the finger pattern of the cells, but it is best to



Figure A.3. Preparing strips of foil. (David Ross Stevens photo)

allow about 1- to 2-mm space between cells. It is also advisable to arrange for two or three parallel strips between each cell to make redundant contacts. This way, the module will not stop working if one solder joint fails, as could happen with single jumper strips. An example of a cell where three jumper strips are possible is shown in Figure A.4. In this design, three wide bars connect all the fine fingers allowing multiple paths for current to flow around a gap or defective finger. It is recommended that thin, preferably crinkled, strips of copper be sweat-soldered the entire length of the wide bands. These strips should also run at least halfway across the back of the next cell. This will allow a cell that accidentally gets cracked to continue producing power at nearly full output.

Instead of copper foil, it is possible to use small-diameter copper wire as the interconnections. B&G No. 24 to No. 26 wire is the most useful size. At least two pieces of wire and preferably three or more should be used. One source for this thin-diameter wire is multistranded No. 16 or No. 18 wire. Once the insulation is stripped, you have 20 or more strands of wire prepared to the same length in one operation. The wire interconnections should be arranged so that they have a slight bend when the cells are positioned properly to allow for thermal expansion and contraction.

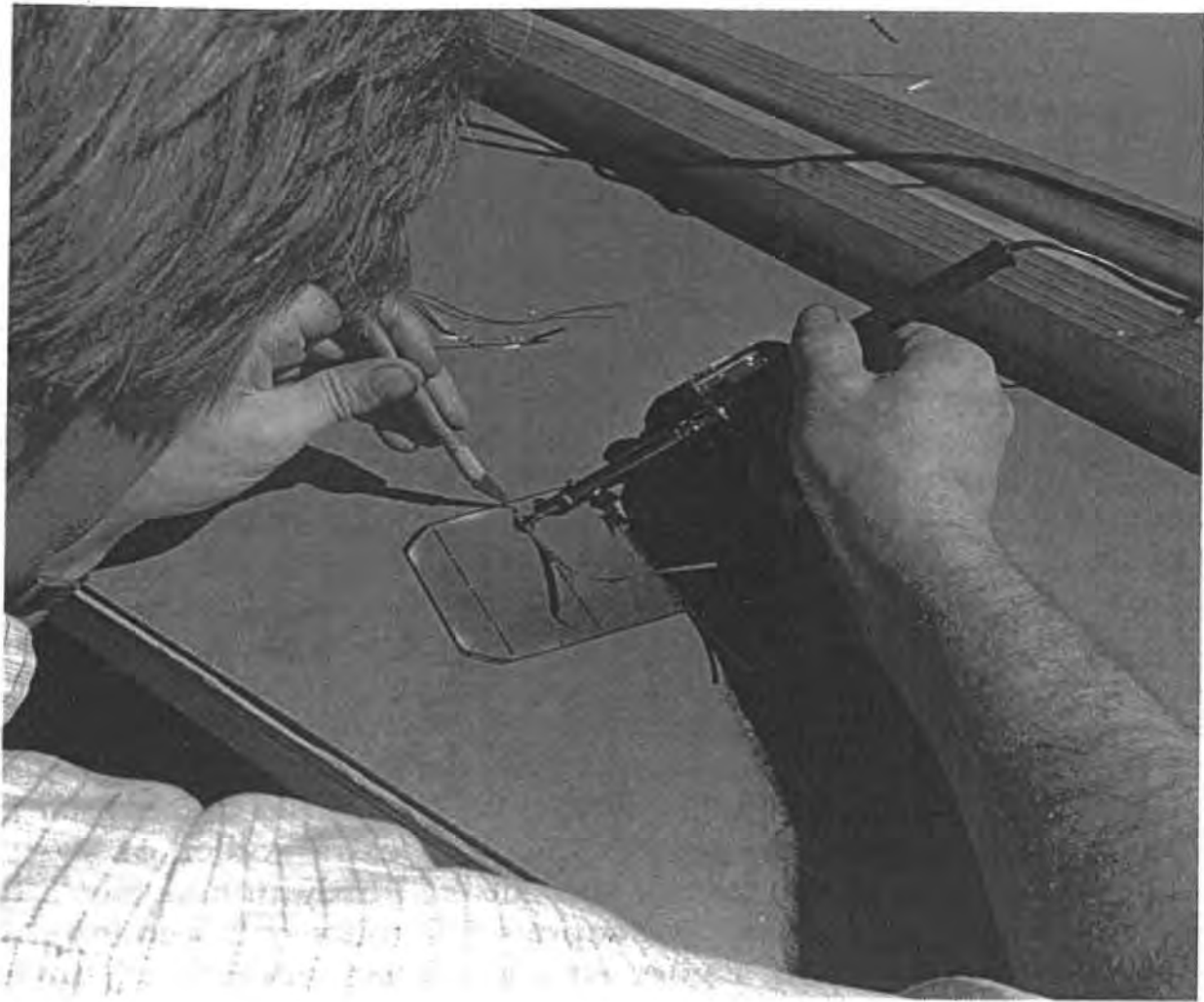


Figure A.4. Soldering copper strips to a solar cell.
(David Ross Stevens photo)

SOLDERING SOLAR CELLS

Most commercially available solar cells are designed to have contacts and wires soldered to them. The back contacts and front fingers are applied to the cells in a number of ways, including electrodeless nickel plating, vacuum metallizing and silk-screening. In addition, many manufacturers tin, or coat with solder, the contact points where jumpers are expected to be fastened. Ordinary electronic-grade (60% tin/40% lead) solder can be used in most cases, but a special solder which contains 2% silver in addition to 60% tin and 38% lead is the best choice if the cell contacts are silver. This will keep the hot solder from dissolving and possibly weakening the bond of the very thin silver fingers. Rosin core solder and rosin-based soldering flux can be used but can be difficult to clean off the cell faces once the module is soldered together. A water-soluble flux is available (Kester Solder Co., Chicago, Illinois) that is normally used by solar cell manufacturers. This flux simplifies cell cleaning after the interconnections have been soldered.

A small pencil-type soldering iron of about 35 to 40 watts capacity is the most useful for this kind of soldering. The cone shaped (pencil) tip or the small screwdriver-shaped tips seem best able to deliver a precise amount of heat to a small area.

The actual soldering of the copper foil pieces to the cells is not too difficult but it does require fast work with a hot iron. As with any soldering job, it is most important that the surfaces are clean. It is best to clean solar cell surfaces with a cotton swab and isopropanol (rubbing alcohol) and let the surface dry before soldering. Some solar cells, like those from Solarex, have an antireflection coating covering the entire top surface, including the fingers. To be able to solder to these cells, first clean the spot on the finger by "erasing" (rubbing lightly with a pencil eraser) until the spot looks shiny and metallic. Then tin the area with ordinary 60/40 rosin-core solder and solder the ribbon to the tinned spot. No extra solder or paste is required for this step. If the cell contact is already tinned, put a thin layer of soldering paste on the copper foil and sweat-solder the foil with the soldering iron. Figure A.4 shows this operation. Use firm pressure, but not enough to crack the cell. No solder is necessary. If the cell contact is not tinned, tin the foil strip first. The strip must be

tinned on every surface that will be soldered, but try to leave an untinned place where the foil jumps from one cell to the next, in order to increase the flexibility. It is best to solder all the foil tabs to the finger side of each cell first, then arrange the cells face down in the position desired for the module. Taping the cells face down to a piece of hardboard in the desired pattern will make it easy to align the cells properly. Then solder down the tab to the back of each cell. If small pieces of masking tape are used, they can be removed easily without breaking the cells. It is best to make the contacts to the final cells in the module with the same kind of foil and then solder wires to the foil a centimeter or so away from the cell to reduce the strain.

If wires are used as the jumpers, they are soldered in a manner similar to that used for the foil strips. The only difference is that it is generally not necessary to pre-tin the wires before fastening them to the cells.

BUILDING A FLAT PLATE MODULE

One simple way to offer protection for the cells is to place them in a flat acrylic box. The collector box has a removable lid that is fastened down with screws and sealed with silicone grease. Though it was not sealed tightly enough to withstand constant exposure to the salt spray on the deck of an ocean-going yacht, a module installed in such a box has been operating outdoors for fourteen years without any decrease in electrical output.

Laying Out the Case

To construct the flat plastic module, the first step is to lay out the arrangement desired for the solar cells. For a 32-cell module, I usually use 4 rows of 8 cells each, but other arrangements are possible: 3 rows of 11 cells for 33 cells, 6 rows of 6 cells for a square 36-cell module, or 4 rows of 9 cells if a rectangular 36-cell module is desired. Other combinations are possible with unequal row lengths—for example, 3 rows of 6 plus 2 rows of 7 for an almost square 32-cell module. I prefer to put the cells in straight rows separated by thin acrylic strips. The strips keep the rows of cells separated without

fastening the cells to the case, and they also help support the lid of the case so that it cannot be pushed inward enough to press onto and possibly crack the cells.

Once an arrangement has been devised, you can calculate how big the case should be. The easiest way to do this is to actually fasten the cells into their final arrangement, lay them onto a flat surface, and measure the set, allowing about 1/2 inch between each row and another 1/2 inch at each edge. Figure A.5 shows a case built for 3-inch circular cells. The dimensions given in the drawing will allow plenty of room for expansion and contraction. They also allow for some error in soldering the cells into absolutely straight rows, but at the same time prevent the sets of cells from moving too far in relation to each other and the case.

Cutting the Plastic

Acrylic sheets (also called Plexiglas™, the tradename for Rohm and Haas plastic) come in a variety of thicknesses and qualities. Cast acrylic sheets are a little easier to use and glue, but they are more expensive; the extruded sheets are cheaper and seem to be a bit stronger. The extruded sheets are 1/10-inch thick (called 100 mil by

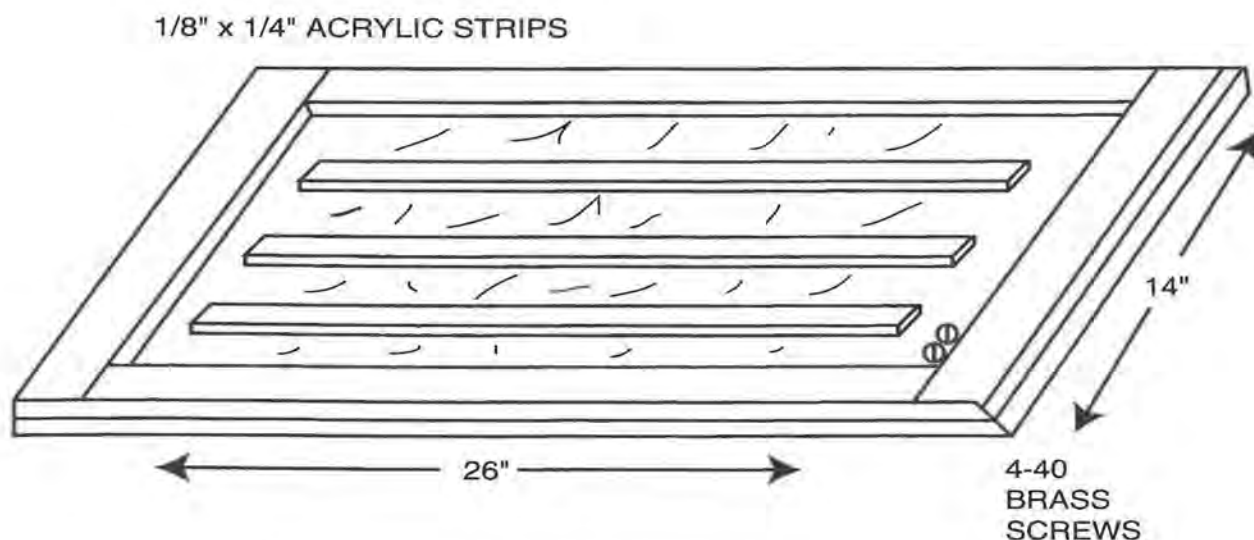


Figure A.5. Drawing of a plastic case for a flat plate module. The dimensions shown are for 75-mm (3-inch) circular cells.

glaziers) and are commonly used to glaze storm doors when using glass would be too dangerous. This thickness is fine for solar cell modules of the size discussed here. With cast acrylic, I generally use the 1/8-inch thickness, which is more than adequate for most purposes. If the module case will be subjected to a great deal of abuse, 3/16- or even 1/4-inch could be used for the front and back covers, but you should use 1/8 inch for the spacer strips unless you plan to put some sort of backing material behind the cells to cushion them. For even more strength, polycarbonate sheets can be used instead of acrylic.

Cutting acrylic is quite simple. The easiest way to cut the 100 mil sheet is to score it with a utility knife and then break it along the score by bending it away from the scored side. Use a metal straight edge to get a straight scratch and score the sheet as deeply as possible. Unlike glass, acrylic can be scored by several passes over the same line, and if the knife cuts almost all the way through in spots, so much the better. Cutting 1/4-inch-wide spacer strips by this method may be difficult unless you are proficient at working with the material.

Acrylic can also be cut with a hand saw or a saber saw or even a table saw or portable circular saw. The problems here are chipping or cracking the plastic if too coarse a blade is used, or melting the plastic if too fine a blade is used. I have cut acrylic only to find the molten plastic and sawdust welded back together behind the saw blade. When using a circular saw, a veneer cutting blade seems to be the best compromise between melting and chipping.

Polycarbonate is very similar to acrylic when cut with a saw, but it cannot be scored and broken as easily.

Gluing the Plastic Case

There are a number of commercially available glues for acrylics. Most of these work on a solvent principle: they dissolve the acrylic slightly to make a sticky surface. I usually use a chlorinated hydrocarbon such as trichloroethylene or chloroform. Chloroform is probably the best solvent glue for acrylic, but it is extremely dangerous and is suspected of causing cancer. Avoid breathing the fumes or getting it on your skin. The commercial glues, while still very dangerous, do not require the extreme caution necessary in handling chloroform.

The best solvent glue for polycarbonate is acetone, but methyl ethyl ketone will also work.

To use solvent glue, place the pieces to be joined in the desired position and, using an eyedropper, let a few drops of the solvent run into the crack between the pieces. Capillary action will pull the solvent into place. Light but steady pressure on the joint will produce a complete bond. Do not move the pieces for five minutes, then examine the joint to see if it has been glued evenly. The glued parts will look wet and transparent when viewed through one of the shiny faces of the pieces, while the spots that are not actually in contact will reflect more light. You can apply a few more drops of solvent to these spots to glue them. It is possible, using this technique, to make a completely sealed, waterproof joint as strong as the plastic.

Fastening the Cover

When you have all the edge and divider strips glued onto the backing sheet, you are ready to install the solar cells and fasten down the cover. If you are sure that the module is soldered correctly and working properly, thus needing no maintenance for quite some time, you can attach the cover using the procedure just described. But a better idea is to fasten the top cover with screws.

After the plastic case is glued together, but before you install the cells, lay the top cover temporarily in place and drill and tap a set of holes around the entire outer edge of the case. I usually fasten the cover with 440 brass-headed screws. To ensure that all the holes will align, install two at opposite ends before drilling the rest of the holes. Drill and tap a couple of holes into the center divider strip to help hold the case together.

Installing the Solar Cells

Now that the cover is ready, remove it and lay the strips of cells into the case. Sheets of polyethylene-foam packing material (1/16-inch thick) can be fitted into the bottom of the plastic case as a cushion behind the solar cells. (Do not use foam rubber for this purpose because it deteriorates in sunlight.) You can also fasten the cells to the case back with a dab or two of silicone RTV behind each cell. This produces a cushioned, permanent mounting; in addition, the

soft RTV will absorb any thermal expansion movement. However, once the silicone has cured, the cells are impossible to remove without breaking; make sure that all the connections are good before taking this irreversible step. If you turn every other string end for end, the jumper wire from the back of the last cell in one string will be at the same end as the jumper wire from the front of the first cell in the next string, making the connections between strings short and easy to make. It is best to slip a piece of cardboard under the jumpers when soldering them in the case because acrylic cannot withstand much heat.

There are several methods for bringing the final wires out of the case. The easiest is to simply file a couple of notches into the top of one edge strip, one on each side of a cover screw, and lay the wires in these notches so that the cover clamps them in place. However, the danger of this arrangement is that someone might yank on the wires and break a cell where it is fastened to the wires. A neater solution is to attach a pair of binding posts to the back, for example, a pair of 6-32 screws that are screwed from the inside through holes tapped through the rear cover. Use a little silicone caulk under each screw to seal the joint. I make the holes exactly $\frac{3}{4}$ inch apart so a dual banana jack can be plugged onto the connection if desired. If it is small enough, you can attach a blocking diode inside the case to one of the binding posts. The cathode end of the diode (the end with the white band) goes to the positive (+) binding post while the anode end is fastened to the rear of the last cell in the string. Of course, the front of the first cell is connected to the negative (-) binding post.

After you have assembled and wired the module, try it out in the direct sunlight or in as bright a light as possible. Then clean the inside of the front cover and install it, using some silicone grease all around the edge as a sealant. Clear silicone caulk can also be used, as it does not adhere very well to the plastic and it will be possible to pry up the cover if you have to get inside to repair the module.

BUILDING A HYBRID CONCENTRATOR MODULE

Figure A.6 shows a second type of module made at a Skyheat workshop. This hybrid module has two advantages over the flat module described above: (1) it can use a Winston concentrator to increase



Figure A.6. Skyheat workshop-fabricated hybrid solar cell array installed on a greenhouse. (David Ross Stevens photo)

the amount of sunlight striking each cell, and (2) it has provisions for heating either water or air with the waste heat produced in the solar cells. We have made two slightly different versions of this collector: one with a sheet metal backing support and water tubes; one with the cells mounted on a strip of wood. The second version can be used only for heating air, but it is simpler and cheaper to make. Both versions will be described here.

The Backing Support

The wooden backing support is simply a piece of wood about 1/2 inch wider than the cells and long enough to carry the desired string of cells. It is probably a good idea to limit the length of a single board to 4 or 5 feet, making the string of cells 16 cells long. Two of these modules then make up one module. If the backing support is made exactly 4 feet long, it is possible to fix 16 three-inch cells onto it. Since each cell has a small flat on one end, the cells can be mount-

ed slightly less than 3 inches apart, leaving a millimeter or so between cells.

A backing support bent from sheet metal will conduct heat much better than wood. A couple of small tubes soldered to it serve to carry water to cool the cells and deliver the heat to a hot water heater. Figure A.7 is a drawing of one possible arrangement.

It is best to make the sheet metal support and the cooling tubes out of the same material to keep differential thermal expansion from warping the system, but small (1/4-inch-o.d.) copper tubing can be soldered into the corners of the backing plate and the combination does not warp. The dimensions shown in Figure A.7 are for a concentrator system using 3-inch-diameter cells. Larger or smaller cells can be accommodated by changing the width, but the 1-inch depth of the legs is good for stiffness. 18-gauge galvanized sheet metal is thick enough for this use.

Another possible backing support for this kind of concentrator module is an aluminum extension. Manufacturers of solar hot water collectors make an extension 6 inches wide and flat on the top surface with a groove in the back that is designed to be fitted with a

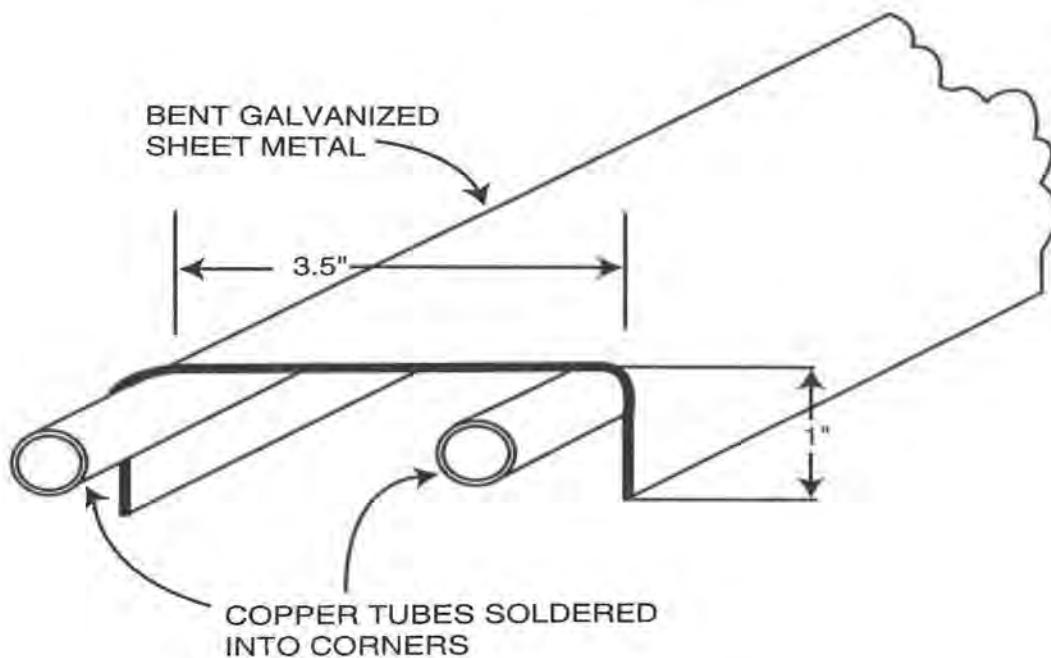


Figure A. 7. Sheet metal backing support.

piece of 5/8-inch-o.d. copper tubing. This makes a rather simple and elegant holder for solar cells. Modules with this type of backing support have been successfully constructed at several workshops.

Isolating and Encapsulating the Cells

If a metal backing support is used, the string of cells must not touch the backing because that would short them. Therefore, the cells must be fastened to the backing so that electrical insulation and adequate heat conduction are ensured. Silicone RTV (transparent silicone rubber caulk) is a very good electrical insulator, a moderately good conductor of heat, and has the added advantage of adhering extremely well to silicon cells. Based on the use of this material, we developed the following method to fasten and seal cells. Two-part, transparent silicone RTV, such as General Electric RTV 615, can also be used with the following instructions. It is easier to use, but more expensive.

Step 1. Using a caulking gun, lay a bead of silicone RTV down the center of the backing plate, and quickly spread this layer to cover the entire plate about 1/16-inch thick (Figure A.8). Speed is more important than perfection at this point.

Step 2. Cut a strip of cloth about 1 inch wider and larger than the backing plate. (Prepare this strip in advance so that no time is wasted while the silicone is setting up. Use polyester or some other synthetic cloth so any moisture that might get into the layer will not rot the fabric.) Press the cloth onto the fresh silicone layer (Figure A.9).

Step 3. Coat the cloth with another silicone layer, taking more care this time to get a level surface (Figure A.10). The purpose of these two steps is to create a barrier to keep the cells from accidentally touching the backing metal. For wood backs, Steps 2 and 3 can be eliminated if desired, although the cloth does strengthen and stabilize the silicone layer.

Step 4. Lay the solar cells carefully onto the wet silicone layer (Figure A.11). It is best, if possible, to solder the copper jumper strips to the back of each cell and place the cells one at a time onto the backing. Then solder them together after testing each cell for proper operation and shorts to the metal base. Press each cell very gently into the silicone to work the air bubbles out from the back. (A few air



Figure A.8. Spreading silicone RTV caulk onto the backing plate.



Figure A.9. Placing the cloth onto the fresh silicone.
(Skyheat Workshop photo)



Figure A.10. Smoothing out a new layer of silicone over the cloth, completely embedding the cloth. (Skyheat Workshop photo)

bubbles are better than a cracked cell, however.) If you must solder the string together before embedding, have someone hold up one end of the string while you carefully place each cell in turn. It is possible, if you are quick enough, to remove a broken cell and replace it with a good one while the silicone is still tacky. It is almost impossible to remove a cell once the module is finished.

Step 5. When you are completely satisfied that the module is working properly, apply a top layer of silicone RTV over the entire module. I usually finish by rolling on a Mylar™ top film while the silicone is fresh. (3-M sells rolls of Mylar™ plastic as an accessory to their overhead projectors.) Simply place a bead of caulk on the cells and slowly roll the film over it, rolling-pin fashion, to spread the silicone (Figure A.12). With practice, this will produce a thin, uniform top surface without any air bubbles trapped atop the cells. Make sure that the wires projecting from the ends of the module do not strain the connections to the end solar cells. I usually seal a couple of S curves in these wires so they are held in place by the silicone caulk.



Figure A.11. Laying the string of solar cells onto the freshly prepared backing. (Skyheat Workshop photo)

If it ever becomes necessary to repair a cell connection, it is possible to cut away the top encapsulant in the area to be repaired (a razor blade works well). Once the repair is made, a dab of silicone RTV smeared over the spot will reseal the system. If you are not sure where the defective spot is, you can use a multimeter with one probe replaced with a needle to poke carefully through the encapsulant to touch the jumper strips. Connect the other probe to one of the wires coming out of the module, and probe each jumper in turn. (Carefully confine this poking to the copper jumper strips because you can break a solar cell by hitting it too hard with the needle.) The bad jumper will be either the one which shows no reading, or the one next to it, depending on which end of the jumper has the bad con-



Figure A.12. Coating the top of the cells with silicone and Mylar film. The film presses out a bead of silicone RTV, eliminating voids and air bubbles. (Remote Power, Fort Collins, CO)



Figure A.13. The finished product is a completely encapsulated set of solar cells. (Remote Power, Fort Collins, CO)

nection. I prefer to measure the short-circuit current with a meter when doing this kind of troubleshooting, as a bad solder joint may be leaky enough to allow the correct open-circuit voltage to be read, even though it will let virtually no current pass.

The Reflector Wings

Design

Once the long modules are assembled and sealed, they are ready to use just as they are, but much more effective use can be made of these expensive solar cells if reflectors are added. For low concentration ratios, the design is not critical. Figure A.14 shows the dimensions of several reflectors that can be used with this type of module. The first is simply a pair of tilted flat reflectors that will almost double the amount of sunlight falling on the cells. This simple system, while very easy to build, does not have the acceptance angle of the second design; thus, the tilt would have to be changed about four times a year for most efficient operation. The second system also has a concentration ratio of 2, but the curved surfaces are more effective in reflecting off-axis light onto the cells; the tilt angle need be changed only twice a year. This design works with reasonable efficiency even if set at a simple fixed angle (equal to the latitude from the vertical).

The third system is simply a 4-to-1 concentration ratio version of the same Winston design. These reflectors are quite tall and will need some bracing to keep their shape. Also, the exact shape is more critical. Wood-backed modules are not recommended for use with this high a concentration ratio: the power input to the cells is quite high and the stagnation temperatures reached on a sunny day will decompose the wood and could cause a fire. In fact, wood-backed collectors could be dangerous in any hybrid system where the chamber above the wood is sealed off from the outside air.

Making the Reflector Wings

The easiest material from which to form the reflector wings is aluminum flashing. It is easily obtained at any lumber yard, stiff enough to hold its shape, and reasonably shiny. However, aluminized Mylar is much more reflective. The extra time and trouble taken to cover the

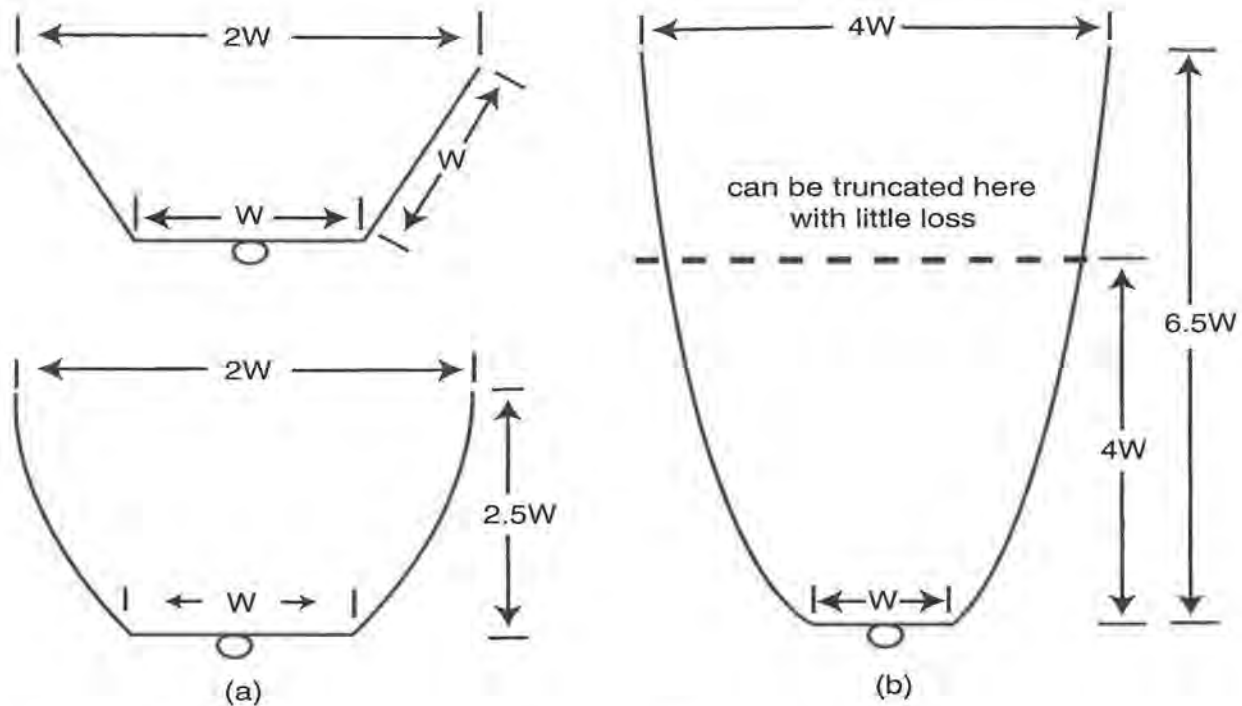


Figure A.14. Dimensions of several reflectors: (a) 2-to-1 concentration ratio; (b) 4-to-1 concentration ratios.

reflectors with this material will make them considerably more effective, producing as much as 30% more electricity than a system with plain aluminum reflectors. Some aluminized plastics are designed for exterior use and will keep their high reflectance for years.

When bending the aluminum reflectors to shape, first put a sharp kink where the reflector is fastened to the backing strip. You can improvise a long bending brake for this light-gauge material by clamping the aluminum between two boards with C-clamps and bending the protruding edge by hand or with a third board. The gentle parabolic curve in the metal can be approximated by bending the sheet around a round object. (We use a piece of 3-inch plastic sewer pipe.) The greatest bend is closest to the crease, and the springiness of the aluminum will keep the outer edge to a barely discernible curve.

The wings can be fastened to the module backing with sheet metal screws. (Be careful not to drill through a solar cell.) Then make the final adjustments to the wing shape and angle. Prop up the module so that you can look into it from about 15 feet away. You will see

a distorted reflection of the solar cells in each wing if you look at the module from straight on-axis. Bend and adjust the reflectors until the blue solar cell images seem to fill the reflectors completely. By moving your head to one side, you can get an idea of how much off-axis sun angle the reflector system will accept.

If two or more modules are installed side by side, they can be mounted so that the top edges of the reflectors just touch. The reflectors can then be fastened together, producing a very rigid support.

A Hybrid Hot Air System

Figure A.15 shows two ways of ducting air through the collector to make a hybrid hot air system. The first incorporates a transparent cover over the entire module to create a series of plenum chambers out of the spaces between the reflector wings. The cover is not a bad idea in any case as it will further protect the cells from the weather and keep the reflectors clean, at a slight loss in efficiency due to the reflection losses in the cover material. If the air is blown through this chamber, the cover should be double-glazed. In the second ducting method, the air is static above the cells and blown through the space behind them. Single glazing is sufficient if this method is used. The basic system is amenable to many variations, and it will be interesting to see what clever innovations develop.

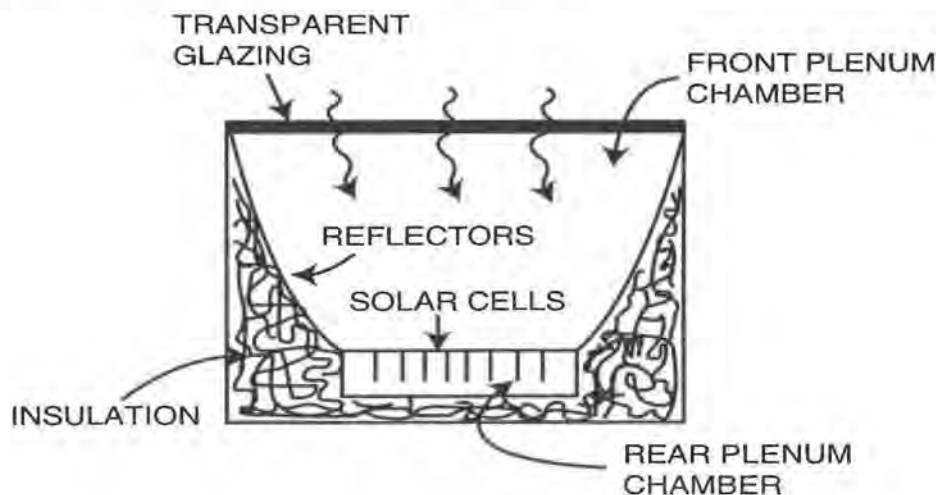


Figure A.15. Two ways to duct air through a hybrid system: through either the front or rear plenum chamber.

Glossary

AC—Alternating current; the electric current which reverses its direction of flow. 60 cycles per second is the standard current used by utilities in the U.S.

acceptance angle—The total range of sun positions from which sunlight can be collected by a system.

acceptor levels—Levels capable of accepting an electron from the valence band.

AH—*see* **ampere-hours**

air mass 0 (AM0)—The amount of sunlight falling on a surface in outer space just outside the earth's atmosphere (1.4 kW/m^2).

air mass 1 (AM1)—The amount of sunlight falling on the earth at sea level when the sun is shining straight down through a dry clean atmosphere. (A close approximation is the Sahara Desert at high noon.) The sunlight intensity is very close to 1 kilowatt per square meter (1 kW/m^2).

air mass 2 (AM2)—A closer approximation to usual sunlight conditions; may be simulated by an ELH projector bulb. The illumination is 800 W/m^2 .

alternating current—*see* **AC**

amorphous semiconductors—*see* **semiconductors, amorphous**

amorphous silicon—A form of silicon with no long-range crystalline order used to make solar cells.

ampere-hours (AH)—A current of one ampere running for one hour.

balance-of-systems (BOS)—All the equipment needed to make a complete working photovoltaic power system—except the solar cell modules.

band, conduction—*see* **conduction band**

band, valence—*see* **valence band**

band gap energy—The energy needed to raise an electron from the top of the valence band to the bottom of the conduction band.

band model—The quantum mechanical model of solids that explains the behavior of semiconductors.

black-body radiation—*see* **radiation, black-body**

battery, marine—A deep-discharge battery used on boats; capable of discharging small amounts of electricity over a long period of time.

battery, motive-power—A large-capacity deep-discharge battery designed for long life when used in electric vehicles.

battery, secondary—*see* **battery, storage**

battery, stationary—For use in emergency standby power systems, a battery with long life but poor deep-discharge capabilities.

battery, storage—A secondary battery; rechargeable electric storage unit that operates on the principle of changing electrical energy into chemical energy by means of a reversible chemical reaction. The lead-acid automobile battery is the most familiar of this type.

blocking diode—A device that prevents the current from running backward through an array, thereby draining the storage battery.

built-in potential—The electrical potential that develops across the junction of two dissimilar solids. The open-circuit voltage of a photovoltaic cell approaches, but is always less than, this potential.

bulk recombination—*see* **recombination, bulk**

carriers, majority—The carrier most present in a doped semiconductor: holes in p-type, electrons in n-type.

carriers, minority—The carrier least present in a doped semiconductor: electrons in p-type, holes in n-type.

cascade cells—*see tandem solar cells*

cell capacity—Expressed in ampere-hours, the total amount of electricity that can be drawn from a fully charged battery until it is discharged to a specific voltage.

composite cell structure—A device consisting of two solar cells built atop one another as one unit. The top cell absorbs short wavelength light and allows the longer wavelengths to pass through to illuminate the lower cell. A tunnel junction separates the cells. *Also see junction, tunnel*

concentration ratio—The ratio between the area of clear aperture (opening through which sunlight enters) and the area of the illuminated cell.

conduction band—The upper, usually empty, band in a semiconductor. Electrons with this energy are free to move throughout the solid.

conductivity, intrinsic—The electrical conductivity of an undoped semiconductor material. This conductivity, which is extremely small in solar cell materials, is produced by the direct thermal activation of electrons from the valence band to the conduction band. It is very temperature-dependent.

current-voltage curve—I-V curve; plots current on the vertical axis versus the voltage on the horizontal axis.

Czochralski process—Method of growing a single crystal by pulling a solidifying crystal from a melt.

DC—Direct current; electric current that always flows in the same direction—positive to negative. Photovoltaic cells and batteries are all DC devices.

deep-discharge cycles—Cycles in which a battery is nearly completely discharged.

depletion layer—The layer between the n and p layers at the junction where there are essentially no carriers.

diffusion furnace—Furnace used to make junctions in semiconductors by diffusing dopant atoms into the surface of the material.

direct band gap semiconductor—*see semiconductor, direct band gap*

direct current—*see DC*
donor level—The level that donates conduction electrons to the system.

doping—The deliberate addition of a known impurity (dopant) to a pure semiconductor to produce the desired electric properties.

electrolyte—A liquid conductor of electricity.

electron affinity—The energy difference between the bottom of the conduction band and vacuum zero.

electronic-grade silicon—*see silicon, electronic-grade*

energy levels—The energy represented by an electron in the band model of a substance.

extrinsic semiconductors—*see semiconductors, extrinsic*

fermi level—Energy level at which the probability of finding an electron is one-half. In a metal, the fermi level is very near the top of the filled levels in the partially filled valence band. In a semiconductor, the fermi level is in the band gap.

fill factor (ff)—The actual maximum power divided by the hypothetical “power” obtained by multiplying the open-circuit voltage by the short-circuit current.

fingers—*see front contact fingers*

Fresnel lens—A segmented lens, usually molded of plastic, used to concentrate sunlight onto a receiver.

front contact fingers—The thin, closely spaced lines of the front electrode that pick up the current from the semiconductor but allow light to pass between them into the solar cell.

heterojunction—A solar cell in which the junction is between two different semiconductors.

holes—An energy level that could be occupied by an electron, but currently is not. Holes act like charged particles, with energy and momentum, and are capable of carrying an electric current.

homojunction—A solar cell made from a single semiconductor; the junction is formed between n- and p-type doped layers.

hybrid system—A system that produces both usable heat as well as electricity.

hydrogen economy—A system in which hydrogen is substituted for fossil fuels. The hydrogen is basically a means of transporting and storing renewable energy.

indium oxide—A wide band gap semiconductor that can be heavily doped with tin to make a highly conductive transparent thin film. Often used as a front contact or one component of a heterojunction solar cell.

infrared wavelengths—Wavelengths longer than 700 nm; they cannot be seen, but are felt as “heat.”

intrinsic conductivity—*see* **conductivity, intrinsic**

intrinsic semiconductors—*see* **semiconductors, intrinsic**

inverter—A device that converts DC to AC.

inverter, synchronous—A device that converts DC to AC in synchronization with the power line. Excess power is fed back into the utility grid.

ion implantation—A method of doping semiconductors by striking the surface with a beam of high-energy ions.

I_{SC} —*see* **short-circuit current**

ITO—Indium oxide doped with tin oxide.

I-V curve—*see* **current-voltage curve**

junction, liquid—A junction with liquid electrolyte as one side.

junction, metal-insulator semiconductor (MIS solar cell)—A junction containing a thin (20 Å) insulating layer between the metal and the semiconductor.

junction, metal-to-semiconductor (MS junction)—A junction produced when a high work function (noble) metal is placed on a n-type semiconductor or a low work function metal is placed on a p-type semiconductor (Schottky barrier junction).

junction, tunnel—A special junction between two solar cells in a composite cell structure. Carriers cross the junction by quantum mechanical “tunneling.” *See* **tunneling; composite cell**

junction diode—A semiconductor device with a junction and a built-in potential that passes current better in one direction than the other. All solar cells are junction diodes.

majority carriers—*see carriers, majority*

metallurgical-grade silicon—*see silicon, metallurgical-grade*

minority carriers—*see carriers, minority*

MS junction—*see junction, metal-to-semiconductor*

MIS junction—*see junction, metal-insulator semiconductor*

n-type semiconductors—*see semiconductors, n-type*

ohmic contacts—Contacts that do not impede the flow of current into or out of the semiconductor.

open-circuit voltage (V_{OC})—An equilibrium voltage, reached when the number of carriers drifting back across the junction is equal to the number being generated by the incoming light.

parallel—In module construction: to increase current output, cells are wired with the back contact of one cell connected to the back contact of the next. The total current is the sum of the individual current outputs of the cells, but the total voltage is the same as the voltage of a single cell. Cells are usually wired in series to form an array and arrays are wired in parallel to obtain desired current.

passivate—To chemically react a substance with the surface of a solid to tie up or remove the reactive atoms on the surface. For example, the air oxidation of a fresh aluminum surface to form a thin layer of aluminum oxide.

polycrystalline solar cells—Cells in which more than one crystal (and crystal boundaries) are present in an individual cell.

power tower—A device that generates electric power from sunlight, consisting of a field of small mirrors tracking the sun to focus the light onto a tower-mounted boiler. The steam produced runs a conventional turbine generator.

p-type semiconductors—*see semiconductors, p-type*

radiation, black-body—Radiation emitted by the sun; it is composed of different wavelengths—some visible.

recombination, bulk—Occurs when the recombination centers are crystal defects or impurities in the bulk of the semiconductor.

recombination, junction—Occurs when the recombination centers are at the junction or in the depletion layers. In heterojunctions, it is often caused by crystal lattice mismatch between the two semiconductors.

recombination, surface—Occurs when recombination centers are surface impurities or surface states; sometimes caused by damage to the surface. These can often be removed by passivation and/or chemical etching.

recombination center—A point, often an impurity or defect, where a hole–electron pair created by the absorbed light can recombine before the electron can pass through the external circuit; acts like an internal short circuit.

rectifier—A device that passes current in one direction only.

refractive index—A measure of the amount of bending or “refraction” light undergoes when passing into or out of a substance.

Schottky barrier junction—*see junction, metal-to-semiconductor*

secondary battery—*see battery, storage*

self-discharge rate—The rate at which a battery will discharge on standing; affected by temperature and battery design.

semiconductors, amorphous—Semiconductor with no long-range crystal order.

semiconductors, direct band gap—The light absorbed can cause electrons to jump directly from the top of the valence band to the bottom of the conduction band. These semiconductors absorb light very strongly and can be used as very thin films.

semiconductors, extrinsic—The product of doping a pure semiconductor.

semiconductors, indirect band gap—When momentum conditions forbid the direct jumping of electrons, a more complex transition is required and light is absorbed less strongly thus requiring thicker solar cells. Silicon is an indirect band gap semiconductor.

semiconductors, intrinsic—An undoped semiconductor. *Also see conductivity, intrinsic*

semiconductors, n-type—Semiconductor in which negative electrons carry the current; produced by doping an intrinsic semiconductor with an electron donor impurity (phosphorus in silicon).

semiconductor, p-type—Semiconductor in which positive holes carry the current; produced by doping an intrinsic semiconductor with an electron acceptor impurity (boron in silicon).

series—In array construction: connecting cells by joining the back contact of one cell to the front contact of the next cell to obtain a higher voltage.

shingling—In array construction: connecting cells by overlapping the front edge of one cell with the back edge of the next, similar to roof shingles, and soldering the edges together.

short-circuit current (I_{SC})—The maximum current a cell can deliver into a short circuit, directly proportional to the area of the cell and the light intensity.

silicon, electronic-grade—Highly purified silicon needed for the manufacture of semiconductor devices (semiconductor-grade). Very expensive and in short supply:

silicon, metallurgical-grade—99.8% pure silicon suitable for most industrial uses. Relatively inexpensive.

silicon, solar-grade—Intermediate-grade silicon proposed for the manufacture of solar cells. Should be much less expensive than electronic-grade.

solar array—A set of modules assembled for a specific application; either in series for increased voltage or in parallel for increased current or a combination of both. *Also see solar module*

solar cell—A device that converts sunlight directly into electricity.

solar-grade silicon—*see silicon, solar-grade*

solar module—A series string of 32 to 36 cells, producing an open-circuit voltage in bright sunlight of about 18 volts, or 16 volts when producing maximum power. Total current output of a series string is the same as a single cell. *Also see solar array*

solar power farms—Large centralized photovoltaic array systems that generate electricity to power the utility grid.

sputtering—A method of depositing thin films utilizing a low-pressure gas discharge, either DC or radio-frequency, to knock atoms or molecules off an electrode onto the substrate to be coated.

sulfation—A condition which afflicts unused and discharged batteries; large crystals of lead sulfate grow on the plate, instead of the usual tiny crystals, making the battery extremely difficult to recharge.

surface recombination—*see recombination, surface*

tandem solar cells—Two photovoltaic cells are constructed on top of each other such that the light passes through the wide band gap cell to reach the narrow band gap cell. These cells very efficiently utilize the sunlight giving a greater output for a given area. Also called cascade cells.

tin oxide—A wide band gap semiconductor similar to indium oxide; used in heterojunction solar cells or to make a transparent conductive film called NESA glass when deposited on glass.

total energy system—Hybrid system producing both usable heat and electricity.

tracking system, one-axis—A mount pointing in one axis only; re-oriented seasonally by hand and used with linear concentrators or flat plates.

tracking system, two-axis—A mount capable of pivoting both daily and seasonally to follow the sun.

tunneling—Quantum mechanical concept whereby an electron is found on the opposite side of an insulating barrier without having passed through or around the barrier.

ultracapacitors—Experimental carbon-based electrolytes used to deliver large current to accelerate large motors.

ultraviolet (UV) wavelengths—Wavelengths shorter than 400 nm; the energetic rays of the sun, invisible but responsible for suntans and sunburns. Our atmosphere filters out most UV rays.

vacuum evaporation—Method of depositing thin coatings of a substance by heating it in a vacuum system.

vacuum zero—The energy of an electron at rest in empty space; used as a reference level in energy band diagrams.

valence band—The band of energy levels occupied by the valence electrons in a solid; always below vacuum zero.

V_{oc} —*see* **open-circuit voltage**

voltage, open-circuit—*see* **open-circuit voltage**

voltage, short-circuit—*see* **short-circuit voltage**

Winston concentrator—A trough-type parabolic collector with one-axis tracking developed by Roland Winston.

work function—The energy difference between the fermi level and vacuum zero. The minimum amount of energy it takes to remove an electron from a substance into the vacuum.

zone refining—Method of purifying solid rods by melting narrow zones through the rods. These zones are slowly moved from one end of the rod to the other, sweeping out the impurities.