energy from the sun

D. M. CHAPIN
Bell Telephone Laboratories

AN EXPERIMENT IN
PHYSICS AND CHEMISTRY
CONVERTING SOLAR ENERGY
TO ELECTRICAL ENERGY

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Telephone Company*

IMPORTANT NOTICE

The Solar Energy Experiment is to be performed only under the guidance and supervision of your science teacher. The materials in the kit, or other materials which you are instructed in this book to use in the experiment, are not to be taken outside of your school laboratory because, as you can appreciate, an experiment of this sort should be conducted under standard laboratory safety procedures. If you carefully follow the instructions in this book and the rules of your school laboratory, the experiment can be conducted with complete safety.

Chemicals and other materials mentioned in this book which are not included in Chapter 6, "Instructions for Making a Solar Cell," are mentioned for educational purposes only. You should not experiment with them unless this book definitely instructs you to do so.

ENERGY

from the sun

ENERGY *from the sun*

Daryl M. Chapin
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Introduction

Because of your outstanding ability and interest in science, your teacher has given you this book and kit provided by your Bell Telephone Company. The book is written and the kit designed to both teach and challenge scholars of science at the secondary school level.

In addition to describing present-day uses of solar energy, the theory of the direct conversion of the sun's radiation into electricity is given so that you may use your own imagination to conceive future possibilities in this growing field. Following the instructions in the book, you will use the Solar Energy Experiment kit to make working solar cells. A number of tests and experiments are described that involve using the cells that you make.

The Solar Energy Experiment is to be performed only under the guidance and supervision of your science teacher and under conditions which are described in the statement on page ii of this book. This statement is made to assure successful performance of the experiment under safe procedures — so please read it now, before you go on reading this Introduction.

It is impossible to talk about solar energy and world needs without reference to astronomical figures of power. When at last you make a solar cell that delivers only 10 milliwatts, there may be a slight letdown feeling. Don't be discouraged. We are standing near the beginning of a new era of solar uses. The first silicon solar cells were feeble indeed. At the time of public announcement in 1954, solar batteries, made up of a number of cells, delivered less than 1 watt. Now, satellite batteries of about 100 watts are becoming common. Admittedly, some real progress is needed to bring this figure up to a kilowatt . . . 10 kilowatts . . . and more. It is our hope that this project will help train the new scientists who will continue this effort.

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1 The Sun–Our Primary Source of Energy

Utilization of Energy

Our material civilization advances with man's use of energy. Civilization can be measured in many ways, but one of the best criteria of a culture is the amount of power available per person. A number of generations ago each person had only his own physical strength — one manpower. Even with the domestication of beasts of burden, the power available per person was not considerably more than man's own strength. It is the same today in primitive societies, but in advanced regions, the power per person is increasing rapidly. In the United States, for example, the average power for each person in 1950 was 56 kilowatt-hours per day. At present estimates this figure will double in 19 years. As automation advances, the demand for power will increase and we will have to draw more and more on our reserves of energy to supply the additional power. Where is it to come from? It may help to consider where it is coming from now.

Sources of Energy

The three heavy burden bearers are coal, petroleum, and gas. More and more uses are being geared to oil, and oil companies are scouring the earth looking for more oil fields. One recent estimate says that the known reserves of oil and gas are sufficient to last us less than 100 years at the present and projected rate of use and at prices comparable to present ones. And, if the backward nations

start using their share of oil, the known reserves will disappear much faster. It took millions of years for natural processes to make these reserves and we are using them up in a fraction of that time. What then? Civilization probably will not grind to a fuelless stop as long as men see the problem and work toward its solution. Maybe some who read this book and perform its experiments will some day contribute to that solution.

Let us examine briefly where our energy comes from originally. It may surprise you that almost all of the energy available to us *is* or *was* solar energy. The fossil fuels, already referred to (coal, oil and gas), were made from plants and animals which derived all of their energy from the sun. Wind power, used to drive ships and to operate windmills, derives its energy from the sun heating our atmosphere. Water power represents energy expended by the sun to evaporate water. Wood, used extensively in some areas for heating and to operate steam engines, represents solar energy stored in the comparatively recent past. And of course the food we eat has energy for us only because plants collected this energy from the sun during growth.

There are, however, other sources of energy which are nonsolar. The vast energy of the tides, for example, comes from the rotational energy of the earth as it interacts with the moon and the sun. The heat of the interior of the earth is thought to be atomic in origin. At any rate, it is not solar energy unless you wish to include the earth itself as once a part of the sun.

Atomic energy, recently unlocked by man, would appear to give the ultimate answer to our power problem. However, there is a limit to the amount of raw material, uranium, that can be collected; the total estimated energy reserve for uranium is not fantastically larger than that for reserves of oil. This still leaves the hydrogen fusion process (also atomic) which has yet to be tamed.

Source of the Sun's Energy

This is a good place to get back to solar energy because the hydrogen fusion reaction is believed to be the main source of the sun's vast energy. *Fusion* is the bringing together of two or more atoms* of matter, under conditions of intense heat, to form a single heavier atom. This, of course, is the opposite of fission which is the splitting of a heavier atom into lighter ones.

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* Strictly speaking, it is the nuclei of the atoms which fuse.

In the special case of hydrogen fusion, four atoms of hydrogen, each having an atomic weight of 1.008 are fused into one helium atom, Figure 1-1. But a helium atom has an atomic weight of only 4.003, whereas 4 times 1.008 equals 4.032. Thus, an atomic weight of 0.029 (approximately 0.7 %) must still be accounted for in this fusion of hydrogen into helium.
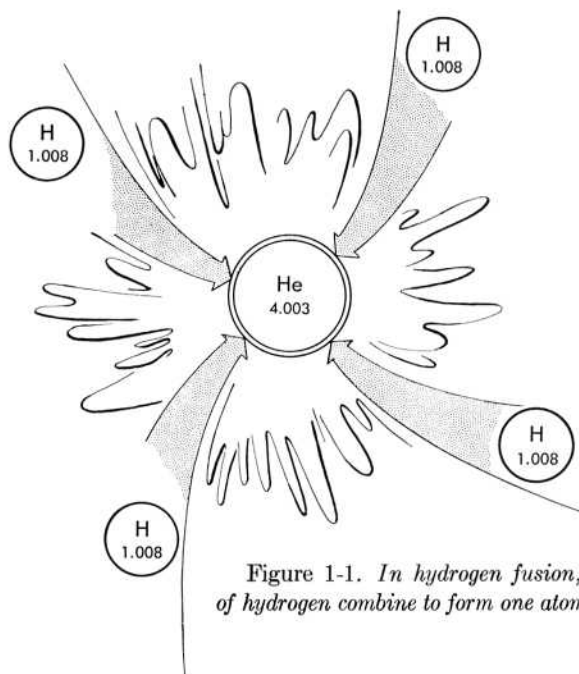
Figure 1-1. *In hydrogen fusion, four atoms of hydrogen combine to form one atom of helium.*

Now, since no known particles of matter are given off in this process of fusion, the loss in weight (mass) cannot be explained on that basis. However, it is found that a great amount of *energy* is released at the time of transformation of one element to another. *It would thus seem reasonable that the disappearing mass is being changed into an equivalent amount of energy.*

Years before the first hydrogen bomb was detonated, Albert Einstein studied the possibility of transformation of mass into energy as part of his researches into relativity. He showed that the energy produced is related to the mass that disappears by his famous equation,

$$E = mc^2,$$

where E is the energy in ergs* that appears when m grams of mass disappear and c is the velocity of light expressed in centimeters per second. The disappearance of 1 gram of matter therefore develops $(3 \times 10^{10})^2$ or 9×10^{20} ergs of energy. This is 25 million kilowatt hours.

Measuring the Sun's Power

How strong is the sun's radiation? Years ago, I found a good round figure easily remembered: On a clear day with the sun high overhead, 1 square meter of the earth's surface perpendicular to the sun's rays receives approximately 1 kilowatt of power. You may not detect any cloudiness when the amount is only 900 watts; radiation above 1000 watts per square meter can be encountered especially in dry climates and at high altitudes. But the 1000-watt figure is sufficiently representative to be referred to in the literature as One Sun.

You may want to check this figure for your locality. To do this, obtain a shallow pan or flat-bottomed glass dish about 6 to 8″ in diameter and 1 to 2″ deep, Figure 1-2. Measure the area of its opening at the top. Weigh the dish. Find the water equivalent of the dish by multiplying its weight by the specific heat for the material from which it is made (see the following table).

SPECIFIC HEAT OF COMMON MATERIALS

Material	Specific heat
Aluminum	0.21
Copper	0.09
Glass	0.16
Iron	0.12
Lead	0.03

Paint the inside of the dish with a good waterproof black paint and let it dry. Pour in a measured amount of water to a depth of about ¾″. (The weight of the water plus the water equivalent of the dish is the water equivalent of the dish and water.) Put a small thermometer in the bottom of the dish so that it can be read in position without disturbing it. Over the dish, place a single pane of clear, clean glass.

You probably begin to see the method which is to absorb a known cross section of sunlight and compute the heat absorbed from the rise in temperature of a measured mass. To get the cross section perpendicular to the sun's rays, multiply the area of the dish by the sine

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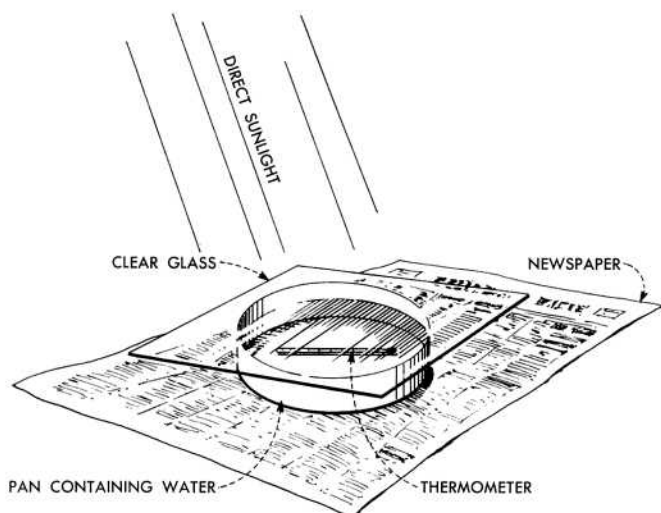* See Appendixes I and II for definition and transformation of units.

Figure 1-2. *Apparatus for measuring the sun's energy.*

of the angle of the sun's elevation, Figure 1-3. (Or make your test at high noon and get the elevation from your latitude and the solar decrement for the date as found in handbooks.)

Obviously, any heat added to or taken away from the dish by its surroundings will give errors. These errors can be minimized by using the rate of temperature rise at a time when the dish and its surroundings are at the same temperature. Set the dish in full sun resting on a few thicknesses of newspaper for insulation. Protect from wind. Start with the dish and water a few degrees cooler than the outside air. Record the temperature and time at frequent intervals until the temperature is several degrees above the outside air (ambient) temperature. Plot these measurements as in Figure 1-4. The slope of the curve at the ambient temperature will give the rate of temperature rise nearly independent of heat losses. Convert the rate to degrees Centigrade rise per second.

Computation of the power of the sun consists of solving the equation which states that the heat gained by the system in 1 second is equal to that received from the sun in the same time. Express each side in gram calories, remembering that 1 watt equals 0.24 calories per second.

$$0.24 \times A \times \sin\theta \times P = W \times T$$
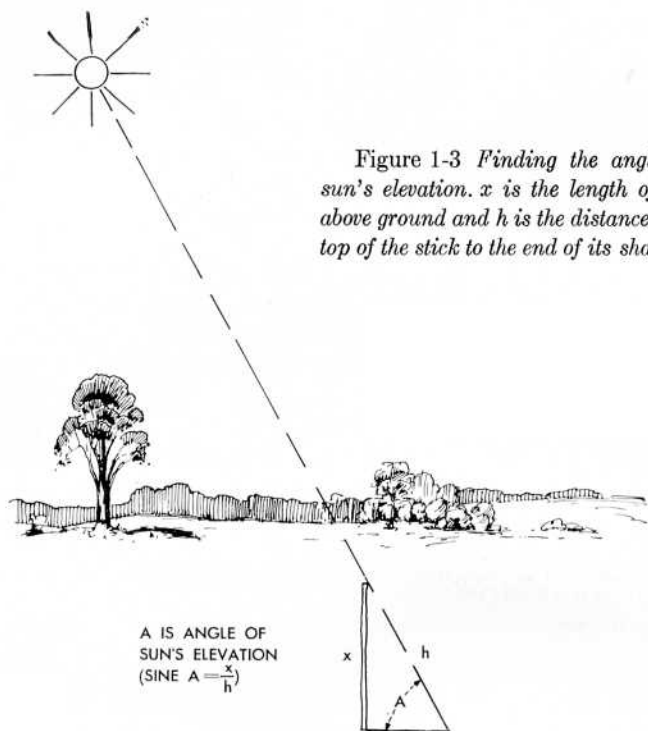
Figure 1-3 *Finding the angle of the sun's elevation. x is the length of a stick above ground and h is the distance from the top of the stick to the end of its shadow.*

A IS ANGLE OF
SUN'S ELEVATION
(SINE $A = \frac{x}{h}$)

where 0.24 = calories per watt-second

A = area of dish in square centimeters*

θ = angle of the elevation of the sun

P = power of the sun in watts per square centimeter perpendicular to the sun's rays

T = temperature rise rate in degrees Centigrade per second†

W = water equivalent of the system in grams‡

The cover glass is used to prevent large losses of heat from evaporation, but the glass also causes losses due to reflection. Maybe you can devise an experiment that corrects for evaporation losses without using the glass cover.

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* 1 inch = 2.54 centimeters

† Centigrade = $\frac{5}{9}$ (Fahrenheit − 32)

  1.8° Fahrenheit = 1° Centigrade

‡ 1 ounce = 28.35 grams

As a measure of the accuracy you can expect, here are my data:

Diameter of dish	= 5$\frac{15}{16}$″ = 15.10 centimeters
Weight of dish	= 92.58 grams
Water equivalent of dish for specific heat of 0.16	= 15 grams
Mass of water	= 180 grams
Total water equivalent	= 195 grams
Ambient temperature	= 32.5°C = 90.5°F
Date and time	— High noon, Sept. 5, 1961

DATA FROM POWER OF SUN EXPERIMENT

Water Temperature, °F	Time Minutes	Time Seconds	Time Minutes (decimal)
67	0	0	
69		22	0.37
70.5	1	7	1.12
72	1	26	1.44
73	1	48	1.80
76	2	50	2.83
78	3	35	3.58
79	3	51	3.85
79.2	4	20	4.33
80.5	5	5	5.08
82.5	5	47	5.78
83.3	6	10	6.17
84	6	35	6.58
85.5	7	18	7.30
88	8	13	8.22
89.5	9	3	9.05
90	9	40	9.67
91	10	7	10.12
92	10	30	10.50
93	10	51	10.85
94	11	26	11.43
95	11	56	11.94
96	12	27	12.45
97	12	52	12.87
98	13	17	13.28

These data are shown plotted in Figure 1-4. The slope of the curve at 90.5°F is 2.04°F per minute. The declination of the sun on September 5 was 6.9° which, added to my colatitude, put the sun at 59° elevation. The sine of 59° is 0.8572.

Putting all these data into the equation, I obtained 0.100 watt per square centimeter or 1000 watts per square meter. It looks as if I cribbed the data because I know from previous experience, and an approximate measurement, that the true value was probably between 970 and 1030. Considering known errors, a measurement by this
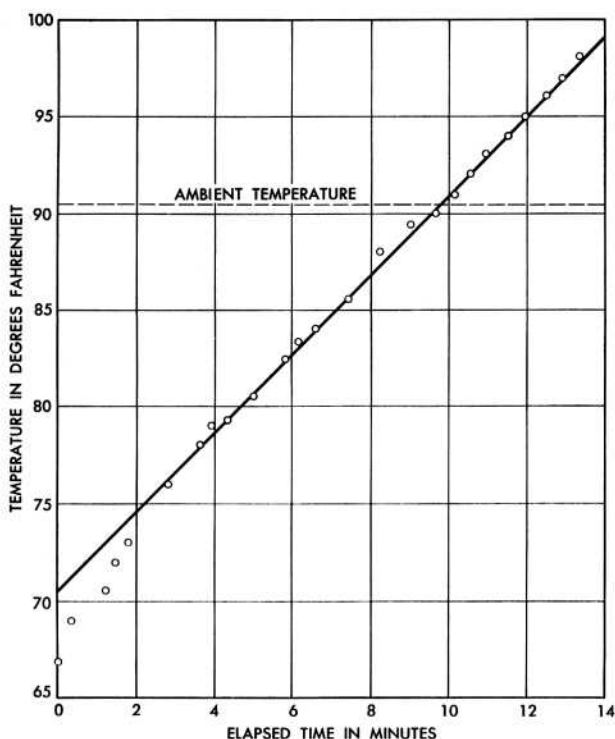
Figure 1-4. *Temperature versus time for energy of sun experiment.*

simple method would be expected to give near to 950, so that actually I probably overshot by at least 5%. But we are not now after great accuracy, and will content ourselves with a first-hand feeling of the power involved.

To get an idea of how much power this represents, translate the 1000 watts per square meter figure to other areas. 1000 watts per square meter is $\frac{2}{3}$ watt per square inch; 93 watts per square foot; 4000 kilowatts per acre, or 2,600,000 kilowatts per square mile. The total amount of radiation falling on the earth is approximately 4×10^{15} kilowatt-hours per day. You can see that there is no shortage of power available, but it is spread out.

How Long Will the Sun Last?

The accepted figure for the intensity of the solar radiation outside the earth's atmosphere is 0.135 watt per square centimeter. This is

at a distance of 93,000,000 miles from the sun. As nearly as we can tell, the sun radiates equally in all directions. If we multiply 0.135 watt per square centimeter by the area of a sphere of radius 1.50 × 10^{13} centimeters* we come out with 3.8 × 10^{26} watts which is equal to 3.8 × 10^{33} ergs per second as the total power radiated by the sun. By substitution in Einstein's equation, we find the sun's loss in mass to be,

$$m = \frac{E}{c^2}$$

$$= \frac{3.8 \times 10^{33} \text{ ergs per second}}{(3 \times 10^{10} \text{ centimeters per second})^2}$$

$$= 4.2 \times 10^{12} \text{ grams per second}$$

$$= 4,600,000 \text{ tons per second}$$

How long can this keep up? From the gravitational constant, our distance from the sun, and the length of our year, we find that the mass of the sun is 1.98 × 10^{33} grams. Approximately 0.7 % of that mass is available for the hydrogen to helium transformation, or 1.38 × 10^{31} grams. At a loss of 4.2 × 10^{12} grams per second, this mass will last 3.3 × 10^{18} seconds, or 104,000,000,000 years. The lowest estimate I recall seeing of the sun's useful life based on other considerations is 10,000,000,000 years. Give or take a few billion years, either estimate is a long, long, time. We will certainly never exhaust this supply. And the total amount of solar energy striking the earth is around 30 thousand times more than we are now using from fossil fuels.

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* 93,000,000 miles = 1.50 × 10^{13} centimeters.

2 Putting the Sun to Work

For untold ages, man made no attempt to use the sun except to warm himself. Very early, however, he must have sensed its importance in the production of life's necessities and he worshipped it as a god. Later, with the development of agriculture, man took a more active part in using the sun's energy to satisfy his needs. Much more recently, there has been a determined search for an economical means of using solar energy.

The Greenhouse Effect

For many years, glass-covered houses (greenhouses) have been used to produce a favorable climate for plants, Figure 2-1. Most greenhouses are equipped with auxiliary heat, using the sun primarily for growth energy and only incidentally for heating. Nonetheless, the heating obtained in full sun is considerable and the principle involved is widely used to collect heat from the sun. Of course, part of the effect is simply that the heated air is blocked from escaping. But there is a further effect of selective transmission by the glass covering. Glass is transparent to about 98 % of the sun's radiation which concentrates its energy in the visible and near infrared. The radiation from the warmed surfaces within the greenhouse is all in the far infrared to which the glass is opaque. The glass, therefore, acts as a one-way valve admitting and retaining the sun's energy.

A very simple experiment will demonstrate the greenhouse effect and fix it in mind. You already know that you can feel the sun's warmth through a window. Place your face near enough to a hot stove or soldering iron to feel its radiant heat. Without moving your face, slip a pane of ordinary window glass between your face and the
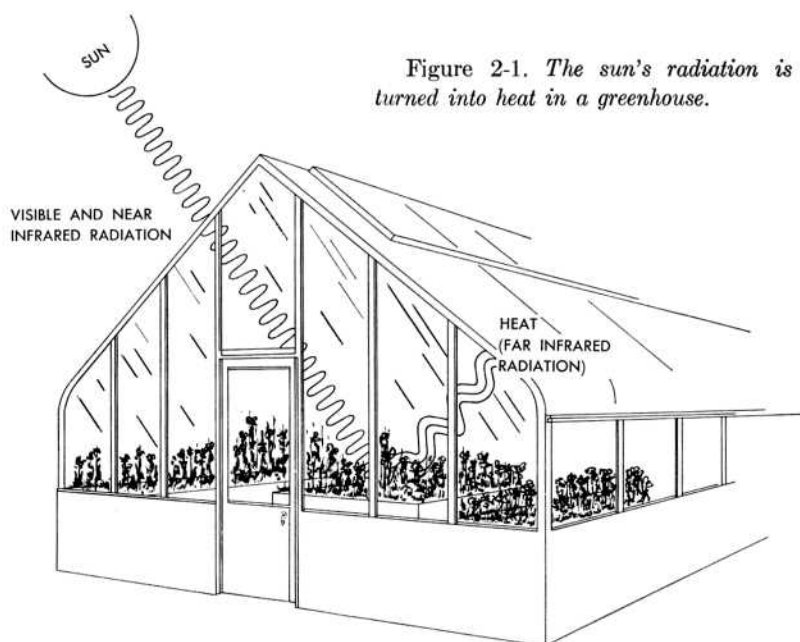
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Figure 2-1. *The sun's radiation is turned into heat in a greenhouse.*

hot object. The decrease in radiation will be pronounced although you can still see the hot object as well as before.

Heat Applications

The greenhouse effect is being used to supply household hot water in certain sunny parts of the world. Solar water heaters have been used in Florida for over 20 years. They use about 50 square feet of collector surface and cost about $300.00.* Properly installed and maintained, they give very good service. Of all of the attempts at direct use of solar energy, the hot water heater appears to be the nearest to large-scale practical use.

An up-and-coming application of solar energy is for space heating in homes and offices. In the Boston area, several small houses have been heated using from 400 to 700 square feet of collector on a vertical or near vertical south wall. Figure 2-2 shows a solar-heated house. Other solar houses have been built in Denver, Colo., Phoenix, Ariz., Washington, D. C. and Montreal, Canada. The cost of materials, acceptable architecture, storage and distribution of heat are the main problems. In most of these houses solar energy is used for only part
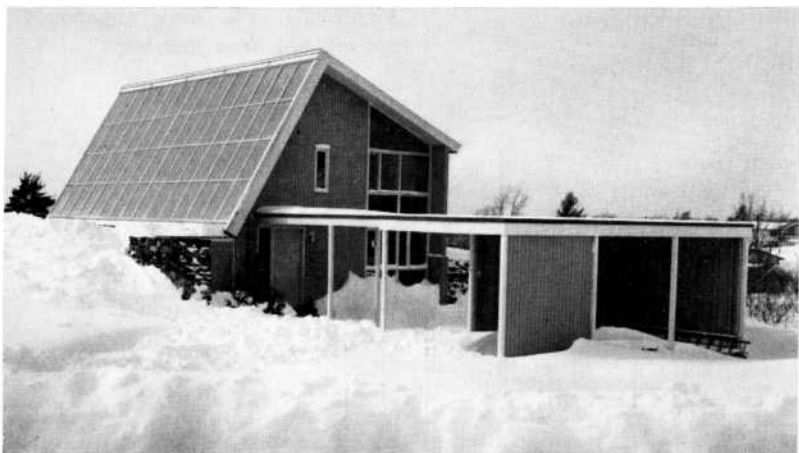
* Based on a 1960 estimate.

Figure 2-2. *Built in 1958 in Lexington, Mass., for experimental purposes by the Massachusetts Institute of Technology, this house uses solar energy for part of its heat supply. Picture courtesy of M.I.T.*

of the heat and conventional methods for the remainder; the designers find the compromise more economical than trying to provide enough collector area and heat storage to allow for the worst possible combination of cold and continuous cloudy weather.

Distillation of salt water by heat from the sun has been under investigation for some time. Basically, the process involves using a pool of salt water, Figure 2-3, covered with glass or clear plastic to allow the sun's energy to come through and heat the salt water. Salt-free water evaporates from the pool, condenses on the slanted cover, and is collected in a storage tank. Many areas of the world are deserts with abundant sunshine and nearby salt or brackish water. If solar distillation could produce sufficient pure water at a low enough price, these areas could be reclaimed. Original equipment and maintenance are the expenses involved since the fuel is free. New materials and novel arrangements are being studied in an attempt to lower the cost.

For years, there was a 51,000 square-foot solar still supplying fresh water to Las Salinas, Chile. The government of Israel is particularly active in this field in the attempt to restore to that land the "milk and honey" of biblical times. It appears that this application is also near to being commercially feasible.
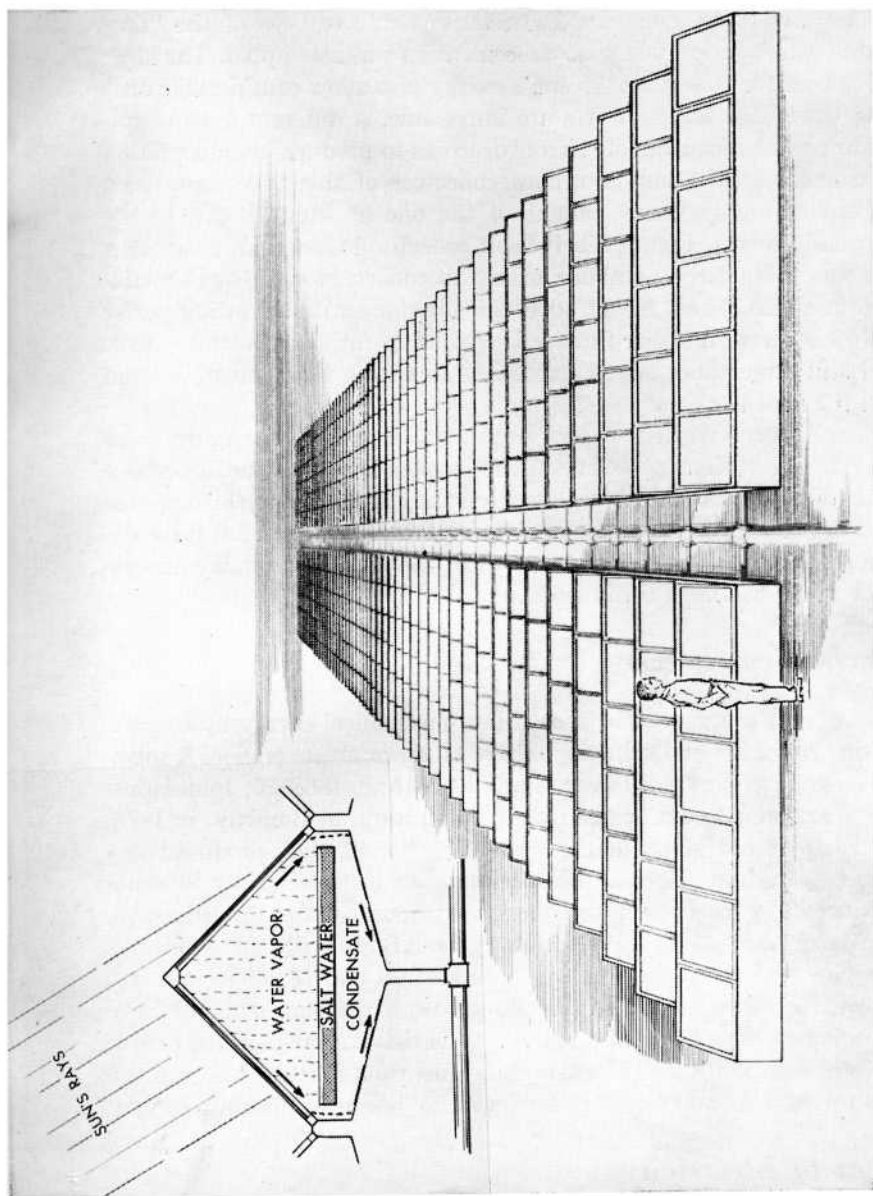
Figure 2-3. *Artist's conception of solar distillation of salt water. Insert, upper left, shows cross section of a unit.*

Concentration Devices

The uses of solar energy discussed so far have been of the "flat-plate" classification where no concentration was attempted. The large areas used for collecting the sun's energy also allow considerable heat loss, thus, high temperatures are impossible. A different type of collector uses the focusing of mirrors or lenses to produce intense heating in a small area. Some enormous collectors of this type have been built. Perhaps the most famous is the one at Mont Louis, in the French Pyrenees, Figure 2-4. It has a collector 30 feet square to follow the sun and a large parabolic mirror to concentrate the sun's radiation in a small area. About 3000°C is obtained with a heating power of 75 kilowatts. A larger furnace is now in operation at Natick, Mass. and still larger ones are planned. The available temperature is high and the heat is clean.

A miniature version of the giant furnaces is the backyard solar cooker. The serious objective of this cooker is the use in fuel-scarce areas of the world. These are usually sunny areas where this application is needed. Although several serviceable cookers have been developed, social customs and the cost of the equipment delay acceptance where the need is the most acute.

Mechanical Power

The sun's energy can be turned into mechanical energy by concentrating radiation and using it to drive an air or steam engine. A solar-powered air engine was built as early as 1615; in 1868–70, John Ericsson operated a steam engine by solar radiation; in Bombay, in 1876, a solar-powered steam engine was constructed that produced $2\frac{1}{2}$ horsepower. In 1907, near Philadelphia, an installation by Shuman produced $3\frac{1}{2}$ horsepower and was used to pump water for irrigation. In Meadi, Egypt, in 1913, Shuman and Boys built an ambitious pumping system with cylindrical collectors. It had 13,269 square feet of collectors and produced 100 horsepower. Gasoline engines have been developed to do so many jobs so well that a solar-powered engine has stiff competition. But when liquid fuel runs short or becomes too expensive, solar-powered heat engines may become important.

Heat to Electricity

One more thermal converson method deserves mention. When two dissimilar metals are joined together in a loop and one junction is

Figure 2-4. Artist's conception of the solar furnace located at Mount Louis in the French Pyrenees.

heated (thermocouple), there is a current of electricity generated, Figure 2-5. Only a few years ago, this effect, the Seebeck effect, was considered useful only for measuring temperature and activating a few control circuits. However, recent study of materials has increased the efficiency of conversion to around 3 % which is enough to make the thermocouple a serious contender in the race to utilize solar energy.
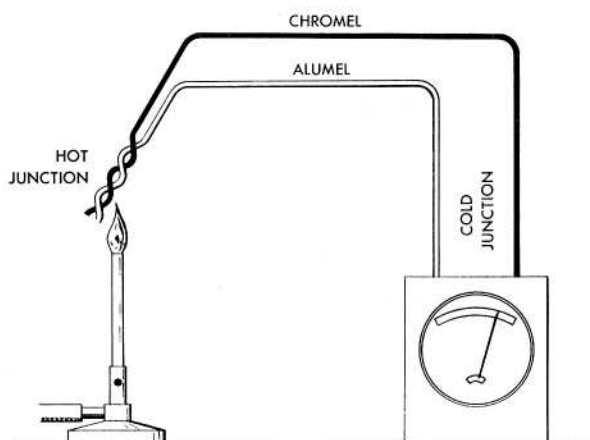
Figure 2-5. *Thermocouple effect.*

The thermocouple has the advantage of simplicity of design. However, efficiency of conversion rises with the temperature difference between the hot and cold junction and reasonable efficiencies require several hundred degrees difference. This implies concentration of solar energy as in the solar furnace with its corresponding tracking of the sun. A diffuse light as from a partly cloudy sky is of very little use for powering thermocouples.

Direct Conversion

With the exception of the agricultural processes, all of the methods discussed first convert solar radiation into heat. This is fundamentally wasteful. It is well known that mechanical and electrical energy can be transformed into heat with 100 % conversion efficiency. But the reverse process takes place only when there is a difference of tem-

perature and then with an efficiency or loss tied in with the temperature difference.*

It is clearly wasteful to convert solar radiation first into heat and then try to reconvert it into electricity or mechanical motion. This is one reason why scientists eagerly welcome any information about a direct conversion of solar energy to electrical energy even though early results are competitive economically only in special cases. Cost reduction and other improvements can come later. The important fact is that more than 10 % of the sun's total radiant energy can be delivered as electrical energy into a load without moving parts and without the wasteful prior conversion to heat energy. The rest of this book will be devoted to an understanding of this direct conversion method and to the making and testing of silicon solar cells.

We will need to study the nature of radiation and the properties of a special class of electrical materials — the semiconductors. First, let us look at radiation.

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* The maximum theoretical efficiency of a perfect heat engine working between a high temperature T_1 (measured from absolute zero) and a lower temperature T_2 is given by the simple expression,

$$\text{efficiency} = \frac{T_1 - T_2}{T_1}$$

3 Radiant Energy

Until recently, it has been customary to think of radiation chiefly as a means of heat transfer. Heat can be transferred by three means: conduction, convection, and *radiation*. This concept is still true. However, it ignores the fact that *radiation is itself a form of energy which can be transformed into heat but which, strictly speaking, is not heat*. Radiation is a separate form of energy not tied to the inexorable thermodynamic laws that limit the usefulness of heat energy. It is necessary that we recognize this distinction to understand all of the possibilities of harnessing the enormous energy available to us from the sun.

As is well known, sunlight is composed of many colors. These colors can be seen separately in a rainbow when sunlight is broken up by water droplets in the atmosphere or by a glass prism as shown in Figure 3-1. Of course, the colors in the rainbow or the light refracted by the prism are the *visible* colors. These visible colors are only a part of the sun's spectrum. "Invisible colors" extend both beyond the violet end and the red end of the visible band. Figure 3-2 shows the distribution of radiant energy within the sun's spectrum.

Although we are not now directly concerned with radiation outside the solar spectrum, we know that solar radiation represents only a small portion of the total electromagnetic spectrum which is known to extend with no omissions from long radio waves to the hardest gamma rays. This broader spectrum is shown for comparison in Figure 3-3.

Wave Theory

The graphs shown are plotted against wavelength. This implies a wave characteristic of light. For this, there is ample experimental
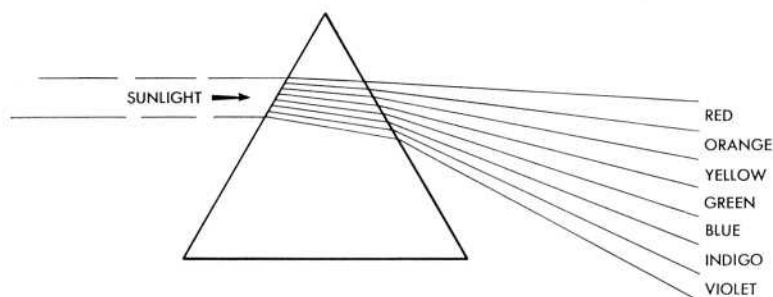
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Figure 3-1. *A prism breaks sunlight up into its individual colors.*

evidence as shown in interference effects and diffraction measurements (Huygens' principle). Each color has been measured and a wavelength determined for it. So well established is the wave theory of light in experimental measurements that the international standard of length, the meter, is now defined as, "1,650,763.73 wavelengths of the orange-red line of krypton 86."*

This useful theory was rudely jolted by several observations that will not conform; the photosynthesis of plants, the action on photographic plates and the photoelectric effects we are now studying will not take place even in very strong radiation if the wavelength is too long for that particular reaction. For the right wavelength, the results are still proportional to intensity, but for too long a wavelength, no amount of intensity will affect the reaction. This is not a simple resonance, as the next fact shows. For electrons discharged by radiation (as from certain substances in a vacuum), the *number* of electrons is increased by increased radiation, but the *energy* of each electron is *completely unaffected*. This does not sound like a wave motion where more intensity would be expected to give more energy to each electron. There are also facts about the shape of radiation curves that the wave theory alone can not explain.

Quantum Theory

About 1900, Max Planck proposed a quantum theory of light that answers the objections. Planck proposed that radiation, while retaining its characteristics of wave motion, is emitted in discrete chunks or photons (the duality principle). Thus, a ray of light becomes a stream of energy units (photons).

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* *Handbook of Chemistry and Physics*, 43rd edition, 1961–1962. (The 21st edition gives "1,553,164.13 times the wavelength of the red cadmium line in air, 760 mm pressure, 15°C.")
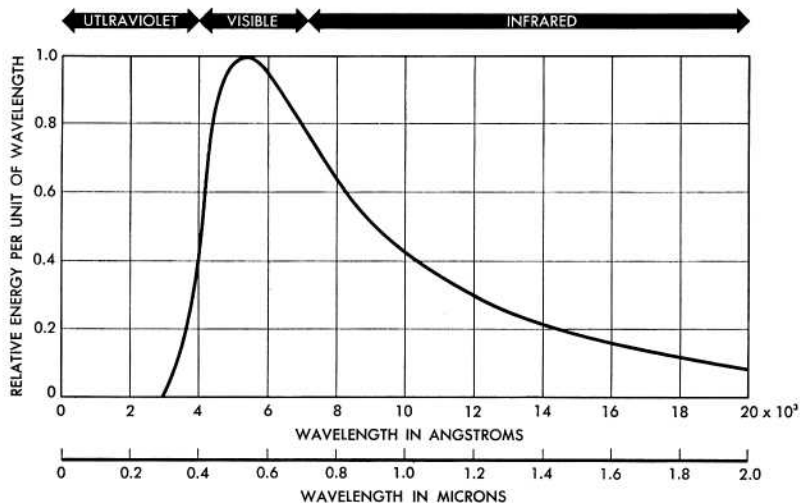
Figure 3-2. *Distribution of solar energy as a function of wavelength.*

The energy of a *photon*, Planck found, was related to the frequency of the radiation by the formula,

$$E = h\nu,$$

where E is the energy in ergs, ν is the frequency in cycles per second, and h is Planck's constant of proportionality, which turns out to be 6.62×10^{-27} erg-second.

The energy of a photon is the smallest division of radiated energy. Thus, it is impossible to have half a photon, and radiated energy must always equal some whole number of photons times the energy of a photon. But you can readily see from the previous equation that all photons will not carry the same minimum unit of energy.

With Planck's simple formula, we can compute the energy per photon of any color. For the frequency, ν, we can use its equivalent, $\nu = c/\lambda$, where c is the velocity of light and λ is its wavelength. Consider, for example, the photon energy for 6000Å in the red:

$$E = h\nu = h \times c/\lambda = \frac{6.62 \times 10^{-27} \times 3 \times 10^{10}}{6000 \times 10^{-8}}$$

$$= 3.31 \times 10^{-12} \text{ erg}$$

Because we will be dealing soon with electrons absorbing photons, it will be helpful to change ergs to electron-volts. This rather descriptive unit is the energy gained, or lost, by an electron moving through
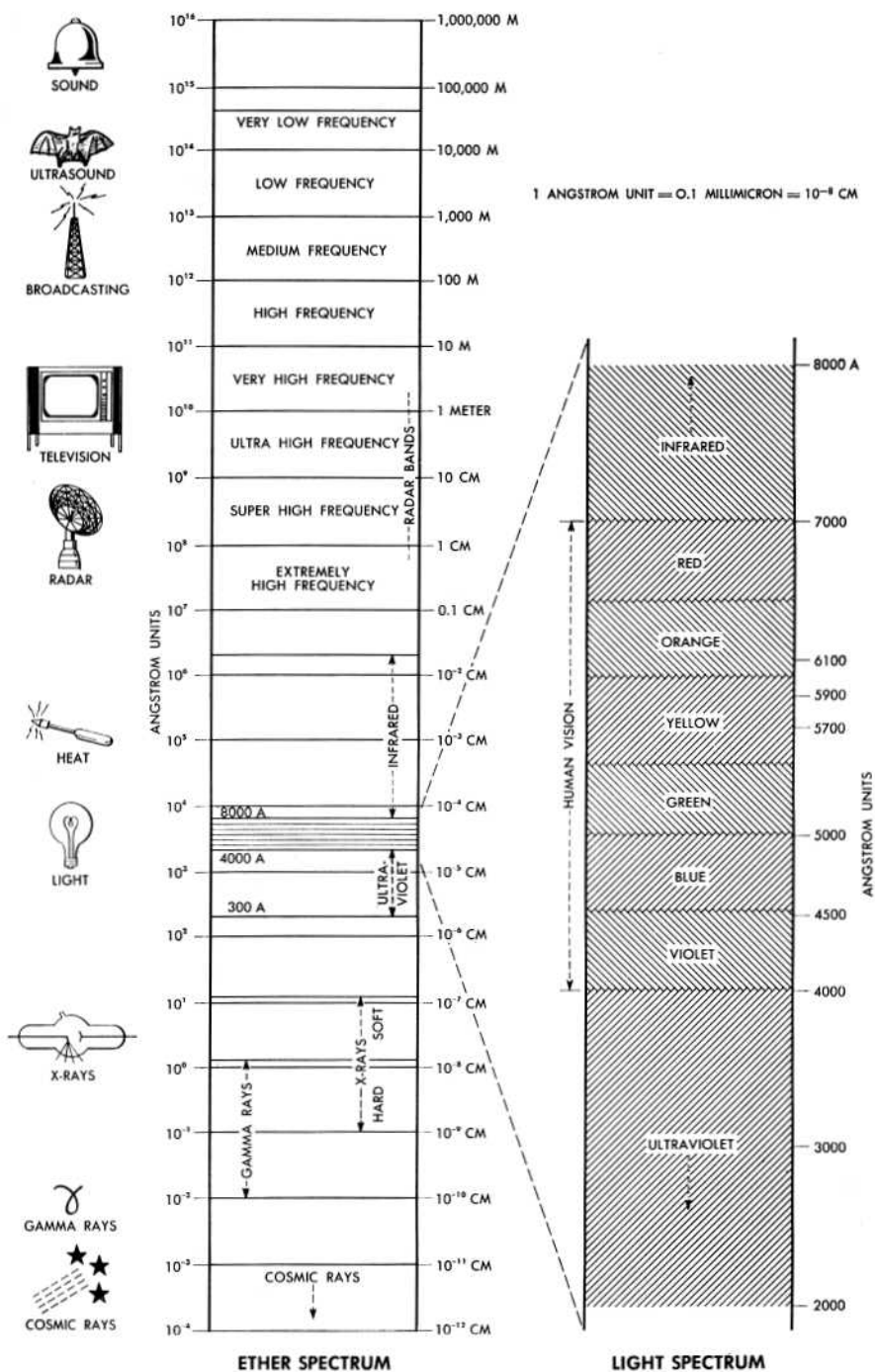
Figure 3-3. *Electromagnetic spectrum.* (Based on information from ELEC-
TRONICS, a McGraw-Hill publication.)

a potential difference of 1 volt. Since an electron equals 1.59×10^{-19} coulomb, an electron-volt equals 1.59×10^{-19} joule (coulomb-volt), or 1.59×10^{-12} erg. It follows that 1 photon at 6000Å possesses

$$\frac{3.31 \times 10^{-12}}{1.59 \times 10^{-12}} = 2.08 \text{ electron-volts}$$

Similarly, the ultraviolet radiation at 3000Å is composed of photons of energy 4.16 electron-volts while 12000Å in the infrared possesses 1.04 electron-volts per photon. Figure 3-4 is a plot of photon energy in electron-volts as a function of wavelength. It is suggested that the student compute a few points and check them against the curve.
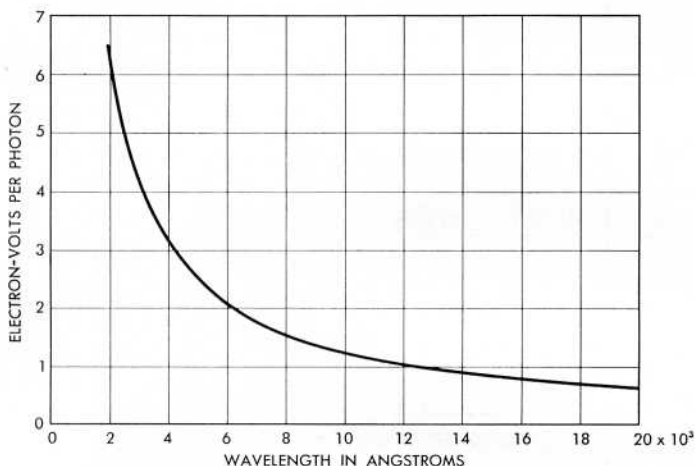
Figure 3-4. *Photon energy versus wavelength.*

We are now in a position to replot the solar spectrum of Figure 3-2 in terms of the number of photons at the various wavelengths. This is done by dividing the energy observed at each wavelength by the energy per photon to get the relative density of photons. Figure 3-5 is this plot. It shows that the greatest concentration of photons is at about 6100Å.

Once we think of radiation as a flow of energy units (photons), we can look for some mechanism that will absorb each photon as energy given to an electron in such a manner that the energy can be recovered as useful electrical energy. We need each electron in absorbing radiant energy to be raised to a higher electrical potential so that later we can

Figure 3-5. *Photon distribution in the solar spectrum.*

make it do work in falling back to its former position. And this is where semiconductors enter the picture. To understand their operation, we must look at the properties of some special semiconductors.

4 Some Properties of Semiconductors

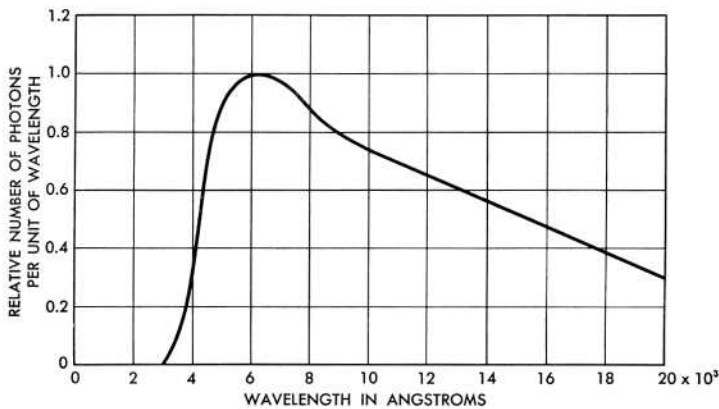Semiconductors are closely related to true insulators. If we were to consider only their conductivities, semiconductors could have been called semi-insulators. However, it is not their conductivities alone that distinguish them, but the mechanism of electrical conduction and the way the conductivity responds to changes in temperature. Very briefly, true conductors become less conductive as the temperature rises; semiconductors become more conductive following a characteristic pattern; true insulators become abruptly conducting at a critical temperature. Most of the semiconductors have conductivities about halfway between true conductors and true insulators if the values are plotted on a logarithmic scale. They have about a million times the resistivity of conductors such as copper and from a million to a million million times the conductivity of good insulators. It is not surprising that they were once considered worthless electrically because they neither were nor were not conductors. Now their properties are recognized as basic to rectifiers, thermistors, transistors and solar cells. Some of the known semiconductors are listed below.

SOME OF THE KNOWN SEMICONDUCTORS

Compounds	Elements
oxides—Cu_2O	carbon (diamond)
sulfides—ZnS	silicon
selenides—$ZnSe$	germanium
tellurides—$PbTe$	tin (gray)
nitrides—BN	boron
phosphides—GaP	selenium
arsenides—$InAs$	tellurium
antimonides—$AlSb$	

Perhaps you have seen copper oxide rectifiers that were extensively used a few decades ago. Selenium rectifiers have been widely used for some time. Selenium is used in self-acting photocells called sun batteries now on the market. Recently, germanium and silicon have rocketed into wide use as diodes and transistors. Take a look in any radio catalog to see the diversity of semiconductor devices now commercially available.

Silicon

The material best suited to our study of solar cells is silicon. Most of what we say about it applies also to the other semiconductors.

The element silicon is in the fourth column (IVa) of the Periodic Table, Figure 4-1. Its nucleus has a net plus charge of four and therefore the atom has four valence electrons in its outer shell, Figure 4-2. The atoms of silicon crystallize into a crystal of the diamond configuration as shown in Figure 4-3. This three-dimensional picture has been redrawn in Figure 4-4 to show a schematic two-dimensional configuration which is easier to visualize in the discussion that follows.

Each atom in the silicon crystal shares its four valence electrons with its four nearest neighbors. In turn, each atom shares ownership of an electron from each of its four nearest neighbors. The pair of electrons mutually shared by two atoms form what is known as a *bond-pair*. Atoms which share their electrons and form bond-pairs hold on to their electrons tenaciously. Since this sharing does not affect the number of positive and negative charges, the crystal remains electrically neutral.

Before the crystal can conduct electricity, some electrons must be torn from their bond-pairs to become *free electrons*. Occasionally, thermal agitations, even at low temperatures, will give an electron enough energy to escape the bond-pair. As the temperature rises, more and more electrons, by favorable thermal collisions with their neighbors, will receive enough energy to escape. But for pure silicon at room temperature, very few electrons are freed by thermal agitation.

It has been determined that 1.08 electron-volts (1.72×10^{-19} joule) of energy must be expended at room temperature to pull an electron loose from its bond-pair in a silicon crystal. This is the amount of energy that an electron acquires moving through a potential difference of 1.08 volts.

If and when an electron escapes from its bond-pair, it is free to move about in the crystal. If an electric field is applied, the electron can move and thereby conduct electricity. Or it can fall back into the

Ia	IIa	IIIb	IVb	Vb	VIb	VIIb	VIII			Ib	IIb	IIIa	IVa	Va	VIa	VIIa	0
1 H 1.008																1 H 1.008	2 He 4.003
3 Li 6.940	4 Be 9.013											5 B 10.82	6 C 12.001	7 N 14.008	8 O 16.000	9 F 19.00	10 Ne 20.183
11 Na 22.991	12 Mg 24.32											13 Al 26.98	14 Si 28.09	15 P 30.975	16 S 32.06	17 Cl 35.457	18 Ar 39.944
19 K 39.100	20 Ca 40.08	21 Sc 44.96	22 Ti 47.90	23 V 50.95	24 Cr 52.01	25 Mn 54.95	26 Fe 55.85	27 Co 58.94	28 Ni 58.71	29 Cu 63.54	30 Zn 65.38	31 Ga 69.72	32 Ge 72.60	33 As 74.91	34 Se 78.96	35 Br 79.916	36 Kr 83.80
37 Rb 85.48	38 Sr 87.63	39 Y 88.92	40 Zr 91.22	41 Nb 92.91	42 Mo 95.95	43 Tc (99)*	44 Ru 101.1	45 Rh 102.91	46 Pd 106.4	47 Ag 107.88	48 Cd 112.41	49 In 114.82	50 Sn 118.70	51 Sb 121.76	52 Te 127.61	53 I 126.91	54 Xe 131.30
55 Cs 132.91	56 Ba 137.36	57 La 138.92	72 Hf 178.50	73 Ta 180.95	74 W 183.86	75 Re 186.22	76 Os 190.2	77 Ir 192.2	78 Pt 195.09	79 Au 197.0	80 Hg 200.61	81 Tl 204.39	82 Pb 207.21	83 Bi 209.00	84 Po 210	85 At (210)*	86 Rn 222
87 Fr (223)*	88 Ra 226.05	89 Ac 227.0															

LANTHANUM SERIES

58 Ce 140.13	59 Pr 140.92	60 Nd 144.27	61 Pm (147)*	62 Sm 150.35	63 Eu 152.0	64 Gd 157.26	65 Tb 158.93	66 Dy 162.51	67 Ho 164.94	68 Er 167.27	69 Tm 168.94	70 Yb 173.04	71 Lu 174.99

ACTINIUM SERIES

90 Th 232.05	91 Pa 231	92 U 238.07	93 Np (237)*	94 Pu (242)*	95 Am (243)*	96 Cm (247)*	97 Bk (249)*	98 Cf (251)*	99 Es (254)*	100 Fm (253)*	101 Md (256)*	102 No (253)*

*MASS NUMBER OF MOST STABLE KNOWN ISOTOPE
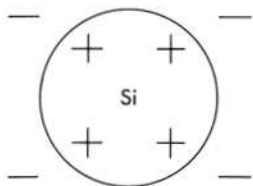
Figure 4-1. *Periodic Table.*

Figure 4-2. *The silicon (Si) atom has four valence electrons (shown by minus signs) in its outer shell, and four plus charges (plus signs) in its nucleus.*

hole it left in the bond-pair, or into another convenient *hole* left by another freed electron, and be captured again. In fact, this recapture is what prevents a gradual accumulation of free electrons due to thermal action. The concept of recapture (recombination) is basic to the understanding of semiconductor devices.
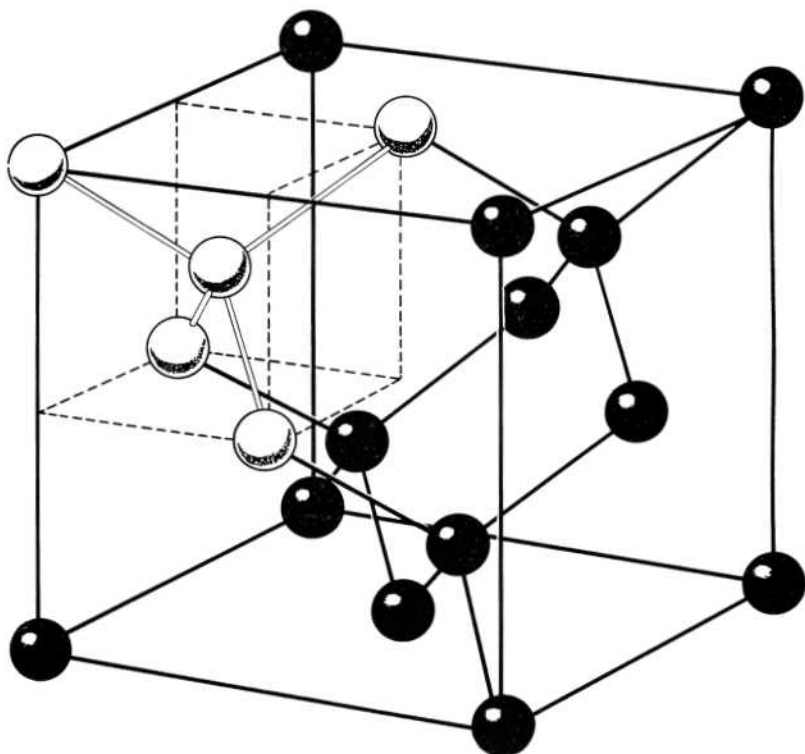

Figure 4-3. *Three-dimensional drawing of the crystal structure of silicon.*

But suppose the free electron drifts away from its former position. That region, once electrically neutral, now has a net plus charge. Can this plus charge move and add to the conductivity? Actually no, but effectively yes, and this concept is also basic in understanding semi-conductors. Although it takes 1.08 electron-volts of energy to free an electron, it is quite easy for an electron to move from one bound position to another one that happens to be vacant. Under the influence of an electric field, this shifting of electrons from adjacent atoms causes the vacancy to move in a direction opposite to the flow of free electrons. The vacancy is termed a *hole* and this type of conduction is referred to as *conduction by holes*. The holes, in this case, are *carriers* of electrical charge.

An analogy may help you to understand this *conduction by holes* more clearly. Consider a class where everyone is seated and every chair is taken. Let one person leave his seat and wander about. An empty chair remains. Without the effort of rising, the person next to that empty chair may slide over and change seats. Then the next person may move into the newly vacated chair and so on until the empty chair appears far from the first chair vacated. All of the chairs may be bolted to the floor and yet an empty chair has "moved" from the front of the class to the back, or vice versa. To complete the analogy, the person who originally got up (energy expended rising) may flop down on the chair vacant at the moment. There are now no persons walking around and no moving seats. The "crystal" is again stable and nonconducting.

Photons Release Electrons

We haven't said much about what could supply the energy to remove an electron except thermal energy which produces very few electron-hole pairs.* Remember, it requires an expenditure of 1.08 electron-volts of energy to free an electron in silicon. You probably suspect by now that we will be most interested in photons having enough energy to release electrons in silicon. Consider what happens when solar radiation strikes a pure silicon crystal. Look again at Figures 3-4 and 3-5. What part of the spectrum would you expect to be able to free electrons? Certainly not that part on the long-wave side of 12000Å because the photons are too weak. These photons pass right through and silicon is transparent in this region. Two or more photons together would have enough energy, but they just do not

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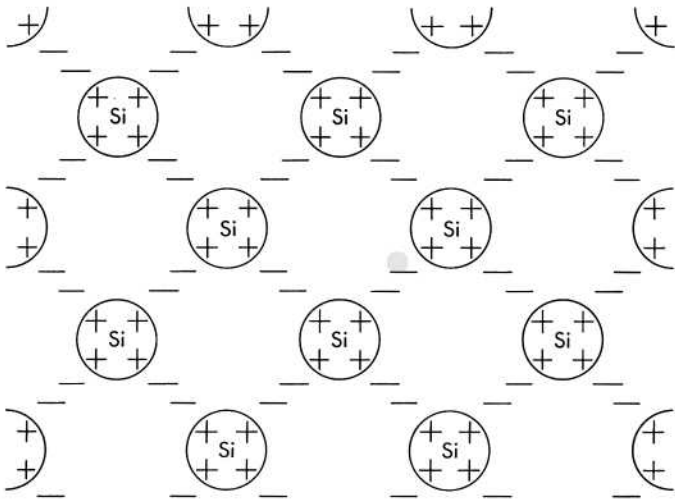* Since the release of an electron also produces a hole, the two charges are commonly called an electron-hole pair.

Figure 4-4. *Two-dimensional drawing of the silicon crystal.*

team up in this manner. On the short-wave side of 12000Å, each photon does have enough energy and it does free an electron. This is the mechanism of *radiation absorption* in silicon. Each electron so freed, Figure 4-5, possesses 1.08 electron-volts of electrical energy relative to its bound position.
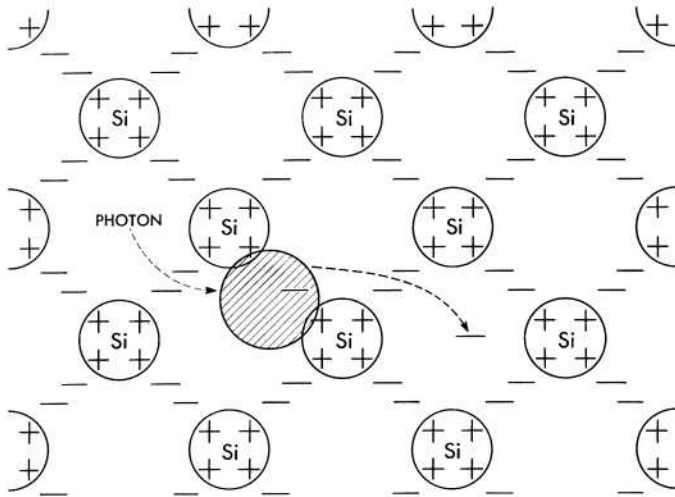

Figure 4-5. *A photon frees an electron in silicon.*

This is the first step. A mechanism has been found that will absorb radiant energy in an electrical form. We need now to find a means of directing this electrical energy into useful channels.

An analogy may help you to see the problem that must be solved in order to utilize the electrical energy. Imagine a man at the bottom of a dry well with plenty of stones at hand. He throws these stones to the top of the well. The stones now have energy relative to their former positions. But the stones fall back into the well beside the man and give up their energy as heat. What a waste! However, suppose we arrange a bucket chain, Figure 4-6, that catches each stone at the top and makes it do work on its way to the bottom of the well. At least part of the stone's potential energy can now be recovered as useful mechanical work done by the bucket chain. Restating our electrical problem, we must find a "bucket chain" to make our free electrons give up part of their 1.08 electron-volts in an external circuit. What follows will lead to the solution of the problem.
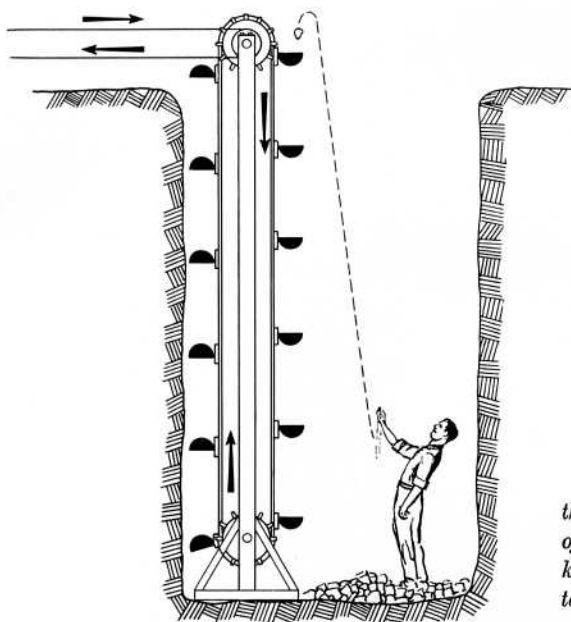

Figure 4-6. *Stones thrown from the bottom of the well turn the bucket chain as they return to the bottom of the well.*

Arsenic in Silicon

Up to this point, we have talked of pure silicon and its properties. We now take up the effect of minute quantities of impurities (dopants).

In the silicon crystal, let about one in every million silicon atoms be replaced by an arsenic* atom. Arsenic is in the fifth column of the Periodic Table. Its nucleus has five plus charges and its outer shell has five valence electrons, Figure 4-7.

Figure 4-7. *An arsenic (As) atom has five valence electrons in its outer shell, and five plus charges in its nucleus.*
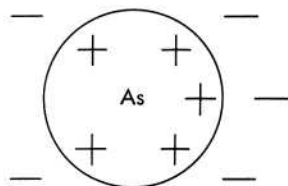
Four of the electrons fit nicely into the silicon crystal, but what of the fifth? It has no fixed position and is held very weakly by the electrical charge of the nucleus. It is easily moved by an electric field and always stands ready to move about, Figure 4-8. It is not in

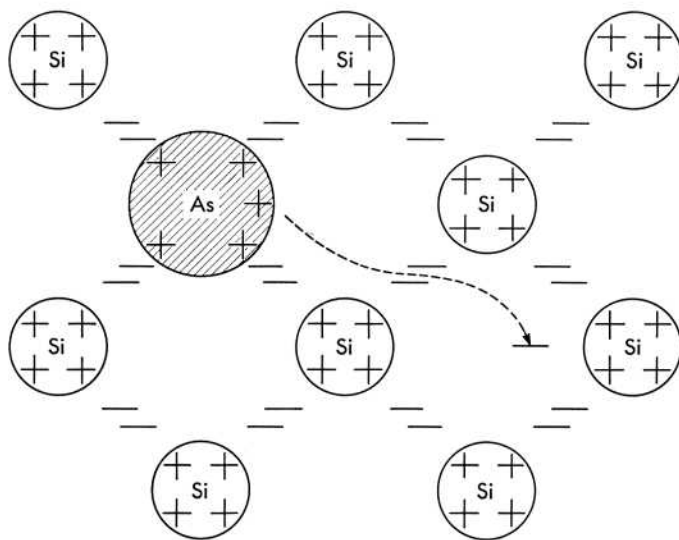Figure 4-8. *An arsenic atom's unshared electron is free to move about in the silicon crystal.*

much danger of being captured by a hole because its separation from the parent nucleus did not generate a hole. Of course, it may fall into a hole left by a thermally agitated electron, but then the replaced free electron is left without a corresponding hole.

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* Phosphorous or antimony may also be used.

Due to the addition, or "doping", of the silicon with arsenic, something else has happened besides the creation of a large number of conducting electrons. By their very number, now much greater than those generated by thermal energy, the free electrons eliminate the few holes that appear by thermal action in pure silicon. The Mass Action Law says that for a given temperature the product of free electrons and holes is constant: $n \times p = $ constant $ = 10^{20}$ at room temperature, where n is the number of free electrons per cubic centimeter, and p is the number of holes per cubic centimeter. If enough free electrons are introduced by arsenic atoms, the holes are almost completely eliminated (become "minority" carriers) and conduction is almost entirely by electrons. Such a material is called *n-type* for the *negative* (majority) carriers.

The addition of arsenic produces another difference in the behavior of pure silicon crystals. Whereas, in pure silicon, the removal of an electron left a positive charge free to move, the positive charge remaining when the fifth arsenic electron leaves is *not* mobile because it is part of the nucleus. Thus, there is a net plus charge but no "place" for an adjacent electron to move into; that is, no unsatisfied bond-pairs. This immobile charge is referred to as a bound plus charge as distinguished from a *hole*.

To sum up, the effect of a few arsenic atoms in silicon is threefold:
1. Electrons are freed to conduct current without the addition of 1.08 electron-volts of energy.
2. Even the few holes normally produced by thermal action are nearly eliminated.
3. Fixed positive charges are bound to the crystal at the arsenic atoms.

Boron in Silicon

Now we turn to another type of dopant, boron. Boron is in the third column of the Periodic Table. Its nucleus has three positive charges matched by three valence electrons, Figure 4-9. When a boron atom is substituted for a silicon atom, one bond-pair is left incomplete, Figure 4-10. The vacancy in the bond-pair is a true hole, and an elec-
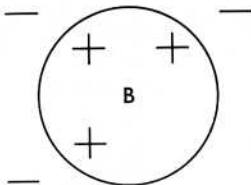
Figure 4-9. *A boron (B) atom has three valence electrons in its outer shell, and three plus charges in its nucleus.*
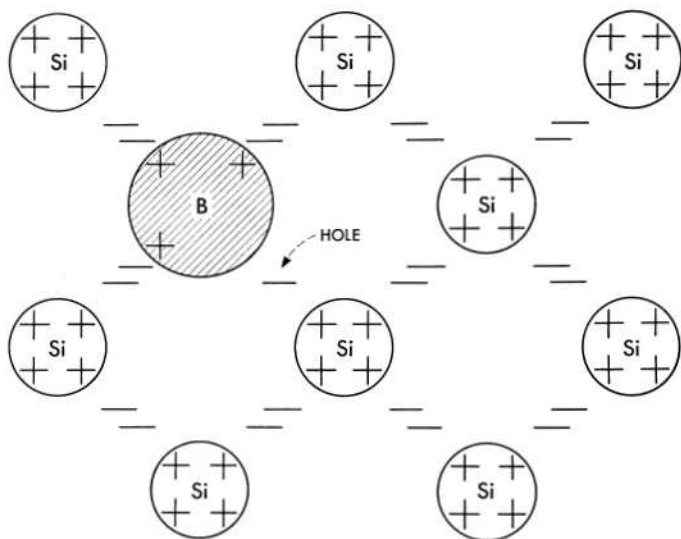
Figure 4-10. *Boron atom leaves unsatisfied bond-pair in silicon crystal.*

tron from a neighboring atom can move in, causing the hole to move and be available to conduct electricity, Figure 4-11. The holes so formed in boron-doped silicon are in very little danger of being filled (neutralized and eliminated) by free electrons because no free electrons are formed by this process. In fact, paralleling the previous argument, even the few electrons normally set free by thermal agitation get swallowed up by the overwhelming number of holes formed by only a trace of boron. In this crystal, the electrons become the *minority* carriers and practically disappear while the *holes remain in the majority.*

Because of their nature, boron atoms complete their bond-pairs. At the boron atom there is, then, an excess negative charge of one electron since the four valence electrons are balanced by only three positive nuclear charges. The excess negative charge in the boron-silicon bond-pair is firmly held and not free to move. Thus we have fixed negative charges and, as has been stated, movable plus charges or holes. Boron-doped silicon is termed *p-type* due to the majority of positive carriers (holes).

To sum up the effects of boron atoms in silicon, we have:

1. Positive charges free to move and conduct electricity.
2. The practical disappearance of free negative charges.
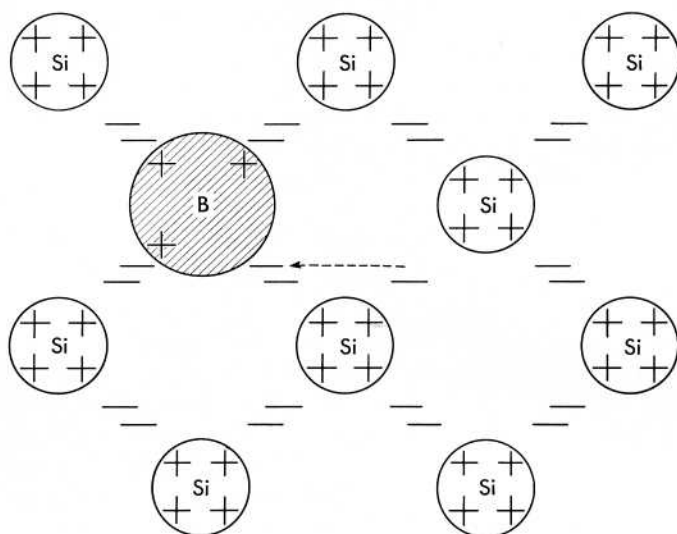3. Fixed negative charges.

Figure 4-11. *Movement of hole in boron-doped silicon.*

The p-n Junction

The next step is to combine n-type with p-type silicon in the same crystal. Leave until later how this is done in practice, and refer to Figure 4-12(a). The line of demarcation between p-type and the n-type silicon is termed a p-n barrier or *p-n junction*. As pointed out before, the electrons moving freely in the n-type section are in very little danger of being captured by holes because they were freed without the formation of holes. The holes in the p-type material enjoy mobility and the same freedom from capture because they were formed without the simultaneous formation of free electrons. But at the border or junction between the two types, diffusion takes place and true mobile electrons meet genuine mobile holes. They join and mutually disappear. But the bound plus charges in the n-type material and bound negative charges in the p-type material are still present. These rows of bound charges on either side of the barrier produce a built-in electric field. In fact, the strength of this field increases with each hole or electron that diffuses over the boundary until the field is strong enough to prevent further diffusion. Or more accurately, the field strengthens until the diffusion that causes it is exactly counterbalanced by the pulling back across the barrier of the same number of carriers. But between these opposing flows, an important difference exists which is vital to solar cell operation. The *reverse* flow is made up of minority carriers in each case and these have been shown

to exist in very small measures. There are, for example, plenty of electrons to diffuse from the n-type side to the p-type side. But in the p-type material very few free electrons can exist to be drawn back by the field to the n-type side. They would go back in quantity if any quantity existed, but it doesn't. And so, in the dark (no photons), diffusion of those carriers that are present causes a net *loss* of electrons in the n-type silicon and a net *gain* of electrons in the p-type material. In equilibrium, the p-type silicon has become negatively charged with respect to the n-type silicon.

At this point, you might think that we have discovered perpetual motion and that all we need to do is attach leads to the two regions and enjoy a continual flow of current. However, this will not work — nature leaves no such loopholes. Similar diffusions also establish potential differences at the places where the lead wires make contact so that the net emf (voltage) around the circuit is zero and no current flows. Can you explain from what has been said why this is so?

How can we get current to flow? If we disregard the lead contacts and let them have their potential differences, maybe we can do something at the p-n junction to lower the potential difference there. If so, a net driving emf will result in the circuit. Before going on, study carefully the diagram of Figure 4-12(a) and (b).
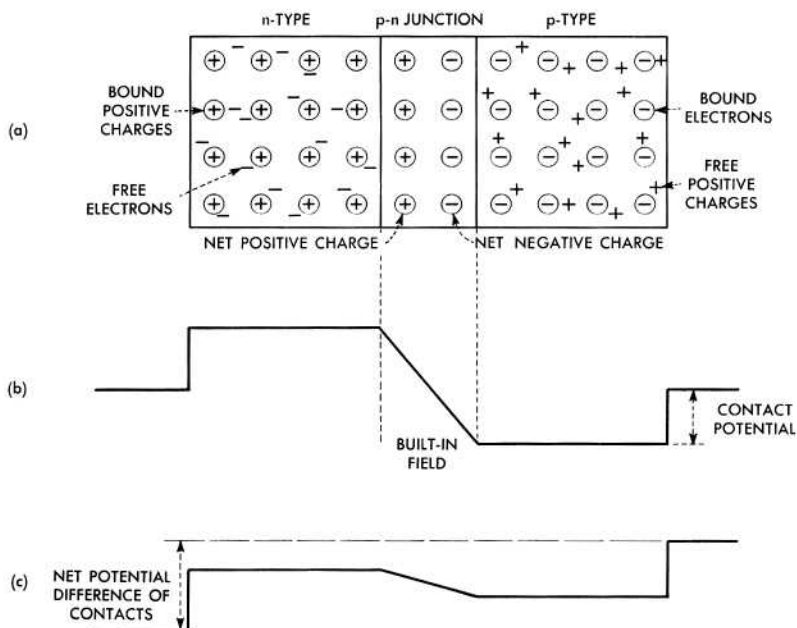

Figure 4-12. *Effect of carriers supplied at p-n junction by photons.*

We said that the reason the built-in potential difference builds up at the p-n barrier is because there are very few carriers of the proper sign on either side which are free to move back over the barrier. Suppose we generate additional carriers in the p-n barrier by absorbing light photons of sufficient energy, that is, greater than 1.08 electron-volts. Immediately, free electrons are available to return to the n-type side and lower its potential; free holes are available to return to the p-type part and raise its potential. The result is shown on the diagram of Figure 4-12(c). The lead connections have not changed in potential so now we have a net useful potential difference. If the lead wires are connected to a load, external work will be done in the circuit as long as photons are absorbed at the barrier region.

This is basically what happens in a solar cell. Of course, the shape of the cell we have postulated is physically wrong to get light into the barrier, but the proper form will be described later. Right now, do you see that this p-n junction is essentially the bucket chain we were looking for? The photons do the work of "throwing" electrons out of their bond-pairs, and the diffusion field, set up at the junction, provides the condition that requires the electrons to do work in getting back to their bond-pairs in the crystal.

Rectifiers

Let us range afield just a bit and show that we have also explained semiconductor diodes (rectifiers).

Suppose, with the barrier in the dark, that is, without photon excitation, an external battery is connected to the leads in an effort to pass current from the n- to the p-type material. That would make the n-type side still more positive and would try to draw electrons to the n-type side and holes to the p-type side. We have already shown that there are extremely few carriers of the proper sign in either section to provide this conduction across the junction. The diode therefore blocks the current. But reverse the polarity. In this direction, there are plenty of electrons in the n-type side to travel across the junction, and plenty of holes in the p-type side to do the same. Current from p- to n-type is in the forward direction and conduction is easy. That is, it is easy after the first few tenths of a volt. Before that the reverse field restricts the flow as pointed out earlier. This forward diode characteristic is an important fact in solar cell operation and will show up later when we study cell characteristics.

5 *A Useful Configuration*

The configuration shown in Figure 4-12 helps to explain the opera-
tion of a p-n barrier when exposed to photons. However, its
physical form is not suitable for a workable solar cell. As it stands,
light can reach the barrier only along a very thin line where the p-n
junction appears at the surface.

If any appreciable quantity of radiation is to reach the p-n barrier,
a different form is required. Instead of an extremely narrow line, a
large sensitive area is needed. If, for example, either the p-type or
n-type sections shown in Figure 4-12 could be reduced sufficiently in
thickness, light could pass right through them to the barrier at all
points and not exclusively at the edges. Note that I said "reduced
sufficiently in thickness." If you hold the silicon wafer contained in
the Solar Energy Experiment kit up to the light, you may easily con-
clude that *no* light comes through. That merely points up the diffi-
culty of getting a thin enough layer of p-type silicon over n-type sili-
con, or vice versa. The thickness we need is 1/10000 of an inch or less.
Suppose you tried to grind silicon down to that thickness starting
from a composite casting. I will not say that it is impossible, but cer-
tainly this approach does not look promising. How then can we get a
very thin surface layer of p-type silicon over an n-type substrate
(under layer) without damaging the barrier?

Doping by Diffusion

The work of diffusion of impurities (doping) into semiconductors by
Dr. C. S. Fuller of Bell Telephone Laboratories led to the solution of
the problem of how to form a thin surface layer. Of course, many of
the facts of diffusion had been known for a long time, but Dr. Fuller

applied the techniques specifically to semiconductors and opened up many new possibilities in the formation of diodes, transistors, solar cells and other devices.

No doubt, you are familiar with the rapid mixing of gases by diffusion. For example, an evaporating aromatic oil can soon be detected at a distance, even if the surrounding air is very still. You probably know that this comes about from the thermal, random motions of the molecules of the gases and vapors. You may have observed the gradual mixing of liquids without stirring. Try, for example, putting a few grains of copper sulfate into a beaker of water. Although the solution first formed at the bottom of the container is more dense than the water above, mixing will be complete by diffusion if you wait long enough.

The above may be commonplace, but did you realize that metals and other materials ordinarily considered completely impervious to almost everything will also mix at the interface under proper conditions hundreds of degrees below their melting points? Here, we are particularly interested in the mixing by diffusion of boron with silicon. Under the proper conditions, boron works its way through the surface and takes up a position in the crystal lattice, displacing the silicon atoms. The result at such a lattice position is just the same as if the crystal had been grown from the melt with the boron atom taking the place of a silicon atom.

As you might readily expect, an important factor controlling the rate of diffusion is temperature. Even at an elevated temperature (say 1000°C which gives silicon a bright glow), the rate of penetration by diffusion is quite slow. This is just what is needed to control precisely the depth of penetration of a very thin layer. Dr. Fuller's data of *depth of penetration as a function of time and temperature* are shown in the family of curves in Figure 5-1. From these curves, we can select a temperature that we can reach with simple equipment and a corresponding time for the depth of penetration we need.

The depth plotted is not actually the greatest penetration depth but rather the depth for *compensation* to occur.

Compensation

By *compensation*, I mean the equalizing effect of opposite dopants — n-type and p-type — added either simultaneously or one after the other. If the two are exactly equal in the crystal in their effect on conductivity, compensation has taken place. Equality of effect can take place because of the nature of the dopants.
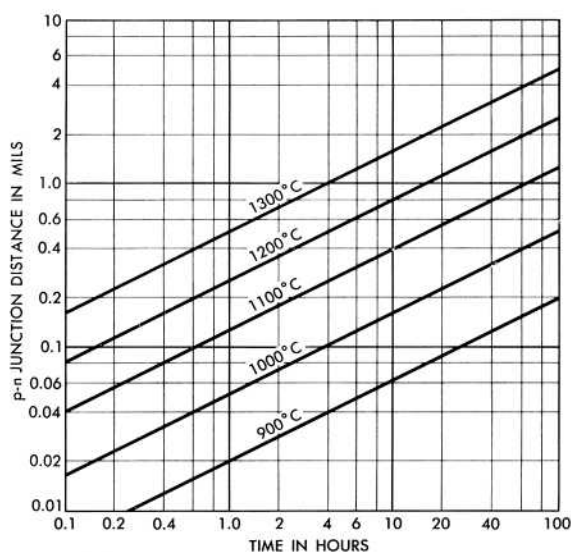
Figure 5-1. *Diffusion curves for boron into silicon.*

N-type dopants are known as *donors*, that is, they donate free electrons to the crystal, as previously discussed. P-type dopants are *acceptors*, accepting and binding free electrons, as also discussed. You can thus see that if just enough p-type dopant is added to accept all the free electrons provided by an n-type dopant, the effect on conductivity is the same, in essence, as if neither dopant were present.

Let us look at compensation in terms of a silicon crystal and dopants of boron and arsenic. We start, for example with n-type silicon; it is n-type because the donor arsenic was added in minute quantities before the crystal was grown. The surface of this material can be changed to p-type silicon by the addition of boron, an acceptor, which will diffuse through the surface at an elevated temperature. This requires that sufficient boron (acceptor) be diffused into the surface to overcompensate the arsenic (donor) still present. Since the diffusion of boron into the silicon will decrease with the depth of penetration, we should find a plane below the surface where the acceptor boron just compensates the arsenic donor. Here the effect on the conductivity is as though neither dopant were present, and the silicon will, for this limited purpose, act as if it were intrinsic (pure). This plane is at the "p-n junction distance," shown in Figure 5-1. Below the compensated layer, the arsenic dopant of the grown crystal will predominate. Thus we have formed a p-type layer on an n-type crystal,

the two being separated by a thin compensated layer. In this way we have a workable and controllable method of producing the structure of Figure 5-2.
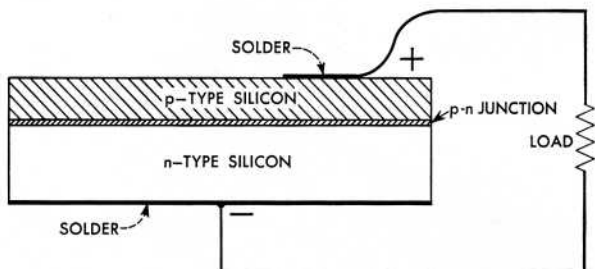

Figure 5-2. *Cross section of a workable solar cell.* (*The diffusion depth shown is greatly enlarged.*)

To complete a solar cell, we must of course make contact to the p-type surface layer and the n-type substrate. It is easy to see that the resultant cell is electrically the same as the drawing of Figure 4-12. Only now it is practical to flood a *large* area of the junction with photons. As might be expected, a new problem of resistance has been raised. Since most of the active surface must be left unobstructed, the collected current has to travel some distance in an extremely thin surface layer having high resistance. If we try to reduce the resistance by making this layer thick, we are right back to the situation of Figure 4-12. In practice, the thickness is selected to maximize photon collection at the barrier. Resistance is held down by the geometrical shape of the cell. This explains in part why most solar cells are small and frequently long and narrow. Of course, a fine grid of conducting material can be laid down over the surface of a wide cell to reduce the resistance without greatly obstructing the sensitive surface. Modifications of these techniques have been used since the earliest days of solar cells.

6 Instructions for Making a Solar Cell

Now that I have explained the principle of the solar cell, let us proceed to make our own. The techniques related here are close to those used early in the development of solar cells, but the principles still apply even though methods more susceptible to mass production have been found.

The Raw Material

Next to oxygen, silicon is the most abundant element on the earth. It makes up a large part of most rocks; some sands are largely silica (SiO_2). Crude silicon sells for about \$0.07† per pound and is obtained by heating silica in the presence of coal, producing carbon dioxide and metallic silicon ($SiO_2 + C \rightarrow CO_2 + Si$). Further purification is by the formation of the tetrachloride ($SiCl_4$) which is purified and broken down in the presence of hydrogen. In the form sufficiently pure for solar cells, silicon costs about \$200† per pound.

Growing Silicon Crystals

From purified silicon, single silicon crystals are grown with the proper impurity content. Figure 6-1 shows a crystal-growing furnace. The purified silicon is placed in a quartz crucible and heated by induction. To the melt is added a small amount of arsenic to produce the proper resistivity type. When the melt is at the right temperature, a small seed crystal of silicon on a quartz rod is lowered to the

† Price based on 1961 estimates.

Figure 6-1. *Crystal-growing furnace.*

surface of the melt. By controlling the temperatures and rate of withdrawal, a long cylindrical single crystal is formed.

It is not absolutely necessary to have the silicon in the form of a single crystal to make a solar cell. However, the best cells have been made from single crystals. This is not surprising when the nature of the p-n barrier to be formed is considered. Crystal boundaries are likely to have impurities, and diffusion of a perfect p-n barrier across a crystalline boundary presents difficulties. The practical solution appears to be the use of single crystals.

Cutting the Crystal

Slabs are cut from the carrot-shaped crystal with a diamond cutting wheel flooded with water, Figure 6-2. The slices need be only thick

enough to give them strength in handling. To conserve material, a thin cutting blade is used. Slices are about 0.025 inch thick.

Your Solar Cell

It would not be practical for you to make and refine your own silicon, nor to grow and cut the crystal. Therefore, this has been done for you; the n-type silicon wafer found in the kit was made according to the process just described. Many techniques for making solar cells are possible, and more is yet to be learned about which
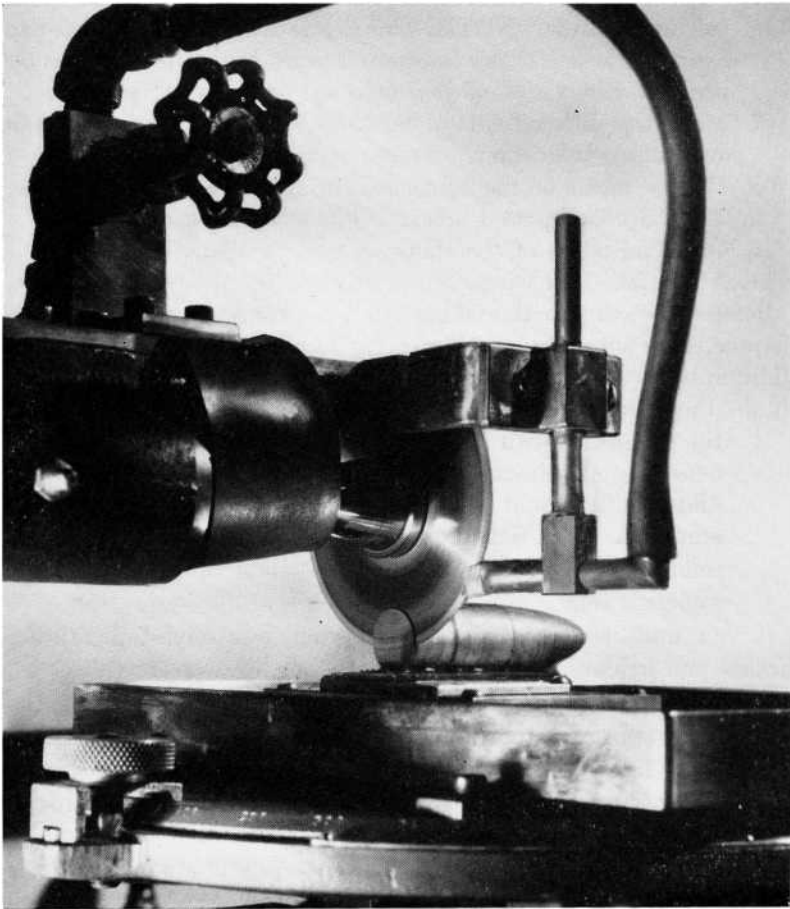

Figure 6-2. *Cutting slabs from a silicon crystal.*

factors are most important. The method, material and apparatus that you will use here have been selected for the greatest simplicity consistent with good results.

Before going into detail, let me very briefly outline the steps you will follow so that you will have an over-all picture of the process.

1. Cleave the silicon wafer found in the kit into six sections.
2. Grind one surface of the silicon to a fine mat finish.
3. Paint a mixture of boric acid* (the p-type dopant), Alundum and water on the ground surface.
4. Diffuse the boron into the silicon by high-temperature heating.
5. Grind the other side of the silicon slab to remove any dopant.
6. Place the cell in dilute sulfuric acid* to which has been added calcium fluoride.* NOTE: *This step is dangerous as sulfuric and hydrofluoric acids* are involved. It must be done only under the personal supervision of your science teacher.*
7. Mask the diffused side of the slab with tape leaving a small strip down the center.
8. Deposit nickel on the unmasked surfaces by electroless plating.
9. Tin the nickel-plated areas.
10. Grind all edges of the slab.
11. Attach the lead wires.

Before proceeding with making a cell, read through the rest of this chapter to be sure you are thoroughly familiar with the process. In addition to the material that is supplied in the kit, you will need to obtain the following things:

1   tin can (coffee-can size) with lid
16 ounces (approximately) of distilled water
    dilute sulfuric acid (small quantity)
    ammonia, 10% * (small quantity)
    cellulose tape
    soldering iron

If you find it necessary to build your own high-temperature furnace you will also need the following:

3   heat-insulating bricks. Try to obtain magnesia bricks (measuring approximately 9″ long by 4½″ wide by 2″ thick) or some other light-weight refractory bricks of the same approximate dimensions that will withstand a temperature of around

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* IMPORTANT! Your attention is directed to page 91 of this book where we have set forth important precautionary information about this chemical, which can be harmful if it is used improperly or is accidentally misused.

1950°F (1066°C). If you cannot find any of these, get the lightest weight firebricks available from a local building supply company. These bricks usually measure about 9″ long by 4½″ wide by 2½″ thick; if possible, get ones that are 2″ thick. Do *not* use regular bricks as these will not furnish enough insulation and may shatter when heated.

1   porcelain rosette socket, 115 volts, 15 amperes
6   feet of insulated heater-type extension wire
1   cap (plug), 115 volts, 15 amperes
2   pieces of wood about 9″ long by 6″ wide by ¾″ thick
2   angle irons approximately 2″ × 2″ × ¾″
8   flat-headed wood screws for angle irons

You will find the following items in the Solar Energy Experiment:

1   glocoil heating element, straight, 660 watts
1   high-temperature paddle
1   glass-jar, 1-ounce, wide mouth
1   plastic dish
1   pair forceps (unassembled)
1   glass plate
3   sheets asbestos, 9″ long by 6″ wide by ¹⁄₁₆″ thick
18 stainless steel cups
9   temperature-indicating pellets
1   vial calcium fluoride*
1   vial boric acid*
1   vial ammonium citrate, 6.5 grams
1   vial sodium hypophosphite,* 1 gram
1   vial nickel chloride, 3 grams
1   vial ammonium chloride, 5 grams
1   vial carborundum, ⋕280
1   vial carborundum, ⋕600
1   vial Alundum
1   wafer n-type silicon
1   strip tape
1   length low-temperature, rosin-core solder
1   length wire, red
1   length wire, black

* IMPORTANT! Your attention is directed to page 91 of this book where we have set forth important precautionary information about this chemical, which can be harmful if it is used improperly or is accidentally misused.

Procedure

Step 1. *BREAKING THE SILICON WAFER*

Take the silicon wafer from the kit and lay it down flat on a piece of wood. Place the point of a straight (common) pin at the center of the wafer and perpendicular to it; tap the pin lightly but firmly with a hammer. The wafer should break into six equal slabs as shown in Figure 6-3(a). If the wafer breaks into two halves, break each half by using the hammer and pin again just to the side of the center of the straight edge of the broken wafer, Figure 6-3(b).
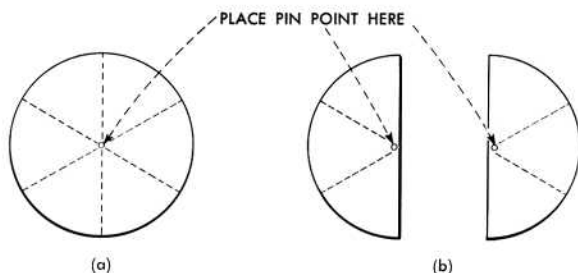

Figure 6-3. *Breaking the silicon wafer.*

Step 2. *GRINDING THE SILICON SLAB*

Remove the piece of flat glass from the kit and place it on a table. Put a small amount of ✻ 280 carborundum in the center of the plate and add a few drops of distilled water. Using light finger pressure, move the silicon slab over the carborundum, Figure 6-4. The grinding is necessary to remove saw marks, scratches and strains, and to form a mat surface for good adherence.

After the visible scratches have been removed and the surface has a mat appearance, use tap water to wash all the ✻ 280 carborundum from the silicon slab and glass. Rinse with distilled water.

Put ✻ 600 carborundum on the plate, add a few drops of distilled water and again grind lightly for a few minutes. This grinding with the finer carborundum will help to remove more of the strains in the slab. After grinding, wash the slab thoroughly with tap water and
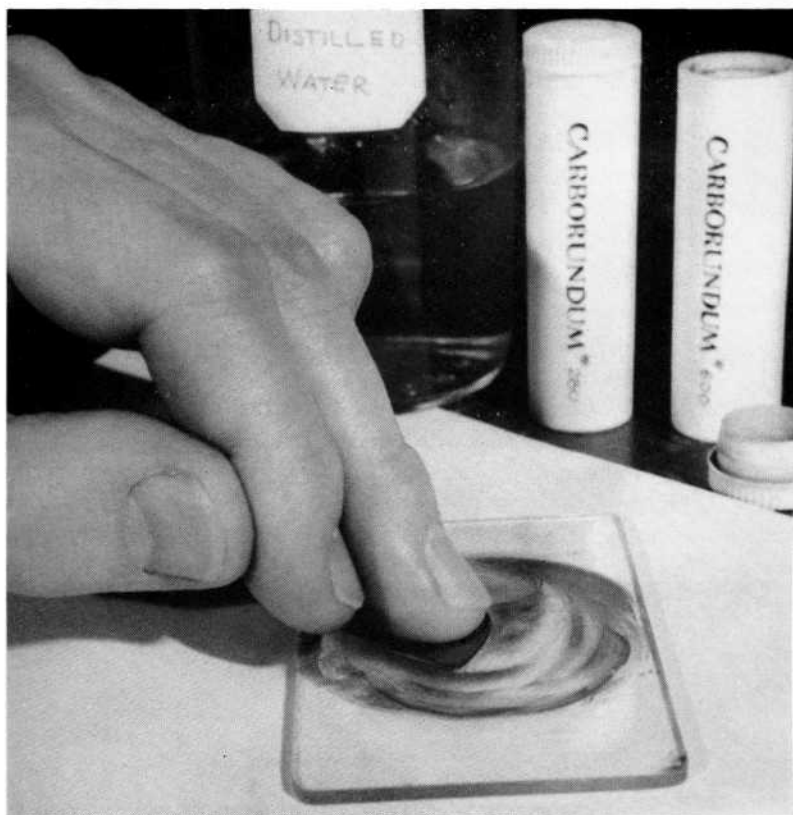
Figure 6-4. *Grinding the silicon slab.*

rinse with distilled water. Only one side of the slab is ground at this time, the other side will be ground later.

Step 3. *PAINTING THE SILICON SLAB WITH p-TYPE DOPANT*

Using the boric acid* and Alundum from the kit, mix 1 part of boric acid with 5 parts of Alundum and make a thin paste from them

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with distilled water. The Alundum is used to dilute the boric acid because it has been found that if boric acid is used alone, excessive strains are set up during heating and cooling which can shatter the slab.

Paint the boric acid-Alundum mixture on the top (the surface you ground) of the silicon slab, Figure 6-5. (A toothpick makes a suitable "paintbrush.") *The mixture must cover the top completely;* it does not matter if some gets on the edges or bottom. Let the mixture thoroughly dry. *Be careful not to remove any of the mixture when handling.*

Step 4. *DIFFUSING BORON INTO THE SILICON*

If you have a small furnace available to you (similar to the type used for ceramic work) that will reach around 1922°F (1050°C), you can use it for heating the silicon slab. If not, you can build your own furnace. Figure 6-6 shows the furnace that I built using 2″-thick magnesia bricks. You can build a furnace like mine by referring to

Figure 6-5. *Painting the silicon slab with boric acid-Alundum-water mixture.*
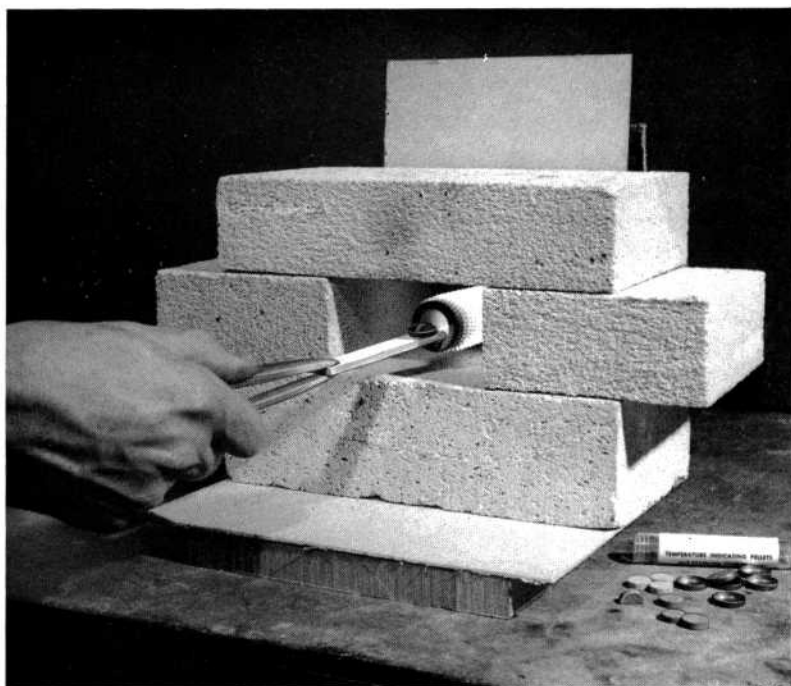
Figure 6-6. *Inserting a temperature-indicating pellet into the center of the glocoil in the furnace.*

Figure 6–7. The materials you will need to build your furnace are described on pages 46 and 47.

After you have built your furnace, you are ready to bring it up to the operating temperature. Start with the center bricks about $2\frac{1}{2}''$ apart.

The temperature-indicating pellets found in the kit will melt when they reach the temperature (°F) that is stamped on one side of them. They are color coded for easy identification:

WHITE:	1850°F (1010°C)
BLACK:	1900°F (1038°C)
GREEN:	1950°F (1066°C)

Break a *white* (1850) temperature-indicating pellet in half and place one half, flat side down, in a stainless steel cup on the high-temperature paddle. Using the forceps† in the kit, practice putting the

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† The wooden forceps supplied in the kit is in three pieces: a "T"-shaped block of wood and two flat sticks. Assemble the forceps by placing a flat stick on each side of the "T" under the top of the "T". Wrap cellulose tape around the block and sticks to hold them firmly together.
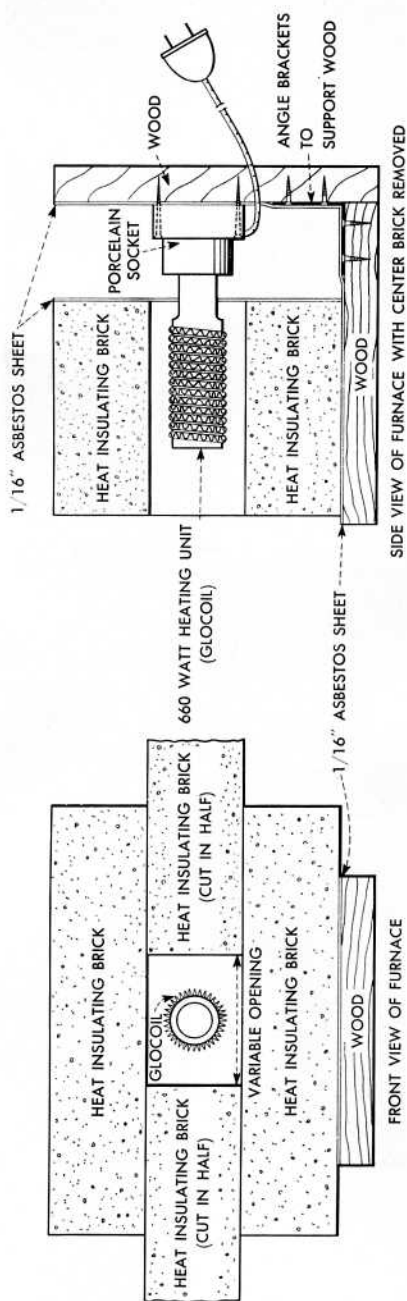
Figure 6-7. *Construction of a high-temperature furnace.*

The three asbestos sheets used in the construction of the furnace are in the kit. Other material you will need is listed on pages 46 and 47.

The two center bricks are made by cutting one brick in half. If the original brick is 9" long, measure in 4½" (the center) on each of the 4 sides; draw a center line all the way around the brick. Using a hard chisel and a hammer, tap lightly following the line around the brick until it breaks in half.

When you mount the socket on the backboard, screw the glocoil into the socket and mount it so that the wire inside the glocoil will be on the bottom. Use a screwdriver to push the wire down snugly against the bottom of the glocoil before plugging it in.

Material to be heated will be put on the high-temperature paddle and inserted into the center of the glocoil.

paddle, with the stainless steel cup and pellet on it, in and out of the furnace (center of the glocoil), Figure 6-6, until you are able to do it easily without knocking the contents off the paddle. *Remember, your furnace is going to be around 1900°F (1038°C), so you must use every precaution to protect yourself from being burned. Also, the heating wire around and running inside of the glocoil is bare so you must be careful not to touch it with anything that will conduct electricity while the glocoil is plugged in. If you do have to reach into the furnace at any time with anything other than the high-temperature paddle, first, pull out the electric plug and allow the furnace to cool.*

After you are confident that you are able to handle the high-temperature paddle and its contents sufficiently well, insert them into the furnace and plug in the glocoil. (Do not allow any of the pellets to touch the sides of the glocoil as this will cause them to melt prematurely.)

When the temperature inside the furnace reaches 1850°F (1010°C), the white temperature-indicating pellet will melt. (Observe the pellet without removing it from the furnace.) If the pellet does not melt after the furnace has been on about 30 to 45 minutes, *gently* move each of the two center firebricks in closer to the glocoil. If the pellet still does not melt after about 15 more minutes have elapsed, move the bricks still closer to the glocoil. *Do not let the bricks touch the glocoil, as this may cause it to burn out.*

After the white pellet melts, remove the paddle from the furnace. Allow the paddle to cool and remove the stainless steel cup from it.

Next, break one of the black (1900) temperature-indicating pellets in half and place one half in a new† cup and put them into the furnace on the paddle as before.

After approximately 15 minutes, the pellet should melt, or it may not melt completely, but may just "round off" at the edges — this indicates that the temperature has been reached. If neither happens, move the center bricks in closer to the glocoil. After the pellet melts or "rounds off", remove it from the furnace.

Place one half of a green (1950) pellet in a new cup and put them into the furnace on the paddle as before. After about 15 minutes have elapsed, this pellet should *not* have melted. If it did, your furnace is too hot, and you should move the center bricks away from the glocoil. If you move the bricks away from the glocoil, use one half of a black

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† Do not use the same cup over again as one material may contaminate the other and cause an error in the melting point.

(1900) pellet again to be sure you did not move the bricks too far away and that your furnace is still above 1900°F (1038°C).

In other words, you may have to jockey back and forth a few times using the 1900°F and the 1950°F pellets and moving the bricks so you end up somewhere *between* these two temperatures. Once you have found the location of the center bricks that will give you the desired temperature, mark their positions with a pencil line so you can relocate them in case they are moved.

When your furnace has been stabilized at approximately 1922°F (1050°C), carefully put the coated silicon slab on the paddle and into the furnace.

After 15 minutes,† remove the paddle and slab and let them cool rapidly in air. Figure 6-8 shows the silicon slab on the paddle after it has been heated and allowed to cool.
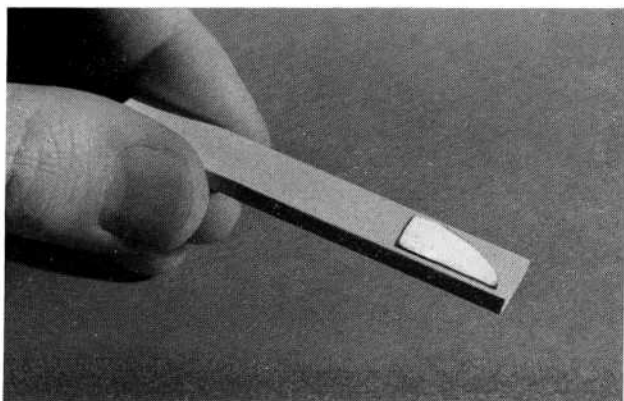

Figure 6-8. *Silicon slab on the high-temperature paddle after diffusion in the furnace and cooling.*

Step 5. *GRINDING BACK OF SLAB*

Put some #280 carborundum on your glass plate and grind the *back* surface of the slab. Note that this is *not* the side you ground before. The top (diffused) surface is not too easily damaged at this point and you may handle it as needed to push the slab around on the glass plate. We do not have to obtain a fine polish on the back surface as no barrier is involved here. We only want to be sure that the original n-type material is exposed again and that the surface will take a nickel plate. After grinding, wash the wafer in tap water and rinse it in distilled water. To help identify the back surface later in the process, put a small scratch on it with a file or other hard tool.

† The diffusion time was determined by referring to Figure 5-1.

Step 6. *ACID BATH*

*CAUTION: THIS STEP IS TO BE DONE ONLY UNDER THE
PERSONAL SUPERVISION OF YOUR SCIENCE
TEACHER.*

You are now ready to remove the excess material from the active surface. In addition to the residue of Alundum, there are other oxides. About the only material that will remove oxides of silicon, yet not attack silicon, is hydrofluoric acid.* *This is a very treacherous acid with lingering and painful physiological effects.*

Weak hydrofluoric acid can be generated by the double reaction of calcium fluoride* and sulfuric acid:*

$$CaF_2 \text{ (in solution)} + H_2 SO_4 \rightleftarrows CaSO_4 + 2HF$$
$$\Updownarrow$$
$$CaF_2 \text{ (solid)}$$
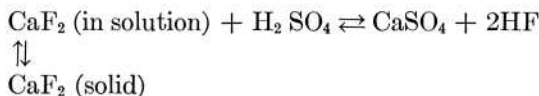
The arrows indicate that this is a reversible reaction and all four compounds will be present with their ions. How then can we be sure that the hydrofluoric acid will be weak? The answer is that calcium fluoride is only slightly soluble in dilute acid. The forward reaction is limited by the limited supply of calcium fluoride in solution, and equilibrium is established at a low concentration of hydrofluoric acid.

What we have said in elementary terms is another example of the Mass Action Law which we discussed earlier. The basic principle is that the rate of any reaction, and therefore, the equilibrium condition, depends on the concentrations of the reacting materials. By limiting the concentration of one of the components (CaF_2), we have effectively insured that the hydrofluoric acid generated will be weak.

Put the slab in the plastic dish and add about ⅛ teaspoonful of calcium fluoride from the kit. Add enough dilute sulfuric acid (one part concentrated sulfuric acid to 10 parts of water) to cover the slab and calcium fluoride. For the first few minutes, agitate the dish now and then to circulate the generated acid. Cover the dish and allow your slab to remain in the acid for several hours.

By then the top crust will usually slip off as a sheet. Sometimes, it crumbles away. The underlying surface may be dark in appearance but may be indistinguishable from the back surface; hence the value of the scratch on the back surface. Using tap water, wash away the

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* IMPORTANT! Your attention is directed to page 91 of this book where we have set forth important precautionary information about this chemical, which can be harmful if it is used improperly or is accidentally misused.

acid,† then rinse the slab carefully with distilled water. *Be careful not to touch the slab with your fingers until after it is plated. Failure to observe this rule will make plating very difficult, if not impossible.* Handle the slab with forceps, a paper towel or soft tissue. Wipe the slab lightly with a paper towel or soft tissue.

Step 7. *MASKING THE SILICON SLAB*

Place the slab on a smooth, clean surface with the top (diffused) side up.

Cut two pieces, each approximately 1″ long, from the tape in the kit. Remove the backing from them and place them, one at a time, on the top of the slab leaving about 1 millimeter of space between them as shown in Figure 6-9. Use a small, flat piece of wood (toothpick) to press the tape firmly against the slab. Be careful not to touch the exposed slab with the wood; do not press down too hard or you may break the slab. However, be sure the tape is bonded firmly to the slab to prevent any liquid from creeping underneath the tape.

Step 8. *ELECTROLESS PLATING*

It would be nice if we could solder leads right to the silicon, but this is not possible. The purpose of the nickel plate is to get a bonded surface to which we *can* solder. The method you will use is comparatively new and is termed "electroless" plating. The name is a contraction of "electrode-less" and it means just that. The process deposits nickel (and other materials) without the use of an electric current.

To save you work and simplify the kit the chemicals needed for plating have been supplied in the proper proportions as follows:

> nickel chloride, 3 grams
> sodium hypophosphite,* 1 gram
> ammonium citrate, 6.5 grams
> ammonium chloride, 5 grams

Dissolve these chemicals in distilled water to make 100 milliliters‡ of solution. Filter the solution.

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† When pouring acid down the drain, flush well with water, being careful not to splash yourself.

* IMPORTANT! Your attention is directed to page 91 of this book where we have set forth important precautionary information about this chemical, which can be harmful if it is used improperly or is accidentally misused.

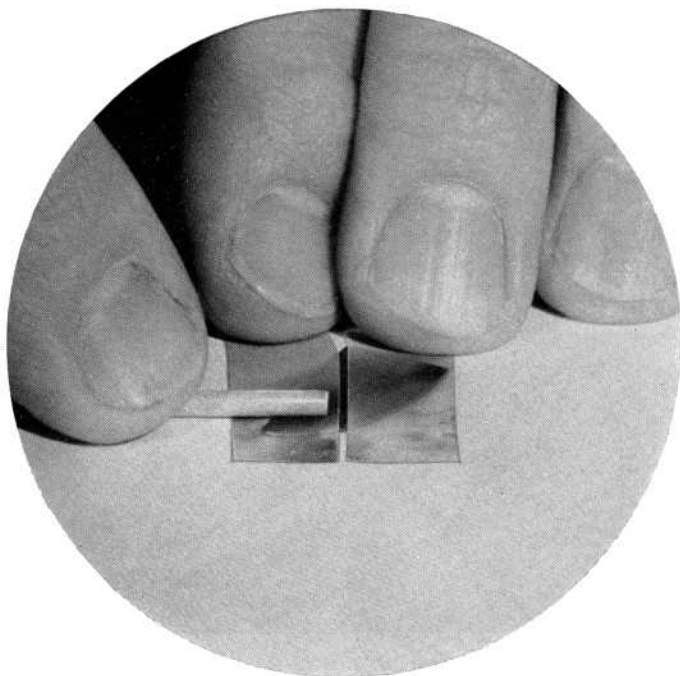‡ 1 fluid ounce equals 29.6 milliliters.

Figure 6-9. *Masking the top of the slab with tape.*

Figure 6–10 shows the set-up for electroless plating. Take the 1-ounce glass jar† from the kit and fill it with plating solution to within about ¾″ from the top. Set the jar in a tin can—an empty coffee can is excellent. Fill the can with water to the same level as the plating solution in the jar. Put the can on a hot plate or over a Bunsen burner and heat until the water boils for about 5 minutes.

Add a few drops of ammonium hydroxide, 10 %, until the solution turns from green to blue (remembering that ammonia* is extremely irritating to the eyes and nose). Weak household ammonia or a solution that has been exposed to the air will only dilute the plating solution and make plating very difficult. Use strong ammonium hydroxide and just enough to get the blue color. An excess can be boiled off.

Put your masked silicon slab into the plating solution. Cover with the glass plate used for grinding to prevent loss of ammonia. The

† Do you know why we cannot use a metal container for plating the slab?

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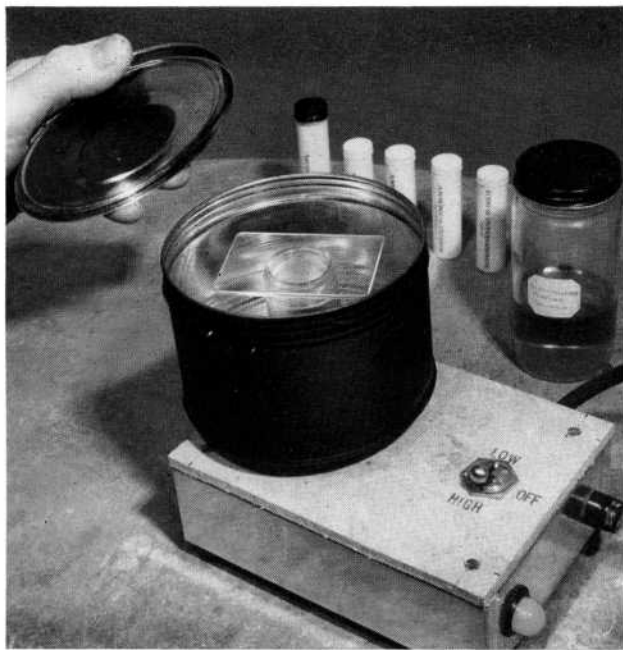
Figure 6-10. *Electroless plating.*

can cover can be placed loosely on top of the can to conserve heat and water. There may be a slight advantage to plating in the dark. Remove the covers occasionally to examine the plating, to correct the bath, or to push the slab back down into the solution. About 20 minutes in the hot bath usually produces a dull-white covering on the exposed surfaces.

Occasionally, the bath seems finicky and plating will not start. This may mean too low a temperature, careless contamination, or an excess of ammonia, but it is more likely to mean not enough ammonia and too much dilution. If the other requirements have been met, wrap aluminum foil around the tips of forceps and hold the slab in the solution by these forceps, being certain that the aluminum foil touches the exposed slab surfaces. After plating has started, remove the forceps.

Step 9. *TINNING NICKEL-PLATED AREAS*

After nickel plating, wash the slab with tap water and remove the masking tape, Figure 6–11. Sometimes some of the glue from the tape will adhere to the slab. A fresh piece of tape pressed against this material will usually pull it off clean. Using the rosin-core solder in the
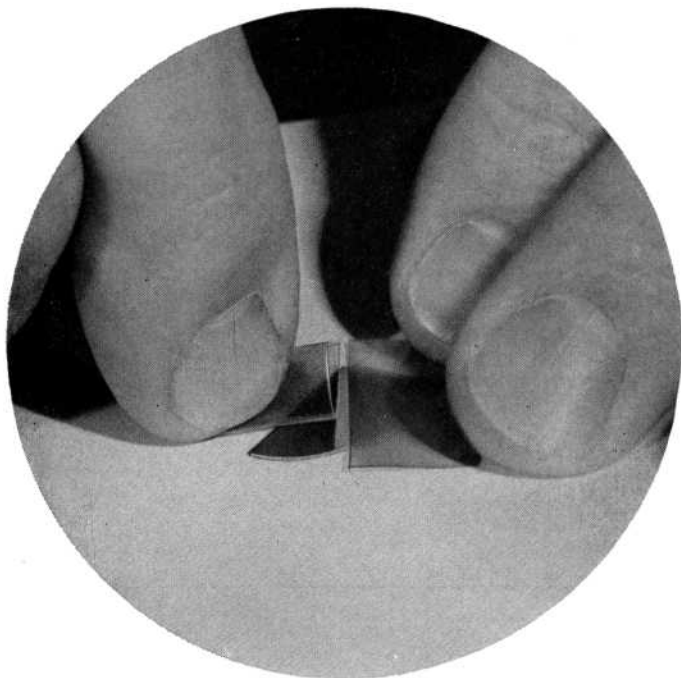
Figure 6-11. *Removing tape from slab after plating.*

kit, put a good tinned surface on the plated strip on the top of the slab, Figure 6–12, and all over the back. Use a moderately hot iron and work rapidly to avoid absorbing all of the nickel in the solder. A speck of acid solder flux is helpful. Avoid scratching the diffused surface.
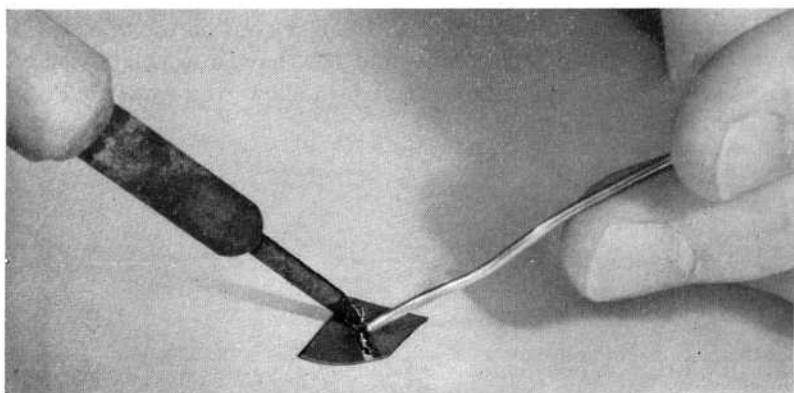

Figure 6-12. *Tinning plated area on top of slab.*

Step 10. *GRINDING THE EDGES*

Your solar cell is still completely shorted. It will be necessary to separate the active surface from the plated back. This is done by grinding all of the edges using ⌗ 600 carborundum on the glass plate. Hold the cell edgewise, Figure 6-13, and grind all edges. This is a place where an acid etch would be helpful to effect separation without damage or shorting of the barrier. But for safety and ease of operation, it is best to finish with a final light grinding with fine carborundum. Usually only the dim light operation is affected by not using acid.
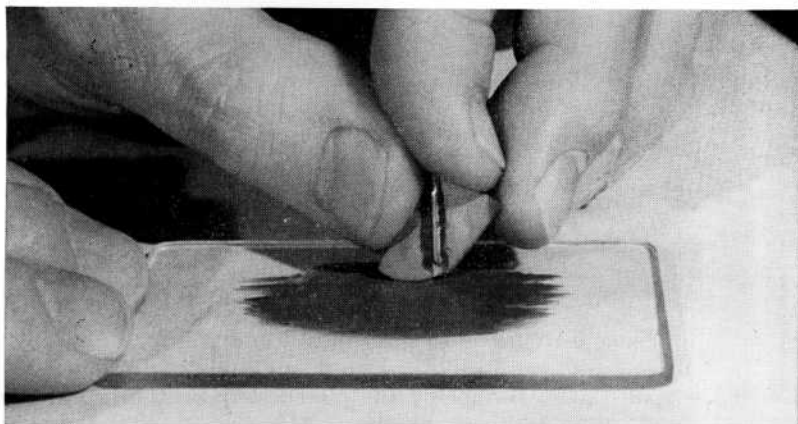
Figure 6-13. *Grinding edges of slab.*

Step 11. *ATTACHING LEAD WIRES*

Solder the flexible leads supplied, putting the red one on the narrow strip on the top (positive lead), and the black one on the back (negative). If all has gone well, you should now have a working solar cell with firmly bonded lead wires. Figure 6-14 shows the front and back of two completed cells.

Figure 6-14. *Completed cells. The top of a cell is shown on the left, the bottom on the right.*

7 Solar Cell Characteristics

Quick Check

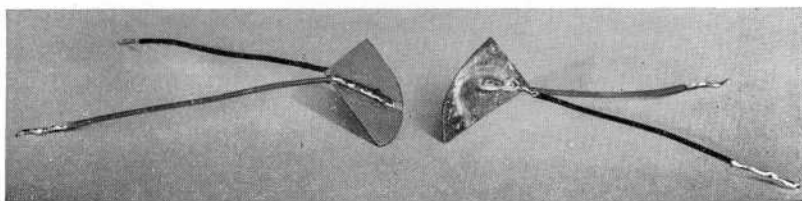Naturally, you will want to test your cell to see if you were successful. As a quick test, connect the cell to headphones. A sharp click should be heard whenever you make or break the connection, even with moderate light on the cell. If this light is daylight, there will be no sound except on making or breaking the connection. Under a tungsten lamp, you may hear the 120-cycle hum (2 peaks for every cycle). Under a fluorescent lamp, the hum is more pronounced.

It will be helpful if you have available two useful instruments. One is a high-resistance voltmeter so that the voltage can be measured with very small current drain. A meter having 0 to 1 volt is an excellent range. The other instrument is a low-resistance milliammeter to measure current without appreciable voltage being required; a range of 0 to 100 milliamperes is preferred. These instruments together with suitable resistors to be used as loads will tell much about a solar cell.

In the next chapter there are suggested uses and demonstrations that will serve as tests of a kind. The present chapter is intended to give a quantitative understanding of cell operation. Even if the necessary instruments are not available, it is recommended that you read this chapter for a discussion of the properties of solar cells. You will be better prepared to make the applications described in the next chapter.

On the recommended voltmeter, you may get an indication with your cell in room light. You definitely should get a reading in full

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sunlight or a few inches away from a 100-watt tungsten lamp. A reading of 0.4 volt in sunlight is good. If you get up to 0.5 volt, which is possible, you have an exceptionally good barrier for this process.

But suppose there is no voltage indication or no click on the headphones. Probably the cell is still shorted. Regrind all edges and examine them with a magnifying glass to find any shorted areas. It is possible that the cell will still give no voltage. However, complete failure is quite unlikely unless you scratched the active surface badly or nickel plated the wrong surface. One of my rare failures was from plating the wrong surface. Another was from using p-type silicon that I mistook for n-type. One failure was completely unaccounted for. But, I repeat, these are rare, and with reasonable care you can be almost certain of at least an active cell.

Under conditions of high-resistance shorts, even active cell performance can be improved by regrinding the edges. After repeated grinding produces no further improvement in measured voltage or click response in the headphones, connect the cell to a milliammeter and place it in strong light. In full sun or its equivalent (not through a window or screen), you should get between 5 and 20 milliamperes; more is quite unlikely. Less than 5 milliamperes would indicate too deep or too shallow a diffusion depth or a dirty surface. In strong light (focused sunlight or close to a powerful lamp), you may get up to 100 milliamperes on short circuit.

Load Curves

Let us assume that you made a good cell and get, in full sunlight, 0.4 volt open circuit and 15 milliamperes short circuit.* Neither of these test conditions represents a useful output of power. What are the conditions for maximum power into a load? To find out, let us make an experiment.

As shown in Figure 7-1, connect the cell to a voltmeter, to an ammeter and to a resistance that can be varied from 0 up to about 200 ohms. Take readings of *voltage* and *current* for values of resistance from 0 ohms to open circuit and plot a curve as in Figure 7-2.

You will note that the load curve just plotted is not a straight line. The cell probably had more than half the open-circuit voltage at more than half the short-circuit current. You can understand this fortunate condition by studying the equivalent circuit of Figure 7-3 and reviewing what was said about the diode characteristics in Chapter 4.

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* If the internal resistance of the ammeter is very low in value, it is equivalent to a short circuit, i.e., a circuit of 0 ohms.
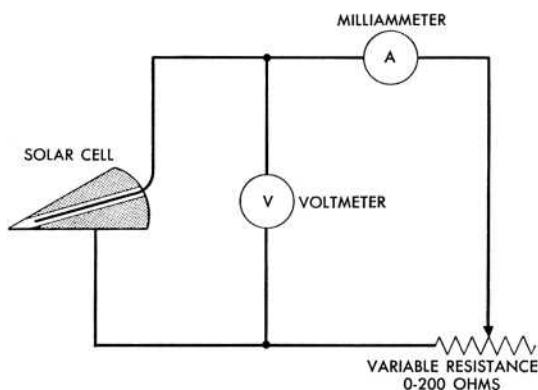
Figure 7-1. *Circuit for measuring load curve.*

The current in the external circuit is equal to the generated current minus the diode forward current for the corresponding voltage. This diode current is, for us, a leakage current as it is opposite to the flow of useful current. At short circuit, the diode current approaches zero; it rises with the voltage, at first slowly and then more rapidly. This explains the curved load curve. If we could keep the diode current
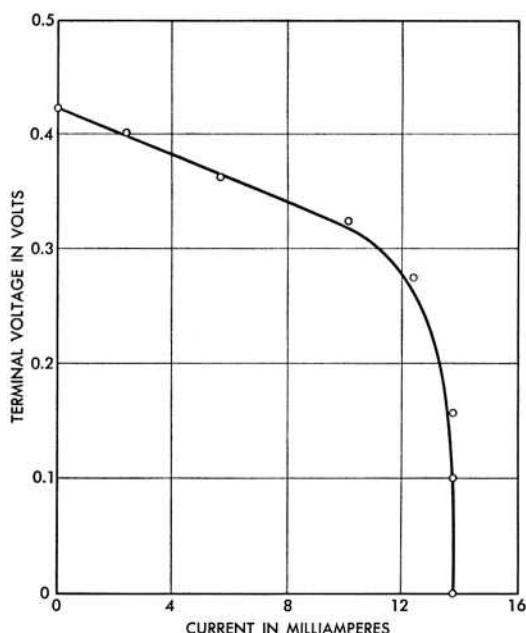

Figure 7-2. *Load curve for typical cell made by simplified process. Measurements made in full sun on December 15, 1961.*
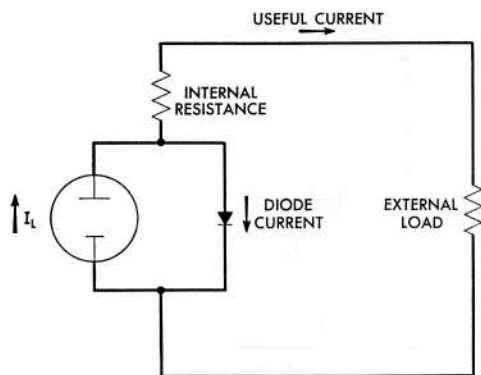
Figure 7-3. *Equivalent circuit of a solar cell.*

zero until the voltage generated was 0.6 volt, for example, our cell would operate at 0.6 volt. Cells of 0.6 volt open circuit have been made and delivered their maximum power at 0.5 volt.

Load Matching

This brings us to the consideration of how to get the maximum *power* from a cell. As was stated before, short circuit gives the maximum *current*, open circuit the maximum *voltage*. What is the condition for maximum *power*? For representative points on your load curve, compute the power output, which is the product of the voltage across the cell and the current drawn; record these values. Put a mark on the load curve corresponding to the maximum product. Is it at about ⅔ the maximum current and voltage? This will depend on the internal series resistance of the cell.

Now, repeat the load curve for several values of "sunlight." For this purpose, use a 100-watt lamp at various distances because you cannot hope to get steady, partly cloudy conditions from the sun. Find the point of maximum power for each condition. The measurements should produce a group of curves like the ones shown in Figure 7-4. A good cell of low series resistance was used for these curves, and values of radiation were varied from about 0.1 of full sunlight to twice normal sunlight. The locus of maximum power points is shown as a dotted line drawn through these points. The important fact here is that the best working voltage is almost the same over a wide range of light conditions. The current is different and the power is different, but always the best condition is for a load voltage of about 0.4 volt. You have the right to be proud of your cell if your optimum voltage is 0.3 volt or more.

This constant optimum voltage makes these solar cells ideally matched to charge storage batteries for constant voltage use. Where they are used without storage batteries, it is necessary to match them to the load (or vice versa) for a particular condition of light. For example, I have a 9-cell battery capable of delivering 1 watt into a 9-ohm load. It delivers maximum power at 3 volts. If I attach it to a 100-ohm load, the voltage will rise to nearly 5 volts, but the power will be only about ¼ watt. Likewise, if I use a 1-ohm load, the current will be nearly ½ ampere, but the power will again be only about ¼ watt. Of course, I could reconnect the 9 cells in parallel (instead of series as they are). In this arrangement, I would expect to get maximum power at about ⅓ volt at a current of 3 amperes.

What we have just said about proper loads is part of the story of impedance matching, which of course cannot be thoroughly covered here. Impedance matching, however, is summed up by the theme of an old song, "Give a Man a Horse He Can Ride." Look at it this way: A light, fast horse may do as much work as a heavy, slow horse. But if you hitch your light, fast horse to a plow, or your heavy, slow horse to a racing cart, neither one will do much for you.

No harm will be done if your solar cell is mismatched, but if you want maximum power out of it, plan on loading it to work at whatever voltage your load-curve test shows at the maximum power
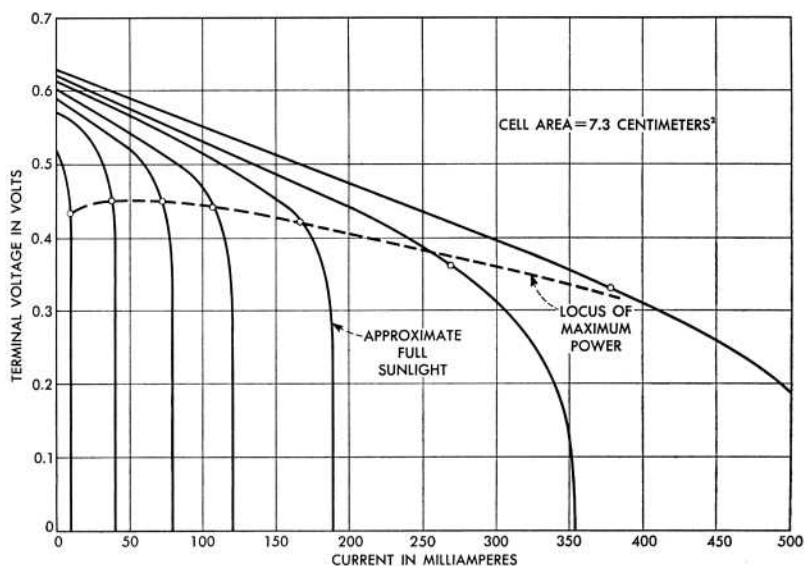

Figure 7-4. *Load curves for solar cell at various light intensities.*

point. To work at higher voltages, use more than one cell and connect them in series. If you need more current than one cell can produce, connect several cells in parallel. The battery used on the Americus, Georgia, Rural Telephone Test* had 432 solar cells connected in 6 parallel banks having 72 cells joined in series. It charged a 20-volt storage battery delivering about ⅓ ampere in bright sunlight. Of course, it delivered less current in partial sunlight, but being properly matched to the load, it gave the most power it was capable of producing for any condition of sunlight.

Efficiency

Let us define what we mean by per cent efficiency and then measure the efficiency of your cell. The efficiency we are interested in is the percentage of the total solar radiation that appears as electrical power in the external load. The power into the load is simply the product of cell terminal voltage and current as already computed in our study of load curves. The total solar radiation is the solar constant (which we discussed in Chapter 1) times the active area of your cell. Measure and compute as best you can, the exposed active area. Unless you have a pyroheliometer† make the test on a clear day near noon and assume that the solar constant is 0.1 watt per square centimeter. Input power is $C \times A$, where C is the solar constant and A is the active area of your cell perpendicular to the sun's rays. Take the output power and divide it by the input. This fraction, reduced to percentage, is the efficiency of your cell.

In January, 1954, the solar cells we were making at Bell Telephone Laboratories had an efficiency of conversion of 4 %. By the time the cells were announced to the public in April of the same year, we had reached 6 % efficiency. A year later, an 11 % cell had been made; there have recently been reported cells of 14 % efficiency. What can we expect as a reasonable upper limit? A calculation of 22 % was made based on reasonable assumptions. The 22 %, calculated as a figure

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* The first field trial of a rural telephone system making use of transistors and the Bell Solar Battery was held in Americus, Georgia. The Bell Solar Battery was installed on a part of this trial system in October, 1955, as an experimental substitute for ordinary batteries. Bell System engineers have ascertained from the Georgia tests that, from the standpoint of reliability and effective operation, the Bell Solar Battery mounted on a pole can be used to furnish electricity for rural telephone equipment. However, until raw material, technology and electrical storage become less expensive, it will be more economical to use conventional power sources for telephone systems.

† Calibrated instrument for precise measurements of solar radiation.

to shoot for, has often been quoted as the upper limit. That calculation disclosed both the possibilities and the limitations of solar conversion and is worth repeating here for you.

The derivation is valid under the following assumptions:

1. Every photon of enough energy to release an electron in the silicon will release *one* and only *one* electron.
2. All of the electric current so generated will be collected by the p-n junction and delivered to the external circuit.
3. The terminal voltage will be 0.5 volt.

The first two assumptions are certainly limiting and maximum. The third was a "guesstimation" looking into the future, but taken from early data. By careful attention, and special processes to reduce resistance, I have made cells that did deliver their maximum power at 0.5 volt so the third assumption is not too unreal for a calculation. Refer to Figure 7-5 which shows the solar spectrum again plotted as relative energy versus frequency. We begin our calculation at 12000Å. At this frequency, as explained before, each photon has 1.08 electron-volts of energy. For simplicity, round that figure off to 1 electron-volt. If our cell will deliver each released electron at 0.5 volt into the load, it follows that at 12000Å, half of the incident energy has been used. If we used light of this wavelength only, we could talk of 50% conversion efficiency. On Figure 7-5 at 12000Å, we will indicate the 50% conversion by a point at just ½ of the ordinate of the solar curve. Consider now a photon at 6000Å. From Figure 3-4 we see that it has an energy of 2 electron-volts. If we still recover 0.5 electron-volt (1 electron at 0.5 volt), we will be recovering ¼ of the energy the sun supplies at this wavelength. Make a point at ¼ of the ordinate of the solar curve. Similarly the ordinate at 3000Å will be ⅛ of the solar ordinate. Other points are computed in the same way, remembering
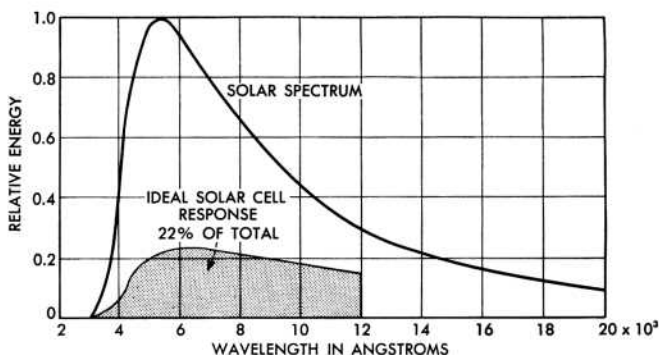

Figure 7-5. *Limiting efficiency of a silicon solar cell.*

that all points above 12000Å deliver zero energy. If we now draw a curve connecting all of our points we enclose an area proportional to the energy developed by the cell.

Maybe the method of taking the total area under a curve is new to you. You will meet it formally when you study calculus. But it need not scare you here. Both curves represent relative energy at various wavelengths. At each wavelength, imagine a narrow strip 1 unit wide (disregard now, the size of the wavelength unit) running from the baseline to the curve. It is a bar graph of the energy at that wavelength in a band 1 unit wide. Add bar graphs on each side. I think you can easily see that the total area under the curve between any two wavelengths is the sum of the bar graphs and is proportional to the energy that is present in the band between those two wavelengths. The total energy under the curve is, of course, equal to the area of all the bar graphs.

If we take the area under our output curve and compare it to the area under the whole solar curve, we have the proportion of the total energy that we can convert to electrical energy under our assumptions. That figure turns out to be 22%.

Losses

There are three serious losses that hold this theoretical figure down to 22%. The first is the loss beyond 12000Å. A different solar converter might use this radiation, but a silicon cell cannot. The second loss arises from the fact that we recover only ½ of the energy used to release an electron. The third is the loss of energy of most of the photons beyond that necessary to release an electron (1.08 electron-volts). The present mechanism cannot use the extra energy and it appears as heat.

But why do we not get *even* the 22%? Let me say in advance that we can be proud of getting 10% in commercial production considering all of the places where we can lose energy. In the first place, not all of the radiated energy penetrates the silicon wafer. The reflection at the surface can be very high. Special coatings can reduce this reflection loss but some reflection will always remain. Some of the photons that do get into the silicon pass right on through. This is especially true of those near the 12000Å cutoff. Or, some photons may be absorbed too far from the barrier to be useful. On the other hand, those photons near the violet end of the spectrum are absorbed so near to the surface that again the free electrons and holes formed are not separated by the barrier. At the very best, we can only hope to

place the barrier at a position that will maximize the useful absorption. Of the electron-hole pairs formed at or near the barrier, some will recombine before the barrier separates them. Then there is the normal diode current that lets the current steal back across the barrier (the wrong way) if a usable voltage is allowed to develop. Finally, the series resistance of the cell and leads lowers the output voltage when useful current is taken. Is it any wonder that we are proud of 10 to 12% efficiency and find higher values almost impossible to attain?

It can be stated that 10% compares favorably with gasoline engines and far exceeds most steam engines. And, of course, if you include the over-all efficiency of the plant growth and other processes that made the gasoline for the gas engine, or formed coal or wood for the steam engine, the efficiency of our solar cell far outstrips them. Besides that, try to make a 10-milliwatt gas or steam engine with the same efficiency as a larger one!

Color Response

From what has been said in the derivation of efficiency, we can learn much about the color response of silicon solar cells. We know that the response is zero beyond 12000Å. For a short distance below 12000Å, the response is low because absorption is too deep in the silicon. At the violet end (4000Å) response is down because of absorption too near to the surface and the waste of the excess energy of each photon. Somewhere in between is the greatest response. The shape of this response for an early cell is shown in Figure 7-6. This is taken from data by Dr. H. A. Briggs at Bell Telephone Laboratories. It shows, Curve A, a peak cell response between 7000Å and 8500Å. This is outside the visible spectrum in the near infrared. Does this suggest to you why a 100-watt lamp at close range can give as much cell output as full sunlight? Curve B of the figure reproduces the solar spectrum. Curve C is the product of the two curves and shows the relative output of the cell versus wavelength (color) when operating in sunlight. The most useful wavelength of the sun's spectrum is just outside the visible spectrum.

From the color response curve, you can see why silicon cells will probably never completely replace selenium cells whose sensitivity, though less, matches the eye. You can also see why they may displace selenium in many photocontrol circuits powered by incandescent lamps strong in the infrared.

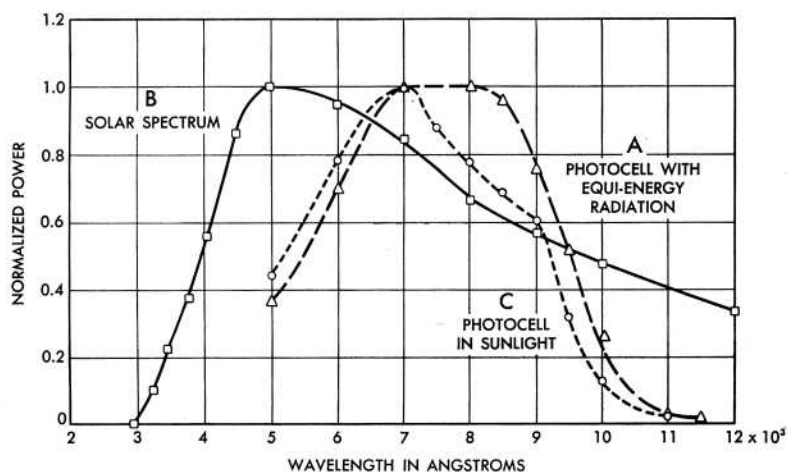You can perform a very simple experiment to show that your cell is

Figure 7-6. *Spectral response of the sun and a photocell (silicon solar cell).*

sensitive in the infrared. Obtain a thin, flat-sided jar or bottle and a spherical glass container (flask). Fill them both with a solution of potassium permanganate of sufficient concentration so that you cannot see through the container. Now put a lamp on one side of the container and your cell connected to an ammeter on the other. With the flat-sided container you will still get moderate response even though most of the visible light has been removed. With the spherical container, you should get an increase of current if you locate the light and cell properly. What you have done is to *focus* the infrared radiation to give more usable photons than in the unfocused radiation.

Effect of Temperature

Another characteristic that governs the behavior of silicon solar cells is their temperature response. Since a change in temperature does not affect the number of photons available, one would not expect a marked change in short-circuit current with changes in temperature. Figure 7-7 shows a slight rise of current with increased temperature. But what would you expect of the open-circuit voltage with a rise in temperature? Since there will be an increase all through the silicon (both p- and n-type) in electron-hole pairs, this will certainly mean an increase in minority carriers; that is, more free electrons in the p-type material, and more holes (positive) in the n-type material. Consider the potential curves of Figure 4-12 for no photon excitation. With increased temperature there will be more minority carriers to

be carried back across the barrier by the built-in field. And these will lower the barrier potential. There will be a similar lowering of the voltages at the contacts at the sides. All of the voltage differences will be less than before. If now we introduce photons at the barrier, we have less voltage change possible before the flood of majority carriers diffusing across the lower potential completely nullifies the effect of the photons. In other words, we cannot develop as much terminal voltage as before because the diode current is larger for a given net change in barrier voltage.

Theory and measurements agree that the open-circuit voltage of a silicon solar cell decreases at about 0.002 volt per degree Centigrade rise in temperature.

Working in the other direction, we once cooled a cell in liquid nitrogen which boils at −196°C. At this temperature, the voltage should be 196 × 0.002 = 0.39 volt higher than at 0°C. The voltage curve of Figure 7-7 (a different cell) shows 0.59 volt at 0°C. Adding 0.39 to 0.59 gives a computed figure of 0.98 volt at liquid nitrogen temperature. We measured 0.99 volt. The voltage for maximum power was 0.80 volt. Before you try this experiment, I must warn you that unequal thermal contractions cracked the cell.

You can safely measure the temperature effect on your cell by using hot and cold water. Put your cell and a thermometer in a small beaker filled with ice water; connect it to a voltmeter and illuminate the cell with strong, artificial light. Take readings of the open-circuit voltage as the water and cell warm up to room temperature. If you can heat the water without disturbing the setup, go up to the boiling point, taking frequent readings. If it is not convenient to heat the water in place, siphon it off and replace with boiling water.
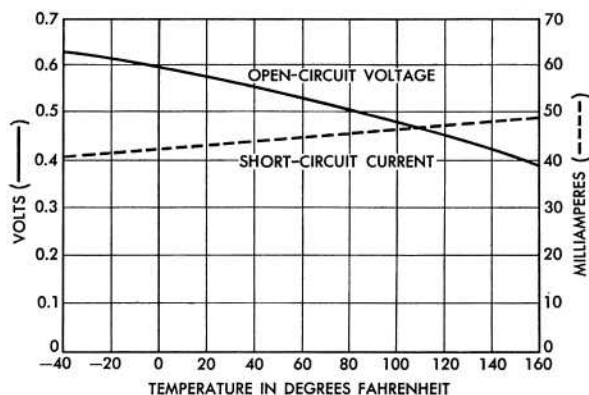

Figure 7-7. *Effect of temperature on the voltage and current of a solar cell.*

Perhaps for safety of the equipment, you should do this in two or more stages using successively hotter water. Then take readings as before as the water cools. When you plot your data (output voltage versus temperature), the two parts of the curve may not join exactly. Why? Does your data agree in percentage change with that shown in Figure 7-7?

A Photometer

You can use your cell like a foot-candle photometer, with certain restrictions. That is, since its color response does not match the eye, it has to be calibrated for each type of light source. For example, if sunlight is your source, then it does not matter that your cell sees mostly the infrared since shaded sunlight will have the same percentage of visible and infrared light as does full sunlight. And, as you might have guessed, on short circuit you get an output proportional to light intensity; that is, more light, more photons, more current. Using a low-resistance milliammeter, measure the short-circuit current in full sunlight. Call this the reading for One Sun. Measure now in partial shadow, then in deep shadow, and finally inside a building lighted only by daylight. (Did you realize before, how very weak light can be and still provide good vision?) You will need a microammeter to measure the light that is still far above the threshold of vision. Tungsten light is far richer in infrared than sunlight. If you use your cell to measure this artificial light, you must calibrate for every type of source, depending on its color temperature.

8 *Uses and Demonstrations*

You have constructed, measured, probed, and computed, and now you come to the predominantly "for fun" part of the project. What can you do to provide your solar cells with a useful task, or just to show them off? Powering satellites is perhaps a little beyond your reach. However, I hope you will get as much fun out of running "down-to-earth" gadgets with light power as I do. I get real satisfaction from the motor over my desk that runs from room light converted to electric power by Bell Solar Battery No. 1. I have a transistor radio that has operated on daylight for several years and a big electric gong that gives an ear-splitting tone when powered by solar-battery energy stored in a giant capacitor. As a stunt last spring, a plastic-bubble greenhouse was kept inflated for over an hour with a small fan powered by a large solar battery. Until the chargeable storage cells wore out, a flashlight was operated by solar energy. Ferris wheels and miniature water pumps are included in the list of gadgets, as is an electric fence charger used to keep wild animals from a garden, and electric clocks that run "forever" with solar-cell power.

The three projects about to be described were selected for operation on a very few cells such as you have made. They are low-power devices intended only to illustrate principles. Two involve mechanical motion because there is nothing as convincing as something that moves. The third is a radio receiver illustrating the operation of electronic circuits and the generation of sound. These are simple devices involving the least possible purchase of supplies. If you like, you can make much more elaborate equipment than that suggested. If a few basic principles are observed, frequently great liberties of design are permissible.

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A Light-Powered Pendulum

Figure 8-1 shows a light-powered pendulum that swings continuously on only the power furnished by one room-lighted solar cell. This pendulum does nothing but swing merrily as long as light is available to it. However, by doing a little computing, you can make one that marks off fixed time intervals which is then the basic movement of a clock.

Can you see what makes the pendulum go? Obviously, as with all moving systems, energy must be supplied to make up for friction losses — in this case, mostly air friction. Energy from the solar cell is fed to the pendulum by means of the pull of a solenoid on a magnetic plunger attached to the pendulum. The bob of the pendulum casts its shadow on the solar cell during half of each swing. If we connected the cell directly to the solenoid, the pull would oppose the swinging as much as help it. Therefore, we must delay the pull so that it occurs only when the pendulum is swinging toward the coil (i.e. put in proper phase). This is the purpose of the capacitor. As the pendulum swings to the left, the cell is uncovered and its current begins to charge the capacitor. When the pendulum has completed its swing to the left and begins to come back to the right, it is ready for a pull. At this time the capacitor is nearly charged and the cur-
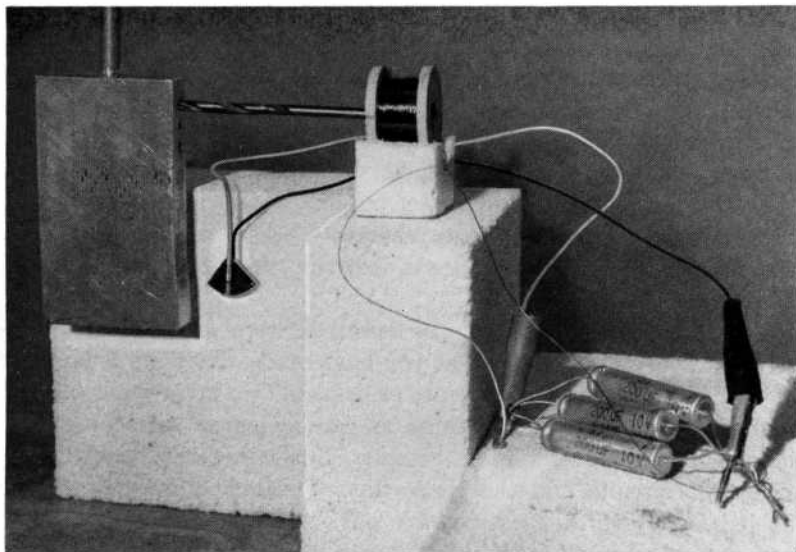

Figure 8-1. *Pendulum operated by light falling on a solar cell.*

rent from the cell energizes the coil which pulls on the plunger. At the bottom of the pendulum's swing toward the coil, the cell becomes shadowed and the capacitor takes over to continue the pull by discharging its stored current into the coil. Thus, the capacitor provides a time delay so that the pull on the pendulum occurs when it will add to the motion. (This may also be expressed as a phase delay of approximately 90°.)

Let us begin our design by considering what we can hope to obtain from one solar cell. This, of course, depends on how much light you supply. I was aiming for dim light operation with a fairly good cell, and so assumed I could obtain about 0.2 milliampere at 0.05 volt. Thus, the coil could be about 250 ohms:

$$I = E/R, R = E/I = 0.05/0.0002 = 250 \text{ ohms},$$

where I is the current, E the voltage, and R the resistance.

I needed as many turns as I could get in a reasonably sized coil of 250 ohms. The one shown in Figure 8-1 was wound on a wooden spool having a core diameter of $7/16''$ and a coil length of $1/2''$. Three thousand turns of No. 36 Formex wire were used to give a resistance of 230 ohms.

The capacitor was selected to give a nominal discharge time of about $1/8$ second. This calls for a capacitor of 500 microfarads:

$$RC = T, C = 1/8 \div 250 = 5 \times 10^{-4} \text{ farad},$$

where R is the resistance, C the capacitance, and T the time.

The capacitor should be a low-voltage type to keep down the cost. Capacities as low as 100 microfarads or as high as 2000 microfarads can be used, but they will not work as well as 500 microfarads. This assumes a pendulum about 36″ long. If you have to use a larger capacity, a longer pendulum will help; for a smaller capacity, use a shorter pendulum.

The pendulum pictured in Figure 8-1 operates on room light with the help of a focusing mirror. It is a good pendulum but made of materials that might be hard to get. The one illustrated in Figure 8-2 works just as well and the materials are readily available.

A steel drill (about No. 27) has fairly good permanent magnet properties and will serve as a plunger. A flooring nail works very well and is cheaper. Common nails are no good for this purpose because they are made of soft iron. It is theoretically possible to operate the pendulum with a soft iron plunger, but the induced magnetism in such a plunger is so weak that the force of attraction is insufficient. A really good permanent magnet in the shape of the plunger would be a help here, but the nail and the drill worked well after they were magnetized.
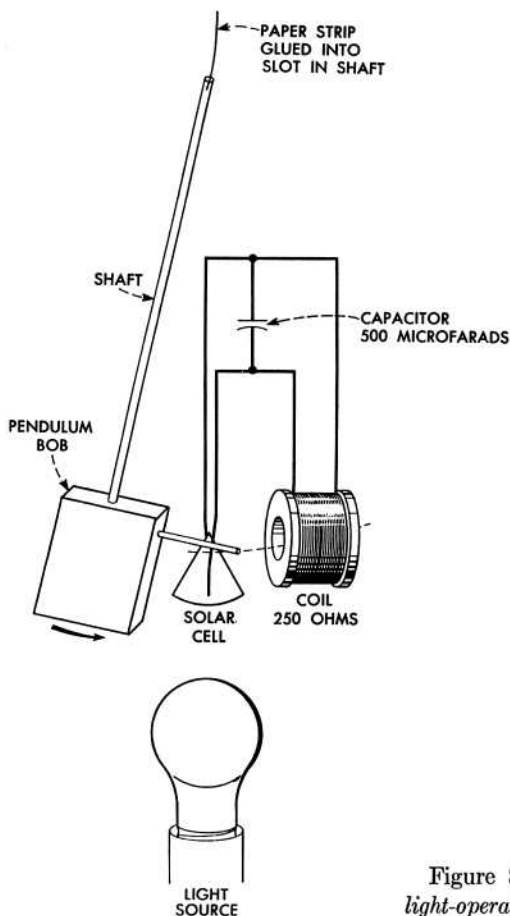
Figure 8-2. *Schematic drawing of light-operated pendulum.*

To magnetize the nail or drill, wind about 25 turns of insulated bell wire (No. 18 will do) around it. Touch the wire terminals *momentarily* to an automobile battery. The plunger should pick up pins after it is magnetized.

Mount the plunger by inserting it in a hole drilled into the side of the bob. Drill the hole slightly smaller than the plunger to make a good press fit. Use a $\frac{1}{4}'' \times 36''$ wood dowel for the shaft and a $\frac{3}{4}'' \times 3'' \times 3''$ block of wood for the bob. The dowel is glued into a hole drilled in the top of the wooden bob. The suspension is a $\frac{1}{4}''$ wide strip of ordinary writing paper (as short as convenient) glued into a slot cut in the upper end of the dowel. This can be glued to a support or held in a clamp. (Using a flat strip tends to dampen all motion except the desired pendulum swing.)

You can vary the method of suspension, use a more beautiful pendulum or make whatever changes that occur to you as long as you observe a few simple rules which may be summarized as follows:

1. Position the cell so that it will be shaded and unshaded for about equal times.
2. Have the rest position of the end of the plunger approximately in the center of the solenoid. Use as good a magnet material as you can get for the plunger.
3. Match the solenoid approximately to the cell as described.
4. Match the capacitor to the coil resistance to give about ⅛- to ¼-second delay.
5. Be sure the polarity of the coil is correct to *attract* the magnetized plunger, and that the capacitor polarity is correct.
6. Be sure that your suspension is flexing freely and that no part of the pendulum is rubbing.
7. Start with a rather strong light and cut it to the minimum for good operation.

Light-Commutated Motor

The next device will also be a conversation piece because it has interesting features not possible without photocells for power. It is a dc motor in which the commutation is done by light (radiation). One real advantage to this method is that the friction normally present in a mechanical commutator is absent. This motor is very easy to make and requires little equipment. I will describe what worked for me and try to point out the important factors. Figure 8-3 shows one of the motors. A slightly more sophisticated version of this motor operates a set of angel chimes originally intended to run with burning candles.

The schematic drawing, Figure 8-4, explains the construction. Two solar cells are mounted on opposite sides of the cork and connected to the coil with opposite polarities. The direction of current flow through the coil is now in one direction for one cell and in the opposite direction for the other. This connection provides the required reversal of current (commutation) for each half rotation of the motor, the light coming in from only one side. The cell in the dark will always have high resistance so that it does not waste the power generated by the cell which is in the light. Note the placement of the field magnet to give the maximum torque to the windings when either one of the cells faces the light.

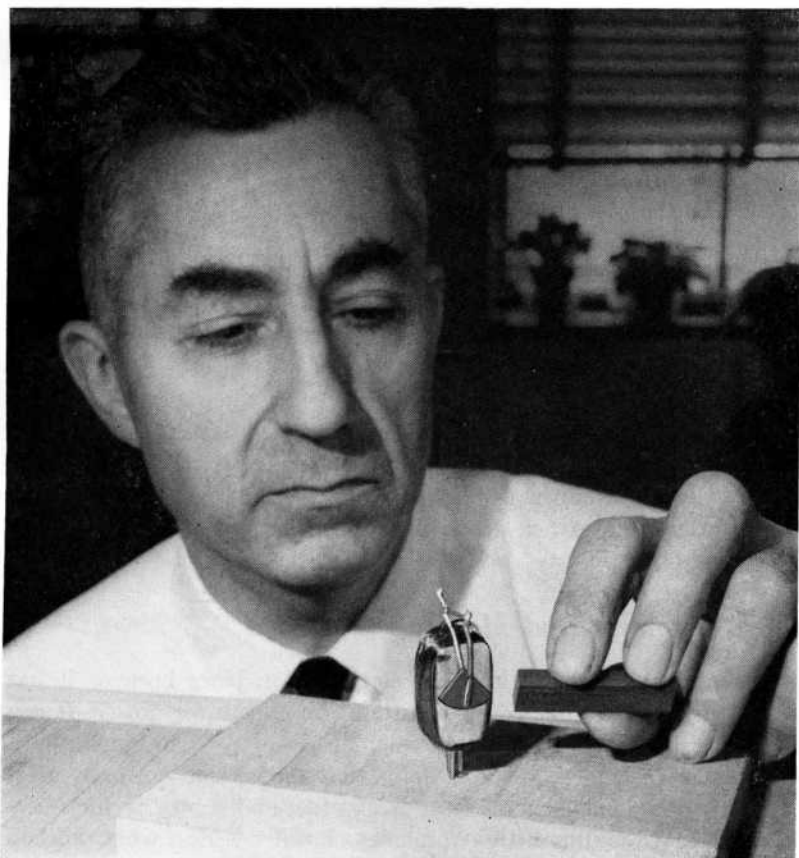The bearing is glass on a steel point to give low friction. Use a

Figure 8-3. *A light-commutated motor.*

large sewing needle or sharpen a long nail. Mount it vertically in the block of wood used for a base.

Select a piece of glass tubing (the glass part of an eyedropper will do) with a hole about ⅛″ in diameter. Fire close one end. There are many ways to do this, but I found it easy to heat a piece of glass tubing in the middle and pull it apart. A little judicious heating and pulling resulted in a closed end which was not too distorted. Break the tubing about 2″ from the closed end and fire polish the broken end. This tubing, set over the point of the needle, will be the bearing. You may want to make several pieces of glass and choose the one that appears to give the least friction.

Obtain a cork stopper about 1″ in diameter on the small end. Bore a hole along its axis from one end not quite to the other end. Make the

hole a snug fit for the glass tubing and push the closed end of the tubing into the cork. The cork and glass should rotate freely on the point of the needle. With a file or sandpaper, make two parallel flat sides on the cork for winding the coil, and two parallel flat sides for mounting the solar cells.

To determine the best wire size, we need to know something about the acceptable resistance of the winding. We determine this from considering what the solar cells can deliver. In reasonably strong light, your cells should be able to deliver about 10 milliamperes of current at about 0.3 volt. If these estimates are correct, the proper resistance load is

$$\frac{E}{I} = \frac{0.3}{0.01} = 30 \text{ ohms.}$$

Note that this load is computed for different conditions from those used for the pendulum. What we want now is the most turns we can
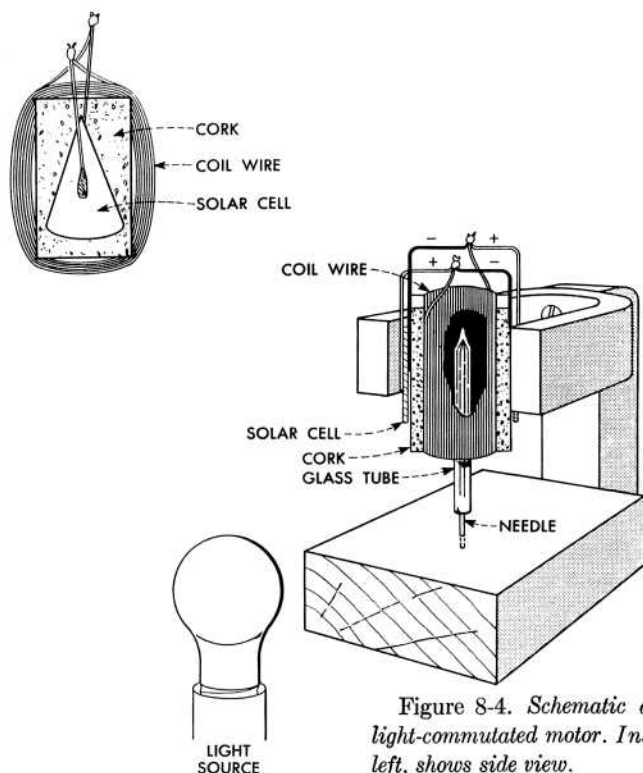

Figure 8-4. *Schematic drawing of light-commutated motor. Insert, upper left, shows side view.*

get in the space available on the cork for 30 ohms of wire. I used 350 turns of No. 31 Formex wire and the resistance was about right. This is not critical. To hold the windings in place, use household cement.

Select two of your cells that will deliver the most current and mount them with the same type of cement on the two remaining faces. Connect their terminals to the coil ends as previously described.

All you need now is a field magnet. A horseshoe magnet (or two bar magnets, one on either side and properly poled) would be excellent. The motor will operate on only one magnet as shown in Figure 8-3, but two will produce better results. An ordinary pair of pliers can be used for a field magnet. These can be magnetized, as described for the pendulum plunger, by wrapping bell wire on the handles and connecting the terminal ends of the wire momentarily to an automobile battery. Be sure to wind each handle of the pliers so that the ends are of opposite polarities. Two large files when given the car battery treatment can be used.

Although makeshift magnets will operate the motor, a really good field magnet will illustrate an important and fascinating property of direct current motors. With a strong magnet, the motor will operate on comparatively little light, but only slightly faster on very strong light. But if the field magnets are now slowly withdrawn, thereby *weakening* the field, the motor will first *increase* in speed before stopping. Before illustrating this to your friends, consult any standard text on direct-current motors for the explanation if it is not already understood.

Your motor should run well on sunlight or with a 100-watt lamp placed close to it. The light must come from only one side in a direction approximately perpendicular to the field of the magnet. In demonstrating this motor, you can show that it will reverse directions if you introduce the light from the opposite side, or reverse the position of the field magnets.

You may have to give the motor a slight push to start it as there are two dead spots where there is no torque. If you want to put on three windings and three cells, you can make a motor that will always start. The windings may be separate or you can keep the resistance down by interconnecting them. I leave this problem to you with the assurance that it is possible and has been done.

Radio Receiver

This project is a very simple solar-powered radio. Here, as in all of these demonstrations, the project has been simplified to a bare minimum for reasonable operation. The radio receiver described

Spectrum.   A continuous range of frequencies, for example, the light spectrum.

Valence electrons.   The electrons in the outermost orbit of an atom. These are the electrons which enter into chemical combination and are responsible for electrical conduction in metals.

Volt.   The unit of (1) potential, or of difference of potential; (2) the unit of electromotive force. It requires 1 joule of energy to move 1 coulomb of charge through a potential difference of 1 volt.

Watt.   1 watt equals 1 joule per second or 10^7 ergs per second. It is the work done in 1 second by a current of 1 ampere through a potential difference of 1 volt.

Wavelength.   The distance between corresponding points in two successive waves.

Appendix II   *Equalities*

1 erg	=	1 dyne-centimeter
1 joule	=	10^7 ergs
1 calorie	=	4.18×10^7 ergs = 4.18 joules
1 watt-second	=	1 joule = 0.24 calorie
1 watt	=	1 joule per second
1 kilowatt-hour	=	3.6×10^6 joules
1 foot-pound	=	1.36 joules
1 electron-volt	=	1.59×10^{-12} erg = 1.59×10^{-19} joule

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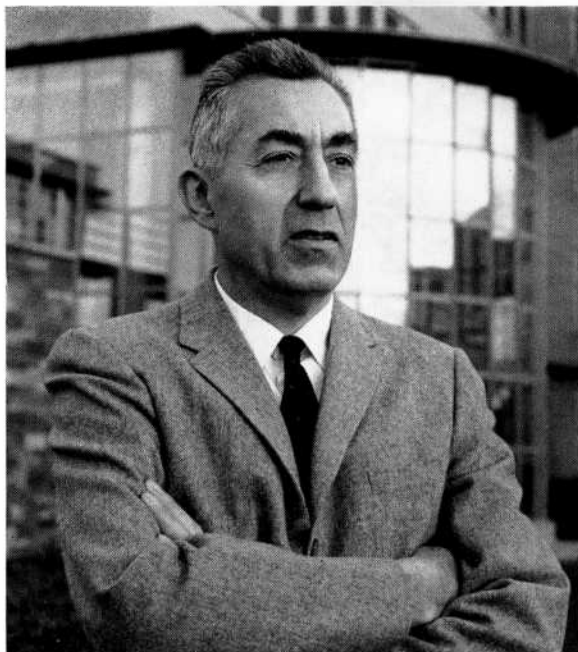
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The Author

For several years after joining Bell Telephone Laboratories in 1930, Dr. Daryl M. Chapin studied magnetic materials. During World War II, he worked on underwater sound devices and later, pulse code modulation, the resonance vocoder and special communication devices and services.

For many years, Dr. Chapin has been interested in solar energy and its many possible uses. Early in 1953, as a part of a study of new energy sources for low-powered transistor telephone systems, he investigated direct conversion of sunlight into electricity. The newly discovered properties of silicon attracted his attention and he succeeded in developing the Bell Solar Battery, of which he is co-inventor.

Dr. Chapin is a member of the Association For Applied Solar Energy. In 1956, he was awarded the honorary Doctor of Science degree by his alma mater, Willamette University. In March, 1957, he received the John Scott Award for his work on the Bell Solar Battery.

Before joining Bell Telephone Laboratories, Dr. Chapin was an instructor in physics at Oregon State College. He has given many lectures on solar energy conversion to high school, college, and technical groups. The writing of this textbook has given him the opportunity to work again in the education field.

PLEASE READ CAREFULLY

Following is important information about certain chemicals used in the Solar Energy Experiment which can be harmful if they are used improperly or are accidentally misused:

HYDROFLUORIC ACID

Hydrofluoric acid is an EXTREMELY HAZARDOUS LIQUID AND VAPOR CAUSING SEVERE BURNS WHICH MAY NOT BE IMMEDIATELY PAINFUL OR VISIBLE!

Avoid contact with skin, eyes and clothing.

Avoid breathing vapor.

First Aid in case of contact or suspicion of contact:

External—Wash with plenty of water until all acid is removed (up to one hour or until medical attention is obtained), paying particular attention to skin under nails. In case medical attention is delayed, apply milk of magnesia or mineral oil generously.

Internal—Give four ounces of milk of magnesia or two tablespoonfuls of mineral oil, or glassful of chalk or soap in milk or water solution.

Eyes—Flush with water for 30 minutes. Prompt medical attention is absolutely necessary.

Remove patient to fresh air and keep at rest.

CALL PHYSICIAN

SODIUM HYPOPHOSPHITE

Sodium hypophosphite is a FLAMMABLE substance!

Keep container closed and away from heat, open flame and oxidizing agents.

CALCIUM FLUORIDE

Calcium fluoride is POISONOUS IF SWALLOWED!

First Aid: Give glassful of lime water (saturated solution of calcium hydroxide) or 1% calcium chloride, or generous amounts of milk if these are not available.

CALL PHYSICIAN

SULFURIC ACID

Sulfuric acid CAUSES SEVERE BURNS!

Avoid contact with skin, eyes and clothing.

First Aid:

External—Wash with plenty of water, using soap freely, then apply sodium bicarbonate solution (two teaspoonfuls per glass of water).

Internal—Give four ounces of milk of magnesia or two tablespoonfuls of mineral oil, or glassful of chalk or soap in milk or water solution.

Eyes—Flush with plenty of water.

CALL PHYSICIAN

AMMONIA

Ammonia is POISONOUS AND EXTREMELY IRRITATING TO THE SKIN AND EYES!

Avoid breathing vapor

Avoid contact with skin, eyes and clothing.

First Aid:

External—Wash with plenty of water, then wash with vinegar.

Internal—Give vinegar or juice of lemon, grapefruit or orange generously, follow with olive oil.

Eyes—Flush with plenty of water, then flush with mineral oil or olive oil.

CALL PHYSICIAN

BORIC ACID

Boric acid is POISONOUS IF SWALLOWED OR ABSORBED THROUGH THE SKIN!

Do not take internally.

Avoid contact with wounds.

First Aid:

External—Wash with plenty of water or solution of sodium bicarbonate (two teaspoonfuls per glass of water).

Internal—Give two teaspoonfuls of sodium bicarbonate, in glass of water, then two teaspoonfuls of epsom salt in glass of water.

Eyes—Flush with plenty of water.

CALL PHYSICIAN