

# SOLAR CELLS

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## A. PREPARATION

### 1. History of Silicon Solar Cells

In 1839, French physicist Alexandre Edmond Becquerel discovered that when light shone on one of a pair of metal plates immersed in a dilute acid solution, the amount of electric energy moving through the circuit increased. This was the first glimpse of the "Photoelectric Effect," the ability of light to generate a flow of electricity. Becquerel's discovery, however, elicited no practical application until 1954, when after considerable theoretical and experimental work from the date 1930's through the 1940's, researchers at the Bell Telephone Laboratories in New Jersey produced the first practical solar cell, a planar junction single crystal silicon cell.

The early cells produced soon after were usually circular in shape with a diameter of approximately 3 cm. They were of the p- or n-, wrap-around contact type with a high internal resistance (5-10 ohms) and excessive material defects thereby resulting in a relatively low conversion efficiency (less than 6%). Since the costs of producing these cells was approximately \$2000/watt of power, they were far too expensive for any use known to man until the advent of the space program. In 1958, Vanguard, the first U.S. satellite, went into space carrying six rectangular 0.5 x 2 cm cells. Not realizing the implications of the long life of the silicon cells, Vanguard continued to send radio signals back to Earth for 6 years due to the omission of an "off" switch by scientists.

Although the space program provided the incentive to develop more efficient solar cells, it was not until 1972 that a 30% increase in energy conversion efficiency was obtained for space application cells. This was achieved by decreasing the internal resistance of the cell to about 0.05 ohms, improving the charge carrier collection process, and increasing the cells "blue" response. The resulting solar cell was best known as the

"Violet" cell.

Another noteworthy development in 1972 was the Vertical Multijunction (VMJ) solar cell, also known as the edge-illuminated multijunction cell. This device was unusual in that it was constructed by stacking alternate layers of n- and p-type silicon into a stack very similar to that of a "layer cake." This stack then stood vertical with the illumination entering on the sides of the layers. A pair of ohmic contacts on each end of the stack allowed for the extraction of usable power. The characteristics of this device included a low internal resistance coupled with a high device voltage at a very low current.

From 1972 to 1976, a variety of cells were designed for space applications while research on terrestrial solar cell uses continued to crag due to the high commercial production costs of silicon cells. These new designs were developed by improving on such cell characteristics as solar energy spectrum sensitivities (resulting in "ultra-blue," "blue-shifted", and "superblue" cells), carrier collection processes ("drift-field" and "p+ " cells), and light reflection processes on the cells exposed surfaces ("non-reflecting", "black", and "textured" cells). Perhaps the most notable improvement in space application solar cells during this time period was the development of the ultra-thin single crystal silicon solar cell. These 0.05 mm cells were tested in 1978 and were found to exhibit efficiencies that reached 12.5% as well as having a high radiation resistance (important for space applications), and a low weight.

Toward the end of the 1970's, it became obvious that in order to make silicon solar cells feasible for terrestrial applications, high efficiency cells would have to be made available at a much lower cost. However, since efficiencies were already in the 10-13% range, the major emphasis was placed on lowering the cell fabrication costs instead of on improving the efficiencies.

This effort was rewarded when it became possible to grow larger, purer, and more stress-free silicon crystals employing new cutting techniques that reduced work damage suffered by the silicon. Due to this major improvement as well as other smaller advances, what once cost \$2000 per watt now only cost about \$8 per watt. Although this is still too expensive for most terrestrial applications, with all the research being performed today on solar energy converters, as well as on other materials such as GaAs, CdS, CdTe, and InP, it is worthwhile to note that while the cost of most electricity generating processes continues to rise, the cost of solar energy keeps falling. Therefore, it is not unreasonable to assume that one day, solar cells may be producing a substantial portion of our electrical needs.

## 2. Parameters of Solar Radiation

The maximum usable power that can be delivered to a load by a solar cell is Proportional to the amount of solar energy incident upon the cell. Therefore, it is obvious that the output can be seriously affected by changes in both climatic and weather conditions. In addition, the cell output will also be determined by such solar intensity variations as those that occur seasonally, diurnally, and with geographical location as well as the spectral content of the solar illumination itself.

The total energy received from the sun on a unit area perpendicular to the sun's rays at the mean earth-sun distance ( $1.496 \times 10^{11} \text{ m} = 1.00 \text{ Astronomical Unit} = 1.00 \text{ AU}$ ) is called the Solar Constant. Originally thought to be  $140.0 \text{ mW/cm}^2$ , it was revised in 1971 to the present value of  $135.3 \text{ mW/cm}^2$ . Because the solar constant refers to the total radiant energy received at 1 AU, when referring to the total radiant energy received at a given distance other than 1 AU, it is best to use the term "solar irradiance" (sometimes called the solar intensity, a term that will appear throughout

the remainder of this report) .

Throughout the year, the distance between the earth and the sun varies due to the fact that the earth revolves around the sun in a slightly elliptic path. This variation in the earth-sun distance in turn gives rise to annual deviations in the solar intensity falling on the earth's surface. Presented in Table 1 are values of the total solar intensity as a function of the earth-sun distance. Note that the peak values occur during the winter months of December, January, and February.

DATE	SOLAR INTENSITY (mW per cm <sup>2</sup> )
January 3	139.9
February 1	139.3
March 1	137.8
April 1	135.5
May 1	133.2
June 1	131.6
July 4	130.9
August 1	131.3
September 1	132.9
October 1	135.0
November 1	137.4
December 1	139.2

Table 1

In addition to the seasonal variations, the amount of sunlight falling on a specific geographic location, known as the solar insolation, is dependent upon such factors as the location's latitude, the prevailing local climate, and even the local air pollution levels. Shown in Figure 1 are the seasonal variations in incident solar energy for two major U.S. cities geographically separated by a large distance, Albuquerque, N.M. (Lat. 35.05 N), and Cleveland, OH (Lat. 41.40 N). These measurements were both taken utilizing an aperture in a plane surface tilted down from a horizontal position toward the South by an angle equal to the local latitude and fixed in position, thus allowing readings of both diffuse sky and direct solar radiation, but

no ground reflections. As is apparent from the figure, different geographic locations due yield quite different values of useful incident energy as Albuquerque is much more desirable for year round solar power generation than Cleveland, all other factors put aside.

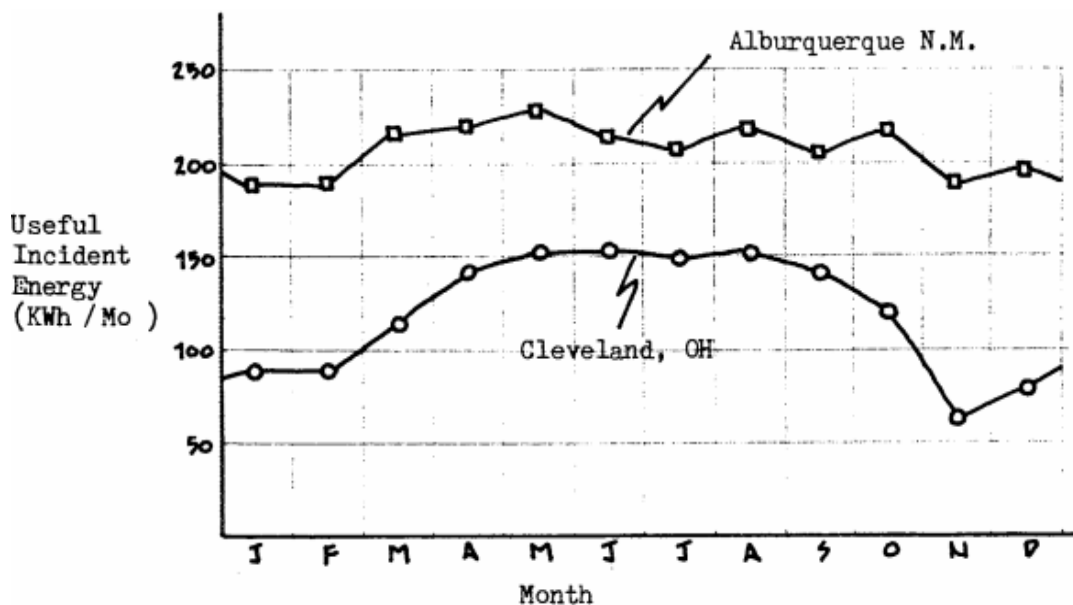


Figure 1

Inasmuch as photovoltaics require a certain minimum amount of solar energy before being able to produce a tactically useful output, it is often desirable to know for how many hours sufficiently intense sunlight will be available. In order to determine the diurnal solar variations for a specific location, measurements of incident solar energy are taken continuously throughout the day and the results are averaged over a period of x number of years. Typical diurnal insolation graphs are shown in figure 2 for a clear day, a partly cloudy day, and a cloudy day in Albuquerque, New Mexico.

Perhaps the most important factor to affect the output of a solar cell is the spectrum of the solar energy incident upon it. Because the earth's atmosphere is a spectrally selective filter which modifies the sunlight, the solar energy incident on a cell at the earth's surface will be quite different, both spectrally and in magnitude, from that incident

upon a cell in orbit above the earth. For example, the direct solar intensity near sea level on a clear day near noontime is approximately 100 mW/cm<sup>2</sup> while in free space the solar intensity is 135.3 mW/cm<sup>2</sup>. This difference in intensity has a profound effect on the output of a solar cell, changing the current delivered by the cell by approximately 120%.

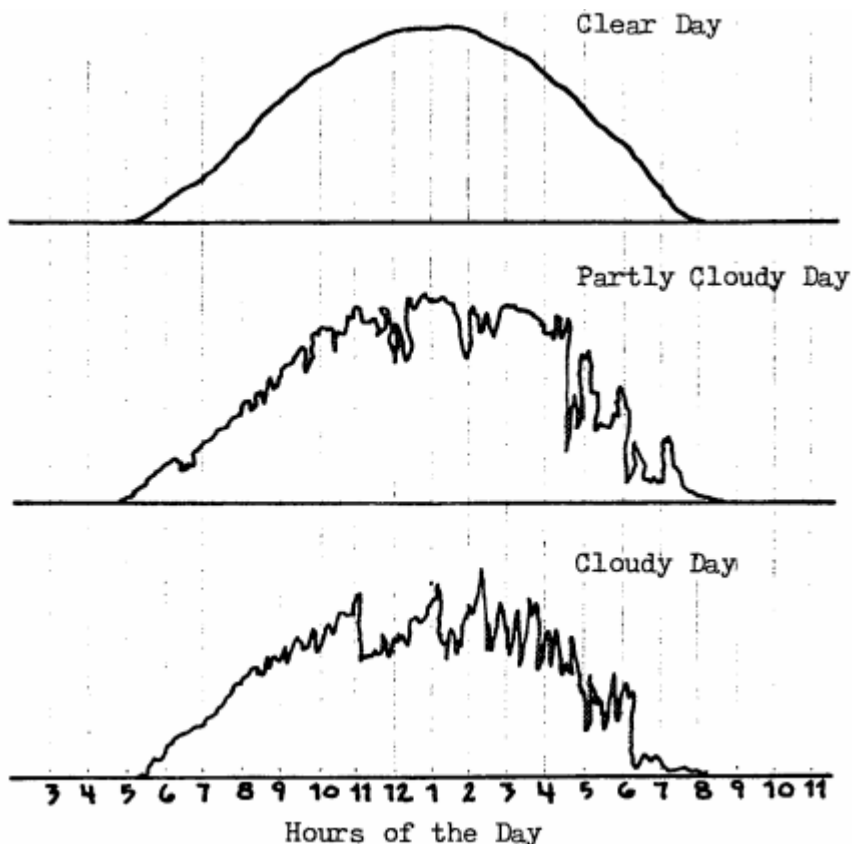


Figure 2

Figure 3a contains a comparison of the solar irradiation curve obtained outside the earth's atmosphere to that measured with atmospheric attenuation, both plotted as a function of wavelength. Note that the curve obtained at sea-level is deficient in the short wavelengths or "blue" region of the spectrum. By comparing this with the spectral response of a typical silicon solar cell shown in figure 3b, it is apparent that the cell's energy

conversion efficiency will be higher for sea-level spectral conditions than for free space conditions. The reason is that, because of the deficiency in the shorter wavelengths, a relatively greater percentage of the total incident solar energy is then in the larger wavelength region of the spectrum, a region where the cell is spectrally more sensitive. Therefore, in the design of photovoltaics for either space or terrestrial applications, the spectral response of the cell should be designed such that it is more sensitive to the solar spectrum available in the environment in which it will be utilized.

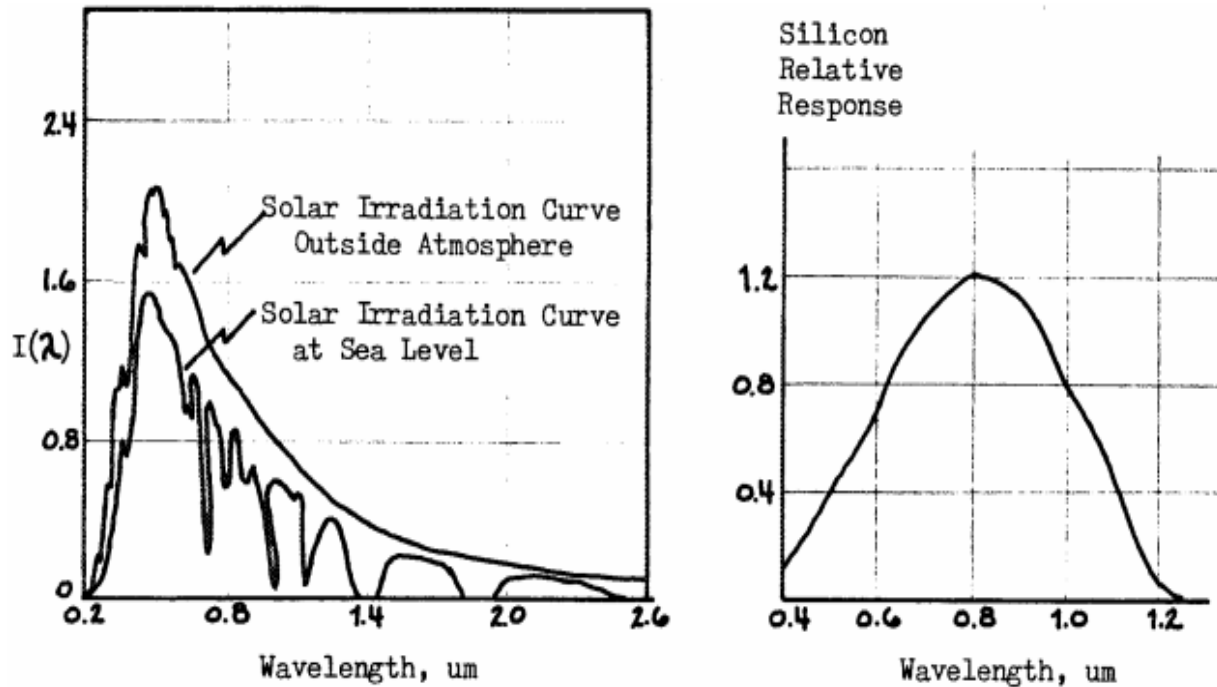


Figure 3

### 3. Solid State Principles

Solid materials can be basically categorized into three major groups: insulators, conductors, and semiconductors. When considering the conductivities of solid materials, we note that the range of values from conductive materials to materials considered insulators is quite enormous. Representative values are from  $6 \times 10^7$  S /m for silver, a good conductor, to less than  $2 \times 10^{-17}$  S /m for fused quartz, a good insulator. However, it is the



materials with the intermediate conductivity values, the semiconductors, which we are most interested in. The basic reason is that all of the practical solar cells developed to date are made with semiconductors. Therefore, this report continues with a discussion on the basic principles of semiconductor materials.

#### i. Band Theory of Solids

When isolated atoms are brought together to form a solid, various interactions occur between the neighboring atoms, particularly those arising from the bonding activities of these atoms and their electrons. In the process, important changes occur in the electron energy level configurations which result in the varied electrical properties of different solids.

If anything, from freshman chemistry, you should recall that electrons in isolated atoms can exist only at discrete or quantized energy levels. Furthermore, it is known that the Pauli exclusion principle limits the number of electrons that can exist at any of the allowed energy levels. As atoms are brought closer together, as in a crystal, so that their electron wave functions begin to overlap, the exclusion principle dictates that no two electrons in a given interacting system may have the same quantum state, therefore, the discrete energy levels of the isolated atoms must split into new levels belonging to the pair rather than the individual atoms. Because of the large number of atoms brought together in a solid (crystal); there may be  $10^{22}$  atoms in a crystal, the split energy levels will essentially form continuous bands of energies. These electron energy levels in the material can be represented by the energy diagrams shown in figure 4, depicting both the allowed energy levels and the ranges of energies in between the allowed bands where electrons are forbidden to exist. This gap is oftentimes referred to as the "forbidden band" since in a perfect crystal it contains no electron energy states. Because every solid has its own characteristic energy band structure,

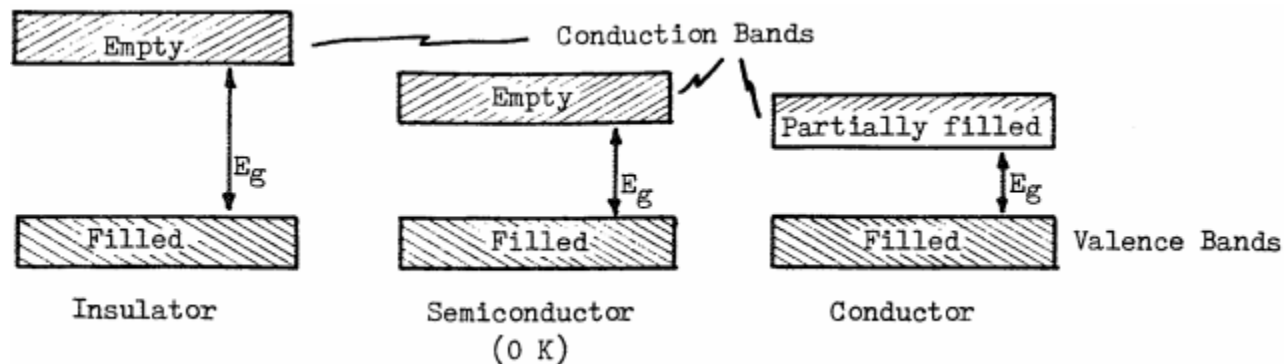


Figure 4

it is the variations in the band structure and the distribution of electrons in the outermost or highest energy bands which are responsible for the wide range of electrical characteristics observed in various materials.

In order to understand why a solid is a good conductor or a good insulator, it is necessary to study the fundamentals of electron movement within the solid, in other words, the mechanisms of current flow. The number of electrons in a solid is usually a small percentage of the total allowed energy locations available with the electrons constantly seeking lower energy levels. However, due to either thermal or optical excitation, the electrons are constantly being excited to higher energy states. The distribution of the electrons in the allowed levels can be described by the Fermi function:

$$F(E) = \frac{1}{\exp[(E - E_f)/kT] + 1}$$

where  $E$  is the energy of the allowed state,  $E_f$  is the Fermi energy,  $k$  is Boltzmann's constant, and  $T$  is the absolute temperature. Of particular interest is the Fermi energy (also called the Fermi level),  $E_f$ , defined as the energy at which the probability of a state being filled is approximately 1/2; or in other words, the highest energy state an electron can have at 0°K. The Fermi level is a very important concept and plays an enormous



role in electron movement.

In order for electrons to experience acceleration from either thermal or optical excitation, they must be able to move into new energy states. This implies that there must be allowed energy states not yet occupied by electrons (empty states) available to the excited electrons. Returning to figure 4, the highest occupied band in this diagram corresponds to the ground state of the outermost or valence electrons of the atom, the electrons responsible for current flow. Therefore, as one would expect, this band is called the valence band while the upper band is termed the conduction band and the distance between these bands is defined as the energy gap,  $E_g$ . As is apparent from figure 4a, b, insulators are very similar to semiconductors at 0°K. For both types of materials the valence band is full and the conduction band is empty. As a result, there can be no charge transport in the conduction band since there are no electrons present and because there are no empty states available in the valence band into which electrons can move, no charge transport can occur here either. However, there is a difference between the insulator and the semiconductor which accounts for their dissimilarity in conductivity. This is due to the fact that the band gap for insulating materials is much larger than that for semiconductors. For example, silicon, a semiconductor, has a band gap of 1.1 eV as compared to 10 eV for Alumina ( $Al_2O_3$ ). The relatively small band gap for semiconductors thus allows for excitation of electrons from the valence band to the conduction band by reasonable quantities of thermal or optical energy. Therefore, at room temperature, a semiconductor with a 1.1 eV band gap will have a significant number of electrons excited across the energy gap into the conduction band whereas an insulator with a 10 eV energy gap will have a negligible number of electron excitations.

Finally, in figure 4c is the band gap diagram for a metal in which the

bands either overlap or are only partially filled. Thus electrons and empty energy states are intermixed within the bands so that electrons can move freely under the influence of any type of excitation. This accounts for the fact that metals have a high electrical conductivity.

The type of semiconductor discussed above is an intrinsic semiconductor in which the conduction of current is due only to those electrons excited up from the valence band to the conduction band. This material is usually produced with ultra-high purity materials and by slowly growing large single grain crystals, very low defect semiconductors can be made. However, by adding small amounts of impurities called dopants at carefully controlled levels to the semiconductor crystals, it is possible to dictate the dominant type of conduction; either electrons or holes\*. This type of material is called an extrinsic semiconductor because the conduction is due to the impurities added. Consider figure 5a., which shows the two dimensional diamond structure of a pure silicon crystal with its normal covalent bonds that exist by the sharing of electrons. This is an intrinsic semiconductor and its band structure is shown below it (note the Fermi level is roughly in the center of the energy gap). In figure 5b, one of the silicon atoms has been replaced by doping with a phosphorus atom which supplies an extra electron. Since this extra electron is held in place only by the coulomb attraction to the phosphorus nucleus, it can be removed and excited to the conduction band with much less energy than is required to move a valence electron across the band gap. On the corresponding band diagram, this has the effect of shifting the Fermi level toward the conduction band plus providing a donor level that donates extra electrons to the conduction band thereby making the electrons

"holes" are empty states in the valence band into which electrons can move; current can also be pictured as positively charged holes moving in the opposite direction of electrons.

the majority charge carriers. This is an example of an "n-type" extrinsic semiconductor.

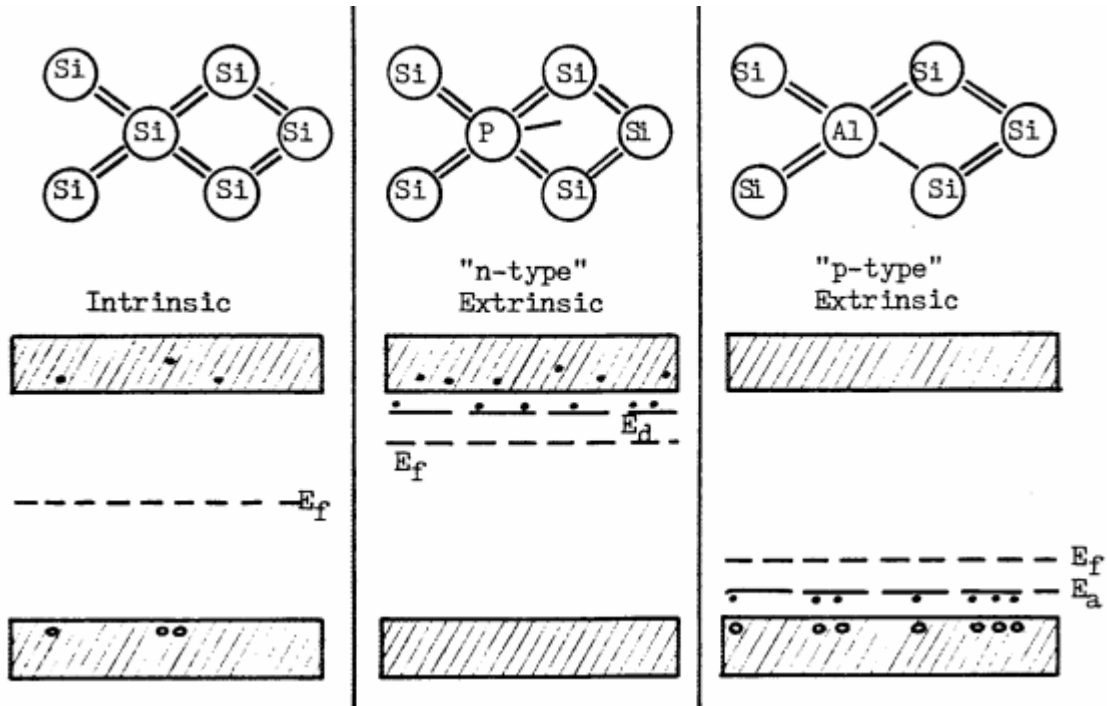


Figure 5

Figure 5c contains an example when the material is doped by aluminum, which has a deficiency of one electron thereby contributing an extra hole to the lattice structure. This allows for a valence electron to jump into this hole with far less energy than that required to excite it across the energy gap, thus creating another hole in its vacated spot and the result is positive charge conduction. The addition of these extra holes into the crystal lattice thus provides an acceptor energy level,  $E_a$ , in the band gap which accepts electrons from the valence band easily. Therefore, in this case, the holes are the majority charge carrier and the resulting material is an example of a "p-type" extrinsic semiconductor.

#### ii. Optical Characteristics

By definition, the photovoltaic effect is the generation of a potential when radiation (photons) ionizes the region in or near the built-in potential

barrier of a semiconductor. However, in order to obtain useful power from the photon interactions in the material, three essential processes must occur:

1. A photon has to be absorbed and result in electrons being excited to a higher potential.
2. The electron-hole charge carriers created by the absorption must be separated and moved to the edge to be collected.
3. The charge carriers must be removed to a useful load before they recombine with each other and lose their added potential energy.

For an incoming photon to be completely absorbed by an electron, it must possess an energy greater than the forbidden band energy,  $E_g$ , thereby allowing the electron to jump the gap into the conduction band. Any excess energy above the minimum energy required is usually given up to the lattice as thermal energy. If, however, the photon has an energy less than  $E_g$ , the material will essentially appear transparent as there is no mechanism with which the electron could interact.

Once the photons have been absorbed and the electron-hole pairs (EHP's) generated, the charges must then be separated. This is typically accomplished by means of a potential barrier formed when a p-type material is brought into contact with an n-type material thus creating a p-n junction semiconductor." The energy level diagram for a typical p-n silicon solar cell is shown in figure 6.

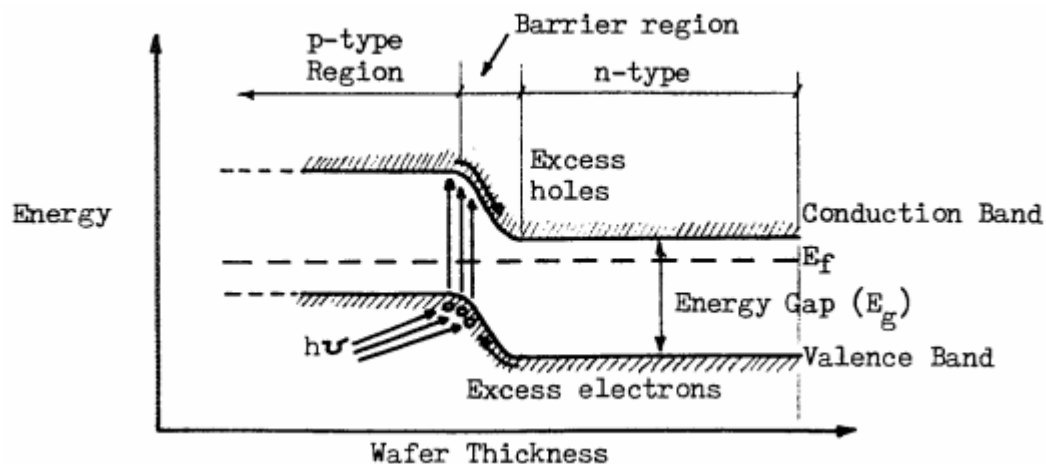


Figure 6

Notice the Fermi level of the n-type material is near the top of the energy gap and thus there are many electrons in the conduction band and only a few holes in the valence band. However, for the p-type material, the opposite is true. This leads to the concept of minority and majority carriers. Since at a given temperature the product of the number of holes and the number of electrons is essentially constant ( $10^{21}$  for silicon @ 27°C), for n-type silicon,  $n$  could be  $10^{17}/\text{cm}^3$  while  $p$  is  $10^4/\text{cm}^3$ . When a solar cell (p-n junction) is exposed to light, all incident photons with energy greater than  $E_g$  create an EHP. For a very intense light source where a large number of EHP's are generated, the result is that the minority carrier concentration will increase many orders of magnitude while the majority carrier concentration will essentially remain the same. Therefore, an excess of minority carriers will occur and they will diffuse throughout the material until recombination occurs, usually within a few tenths of a microsecond.

However, if the excess carriers are generated within a diffusion length\* of the p-n potential barrier, the electric field induced by the junction will sweep the excess carriers across the junction in an attempt to reduce their energy. As depicted in figure 6, the excess electrons will flow to the left and the excess holes to the right. This creates an electric current moving from the p-type to the n-type material which can be funneled to deliver power to a load if the proper connections are made as in figure 7. The current generated will be proportional to the number of photons absorbed and the voltage produced will depend on the height of the barrier which in turn depends on how heavily the n and p regions are doped.

\* The diffusion length is the average distance a carrier diffuses before recombination.

\*\* A typical silicon solar cell (like the one used in this experiment) is made by first slicing a .015 inch thin wafer from an ingot of silicon that contains traces of boron, which makes the wafer receptive to electrons. Then it is heated to remove stresses and put into a furnace containing phosphorus vapor. The phosphorus then works its way into both sides of the wafer, forming a thin layer of n-type silicon. One of these sides is chemically removed and the wafer is



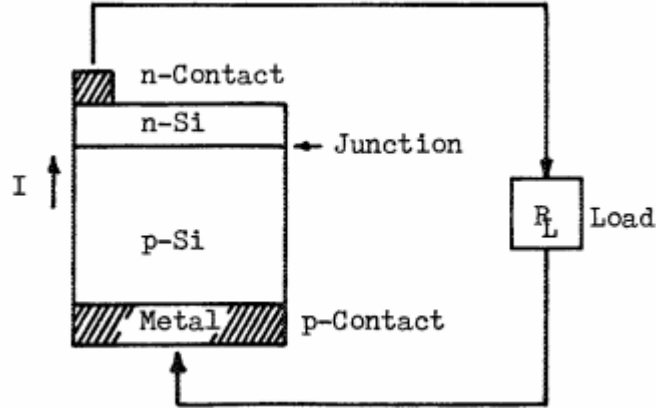


Figure 7

#### 4. Silicon Solar Cell Characteristics

The silicon Solar cell used in this experiment can essentially be represented by the simplified equivalent circuit shown in figure 8, which consists of a constant current generator in parallel with a nonlinear junction impedance ( $Z_j$ ) and a resistive load ( $R_L$ ). When light strikes the cell, a current  $I_s$  (short-circuit current) is generated which is equal to the sum of the current through the load,  $I_L$ , and the current flowing in the nonlinear junction,  $I_j$ .

Therefore: 
$$I_s = I_L + I_j \quad (01)$$

With 
$$I_j = I_0 (e^{qV/kT} - 1) \quad (02)$$

where  $q$  is the electron charge,  $V$  is the applied junction voltage,  $k$  is the Boltzmann constant,  $T$  is the absolute temperature, and  $I_0$  is the dark (reverse) saturation current. Hence, the current through the load is given

by: 
$$I_L = I_s - I_0 (e^{qV/kT} - 1) \quad (03)$$

and the maximum voltage obtained from the cell,  $V_{max}$ ; occurring when  $I_L=0$ , is:

$$V_{max} = 1/(q/kT) \ln((I_s / I_0) + 1) \quad (04)$$

$$= 1/\lambda \ln((I_s / I_0) + 1) \quad (05)$$

where  $\lambda = q/kT$

Shown in figure 9 is a general solar cell VI characteristic with both  $I_0$  and  $I_s$  Plotted. Note that the curves appear in the fourth quadrant, there

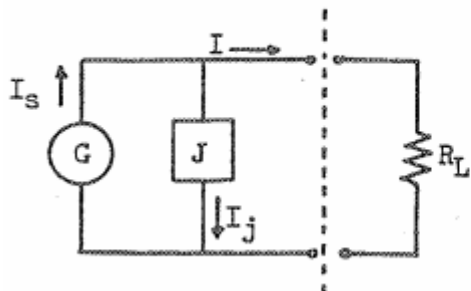


Figure 8

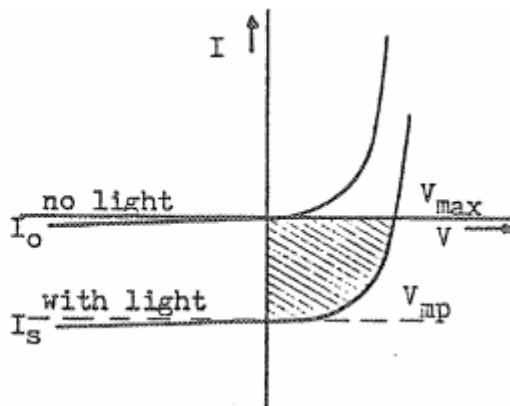


Figure 9

fore power can be extracted from the device according to Theory.\* The short-circuit current  $I_{sc}$ , and the open-circuit voltage  $V_{oc}$ , are determined for a given light level by the cell properties, whereas the maximum current and voltage deliverable to the load is determined by the largest area rectangle that can be fit under the VI curve as shown in figure 10. The point where this rectangle is tangent to the VI curve is therefore defined as the Maximum power delivered to the load:

$$P_m = V_m \times I_m \quad (06)$$

and is a very important value in calculating the efficiency of the unit.

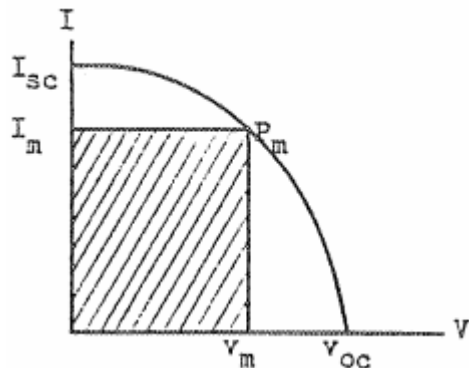


Figure 10

\* Throughout the remainder of this report, all VI plots will be translated to the first quadrant for ease of understanding.

\*\* (cont.) coated with chemicals and dipped in solder to form a metallic, electricity-collecting grid.

Another important value very useful in evaluating the overall efficiency of a solar cell is the "fill factor", defined as the ratio:

$$F.F. = I_m V_m / I_{SC} V_{OC} = P_m / I_{SC} V_{OC} \quad (07)$$

The fill factor, which is always less than unity, is typically used to describe quantitatively the "squareness" or "sharpness" of the VI curve. This is very informative in that the squarer such a curve is, the greater the maximum power output,  $P_m$ . Typical fill factors of contemporary silicon solar cells range from 0.75 to 0.80.

Plotted in figure 11 are the VI characteristics for four different silicon solar cells tested within the last eight years with the most recent being the largest curve. For one of these curves the power rectangle is also shown. As mentioned above, as the VI curve becomes "squarer" in shape, the greater the maximum power output obtained from the cell. However, since all of these curves were determined with the same light intensity of  $135.3 \text{ mW/cm}^2$  at a temperature of  $28^\circ\text{C}$ , as the curves become "squarer" and larger, the efficiencies also increase. It is left to the reader as an exercise to compare the efficiencies of these various solar cells<sup>#</sup>

Changing the illumination intensity incident on the solar cell has a great effect on the cell's output characteristic, most notably  $I_{sc}$  and  $V_{oc}$ , shifting the VI curve but generally not changing its shape. Figure 12 illustrates how the voltage and current vary as functions of the sunlight intensity, technically known as the radiant solar energy flux density. As is obvious from the figure, the short-circuit current is directly proportional to the flux while the open-circuit voltage varies as the log of the flux. Note that at high flux densities, the voltage exhibits a saturation level. Therefore, even with fluctuations in the intensity in this saturation range, the voltage will essentially be insensitive to the changes. This is

# Active area of cells:  $3.8 \text{ cm}^2$

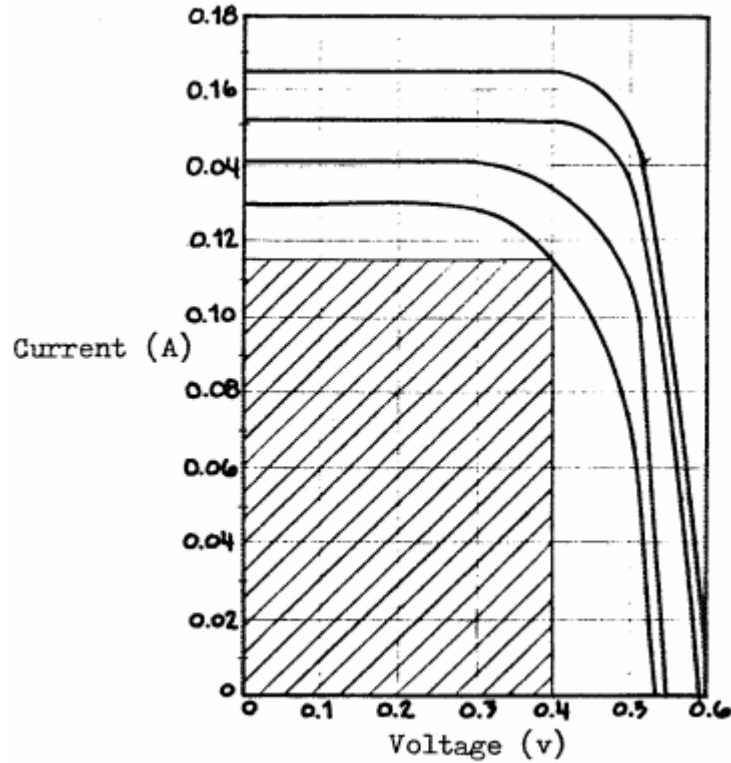


Figure 11

quite an advantage in that the cell can be employed for the charging of storage batteries without the need of a constant light source.

#### 5. Theoretical and Practical Efficiencies

The efficiency of a typical solar cell is defined by the following equation:

$$\eta = P_{out} / P_{in} = P_{out} / (A_c)(\rho_{in}) \quad (08)$$

where  $P_{out}$  is the electrical power output of the cell,  $P_{in}$  is the energy input to the cell,  $\rho_{in}$  is the solar illumination level per unit area, and  $A_c$  is the active solar cell area upon which the solar energy is incident. When speaking of the efficiency of a solar unit, a clarification as to what efficiency value must usually be made. If comparing various cells by their efficiencies, it is best to speak of the maximum efficiency,  $\eta_{max}$ , obtained. This is defined by the maximum power output capability that can be utilized by an optimized load at a particular illumination intensity and cell operating temperature. Throughout this report, when referring to the efficiency of a Particular cell,  $\eta_{max}$  is the quantity quoted. However, one can also speak

of the operating efficiency,  $eL_{op}$ ; the efficiency at which the solar cell or array is actually being utilized. This quantity is useful when comparing units operating at a less than maximum output.

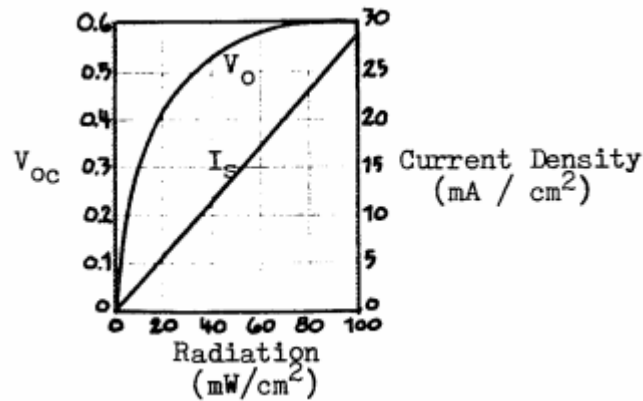


Figure 12

Equation 8 is very useful in calculating the practical efficiencies of various types of solar cells. Although 20% efficiencies have been achieved in the laboratory under strictly controlled optimum conditions, under normal operating conditions, the cell efficiencies vary from 10% for an OCLI Conventional silicon solar cell to 15% for a Comsat non-reflecting,  $p^+$ , textured silicon solar cell. Thus far, it seems the most efficient per unit cost solar cell available today is that produced with silicon even though other cells made with different materials have comparable efficiencies. However, these cells on the whole, are more costly to produce commercially .

According to theory, the maximum theoretical efficiency obtainable from silicon solar cell is approximately 22%. This value results from an analysis of the equation for the maximum solar conversion efficiency;

$$\eta_{\max} = k \left( \frac{\lambda V_{mp}}{1 + \lambda V_{mp}} \right) \cdot \frac{n_{ph}(E_G)V_{mp}}{N_{ph}E_{av}}$$

where  $k$  is a constant depending on the reflection and transmission coefficients

and the collection efficiency,  $V_{mp}$  is the voltage delivered at maximum power,  $n_{ph}(E_g)$  is the number of photons that generate EHP's in a semiconductor of energy gap  $E_g$ , and  $N_{ph}E_{av}$  is the input power where  $N_{ph}$  is the number of incident photons and  $E_{av}$  is their average energy in electron volts. Assuming  $\lambda V_{mp} \gg 1$  and  $k \cong 1$ , this equation reduces to :

$$\eta_{max} \cong \frac{n_{ph}(E_g)V_{mp}}{N_{ph}E_{av}} \quad (10)$$

By further assuming that for silicon,  $n_{ph} \cong (2/3) N_{ph}$  and  $V_{mp} \cong (1/3)E_{av}$ , the equation yields:

$$\eta_{max} \cong \frac{(2/3)N_{ph}(1/3)E_{av}}{N_{ph}E_{av}} = \frac{2}{9} = 22\% \quad (11)$$

In a report written by M.B. Prince and published in 1955, this value was determined to be approximately 21.7%. This is considered the ultimate maximum theoretical efficiency obtainable for a silicon solar energy converter. An interesting note here is that if mono-chromatic light is used with an energy equal to the band gap,  $n_{ph}$  will be equal to  $N_{ph}$  and  $V_{mp} = .75 E_{av}$ , therefore, the maximum theoretical efficiency could be approximately 75%. As is evident from the equation for  $\eta_{max}$ , the theoretical maximum efficiency is a function of the semiconductor energy gap. Although for increasing values of the energy gap, the number of photons absorbed decreases, because  $I_0$  is also reduced, the cell voltage is thus increased. Shown in figure 13 is a graph illustrating the relation between  $\eta_{max}$  and  $E_g$  for several solar cell materials.

In terms of efficiency versus band gap, cadmium telluride (CdTe) appears to be the best suited material for producing photovoltaic devices. However, due to a combination of low electron mobilities (thus resulting in poor collection efficiencies) coupled with a high internal resistance, the practical efficiencies obtained to date for this material have been less than 8% under ordinary operating conditions. When comparing the efficiency per

unit cost of CdTe cells to that of silicon, silicon cells hold a distinct advantage over CdTe.

On the other hand, InP has high electron mobilities and laboratory efficiencies have been achieved that are competitive with silicon ( $\eta = 12\%$ ). However, here too, silicon possesses a much greater efficiency when considering cost aspects as InP solar cells are still quite expensive to produce commercially.

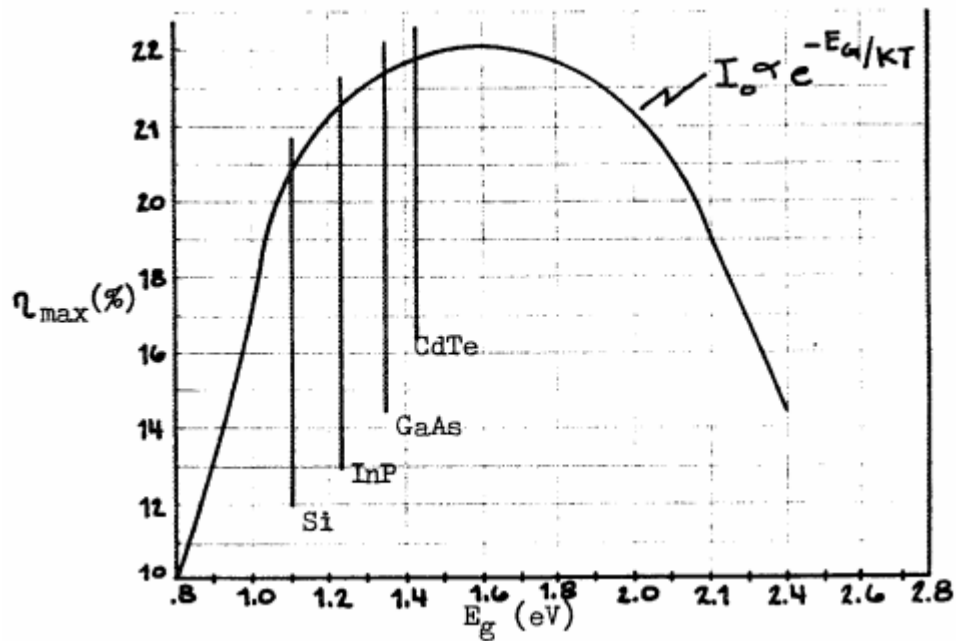


Figure 13

Perhaps the most promising material other than silicon for producing solar cells is Gallium Arsenide (GaAs). Possessing an energy gap close to the peak of the curve in figure 13, and an electron mobility higher than that of silicon, this material has the potential for replacing silicon as the most common photovoltaic material. Even though this type of material has its drawbacks, such as a minority carrier lifetimes and an absorption coefficient much lower than for silicon, practical efficiencies of 14% have been reported (very comparable to Si). Although at present, GaAs is a very

Lifetime: the average time between EHP creation and recombination.

expensive material; Ga and As material costs have been decreasing steadily and it is predicted that by 1990, the material costs of Si and GaAs will probably be equal thus making GaAs solar cells extremely competitive with Si cells.

Although as of late, higher maximum solar energy conversion efficiencies have been obtained, the percentage increase has not been substantial due to the many factors on which the efficiency depends. Since not all of the desired specifications can be met in the design of a solar cell, trade-offs must be made in order to yield the highest efficiency unit at a reasonable cost. In general, the maximum solar efficiency depends upon the following

factors:

- the solar cell internal construction,
- dimension,
- active area,
- specific material properties,
- photovoltaic junction characteristics,
- the anti-reflective coating,
- surface texture,
- contact and grid configuration,
- the illumination', level,
- cell operating temperature,
- and various environmental factors.

## 6. Effects of Temperature and Internal Resistances on Cell Efficiency

One should expect any device utilizing semiconductors to be quite sensitive to temperature deviations from normal operating temperatures, and solar cells are no exception. An increase in the operating temperature of a solar cell typically has the effect of slightly increasing the cell's short-circuit current and significantly decreasing the cell voltage. Therefore, as the temperature of the solar cell rises, the result is that the maximum efficiency decreases. (the area of the power rectangle under the VI curve decreases). In a silicon solar cell, the short-circuit current is relatively independent of temperature, being only a function of the illumination level. Thus, the increase in  $I_{sc}$ , typically less than  $0.1\%/^{\circ}C$ , depends only



upon the spectral distribution of the illuminating light and the spectral response of the solar cell. The cell voltage, however, decreases substantially for increasing cell temperatures due to changes in the diode conduction characteristics; in other words,  $V$  is a function of  $I_0$ , a quantity quite sensitive to temperature changes. Typically, the voltage usually decreases at a rate of approximately 2.0 - 2.3 mV/°C.

For the silicon solar cell used in this experiment, the temperature coefficients are as follows:

Temperature Range: -65°C to +125°C				
Voltage:	increases by	2mV/°C	below	25°C
	decreases by		above	
Current:	increases by	25 A/cm <sup>2</sup> /°C	above	25°C
	decreases by		below	
Power:	decreases by	0.3%/°C	above	25°C
	increases by		below	

Because a typical solar cell contains internal resistances that can reduce the cell's maximum efficiency dramatically, the simplified circuit in figure 8 can be modified as illustrated in figure 14 to show these internal resistances.

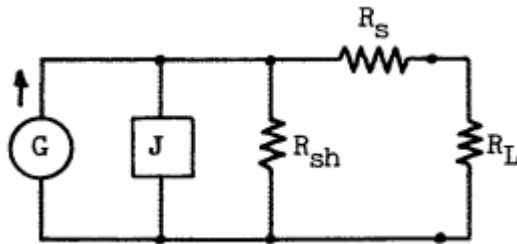


Figure 14

In the above figure,  $R_S$  is the cell's series resistance and  $R_{sh}$  is the shunt resistance. The solar cell's series resistance represents in lumped fashion all distributed resistance elements in the device, its ohmic contacts, and the semiconductor/contact interfaces. Because  $R_S$  is a lumped quantity, it varies with practically every cell parameter, such as the VI characteristic,

illumination level, and temperature. The solar cell's shunt resistance, on the other hand, represents the portion of the generated electrical energy lost through the cell's internal leakage paths such as that through the p-n junction (recombination current), and along the outer cell edges (surface leakage).

Both of the solar cell internal resistances effect the output of the solar unit, however, for operation with illumination near one solar constant, the effect of the shunt resistance is negligible. The series resistance, though, has a dramatic effect on the output and thus the energy conversion efficiency of the solar cell. Ideally, it is desired that the series resistance approach zero while the shunt resistance approaches infinity. As an example, a shunt resistance as low as 100 ohms does not appreciably change the shape of the VI curve (and thus the power output) of a cell whereas a series resistance of only 5 ohms reduces the available load power to less than 3096 of the optimum power with  $R_s = 0$  ohms. The effect of both  $R_s$  and  $R_{sh}$  on the VI characteristic curve for a 2 x 2 cm solar cell is shown in figure 15 .

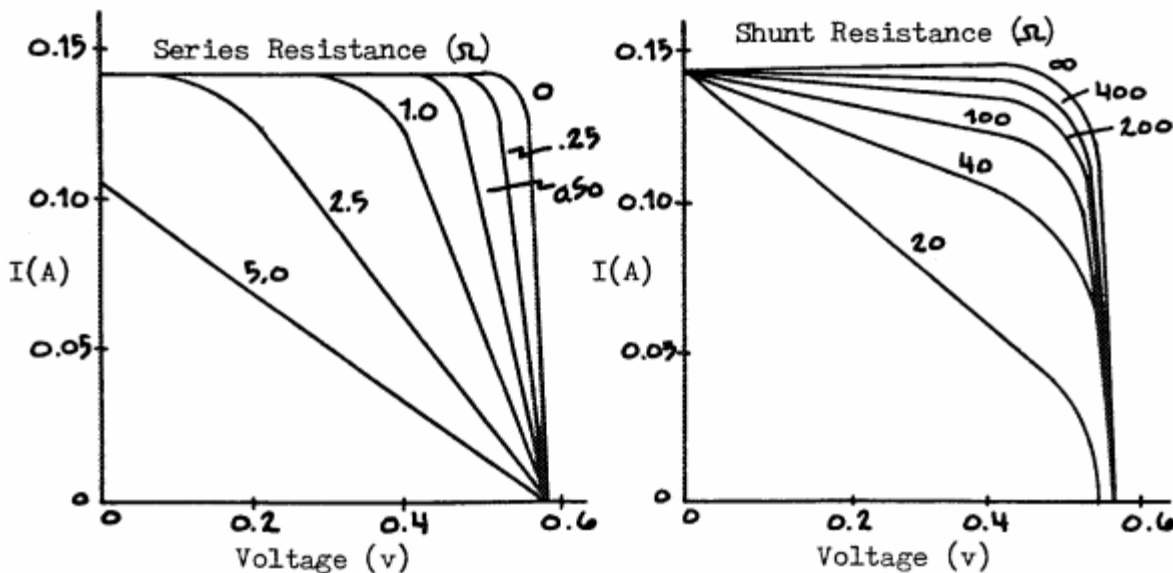


Figure 15

## 7. Practical Realizations

It can hardly be said of photovoltaics that their day has arrived. However, in the comparison of solar cells versus conventional means of generating electricity, it is obvious that solar energy converters are gaining ground rapidly ( as natural resources dwindle and costs soar) and in the long run will most likely either come out on top or at least be a competitive energy source in the future. As with all new technologies, it takes time and effort before any practical applications can be realized. Throughout the world, this effort is being put forth in the form of advanced research on photovoltaic systems and hence it is only a matter of time before the day of the solar cell is upon us.

### i. Applications

Although the cost of solar energy is still too expensive, yielding power ten times more costlier than that generated by oil, there are still applications for which solar power is economically feasible. It is particularly suited for remote applications where there is no direct tie-in to an electric utility feeder, or where the transportation of fuel to the generator site is impractical. In conjunction with an electrochemical storage battery and suitable charge control electronics, solar cell arrays can be designed to provide practically continuous power. Some examples of this type of application include:

1. electronic and optical beacons and warning devices such as channel buoys and shoreline barkers.
2. remote television and radio receiver stations.
3. radio transmitters and transponders, microwave repeater stations.
4. weather and earthquake monitoring stations.
5. electronic (galvanic) corrosion protection of metal structures such as bridges and towers.

With the assistance of federally funded programs, numerous other practical

applications are then made economically feasible. Some of these applications include:

1. solar panels installed on the rooftops of homes can provide either heating and hot water or a percentage of the total electricity consumed.
2. solar panels installed on the rooftops of commercial and public buildings can provide a portion of the total electricity consumed; some examples where implementation has already occurred include a national park headquarters, some schools, and a daytime country music station in Ohio.
3. irrigation projects.
4. use of solar cells for hydrolysis and other electrochemical processes.
5. emergency, surveillance, and security systems.

Although the applications noted above can be termed small scale, large scale solar generating stations have been proposed but due to the efficiency limitations and the high per watt cost of these plants, it does not appear that these proposals will be economically feasible and therefore, not realized for quite awhile. However, it is worthwhile to examine a typical solar energy generating scheme in order to get an idea of how to power from large solar arrays will interface with the conventional power grid. The basic block diagram for a typical solar power generating system is shown in figure 16 .

The basic operation is quite simple, beginning with the power generation by the solar array. By employing an array orientation system, the array output capability is maximized by having this subsystem orient the solar cells at the right angle to the sun during all operating periods. The generated power is then gathered by a power collection system which then routes a portion of the power to an energy storage system and the rest to the conversion/regulation system. The energy storage is necessary to provide electricity during periods when the solar array is not sufficiently illuminated to generate a usable output. The power proceeding to the c/r subsystem

is then "smoothed" and fed into a distribution center which reroutes a portion of this usable back into the system for control purposes, The remainder is then fed into the main power grid via an interfacing system and distributed to the various user loads.

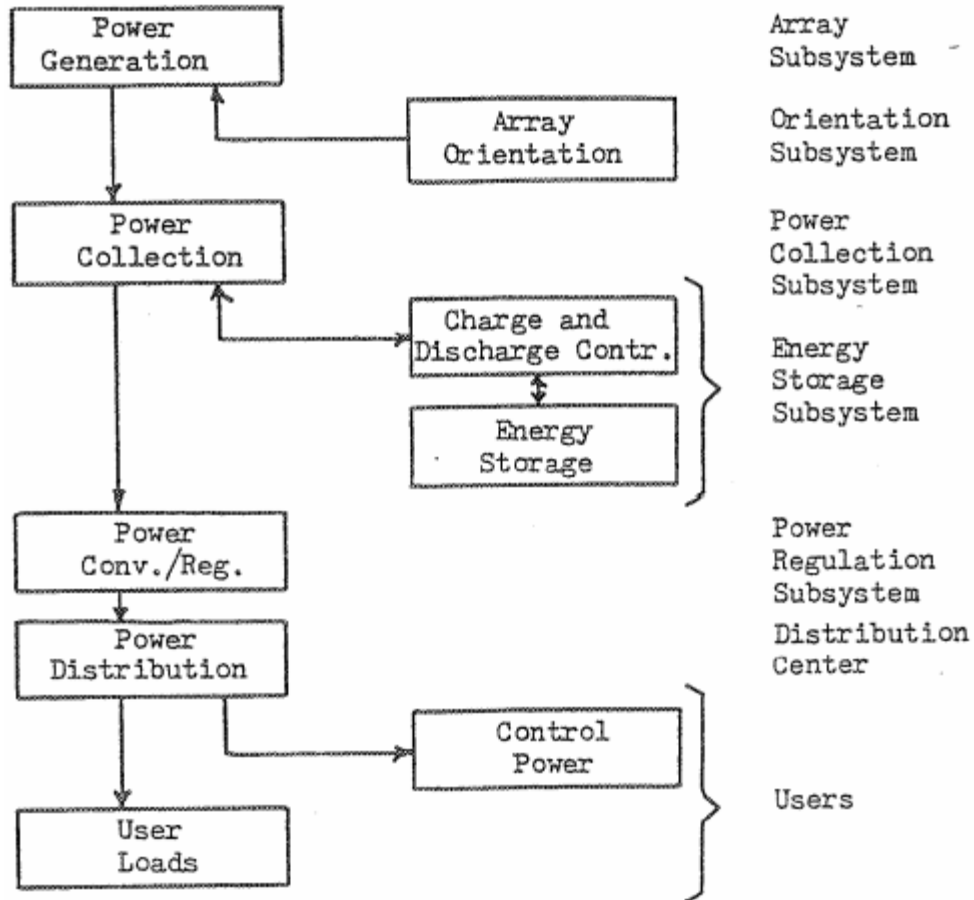


Figure 16

Even though at this time, this type of large scale solar energy generation is not economically feasible, the prospects far a system of this type in the future are excellent and should not be ignored.

Because solar cells consume no fuel, do not emit harmful exhaust products or radiation, and operates with little or no maintenance for a long period of time, they are especially well suited for applications in the space industry. This is apparent in that most of the satellites and space

vehicles launched to date have utilized power from on-board solar cell arrays to operate the internal equipment as well as the communication equipment. In addition, recently a new area under investigation is that of solar-electric propulsion for space vehicles. The basic concept is that high voltage electric energy produced by a solar cell array is utilized by an ion drive to ionize a substance and to eject a stream of ionized particles which propels the spacecraft in a manner similar to a rocket engine. Although still in the planning stages, it nonetheless conveys the idea that in the future, solar cells will be doing more than just providing electricity for our homes.

ii. Concentrators

For many photovoltaic applications, it may be desirable to improve the output of the solar cell by the use of solar concentrators. The purpose of the concentrator is to increase the intensity of the sunlight incident on the cell over its naturally occurring value thus increasing the cell output by a proportional amount. Solar concentrators can be described on the basis of their "geometric concentration ratio,"

$$C_g = A_a / A_t$$

where  $A_a$  is the entrance aperture area and  $A_t$  is the smaller target area or exit aperture area. However, because of optical imperfections in most concentrators, it is best to relate the performance of a concentrator by its "actual concentration ratio,"

$$C_a = S_t / S_i = \eta_0 C_g$$

where  $S_t$  is the solar intensity incident on the target plane,  $S_i$  is the solar intensity incident on the entrance aperture, and  $\eta_0$  is the concentrators optical efficiency. Because solar intensity measurements are very time consuming and difficult to obtain accurately, it is preferable to utilize an equation relating the overall concentrator/ array system efficiency.

This is given by:

$$\eta_s = P_{out} / S_a A_a \quad (14)$$

where  $P_{out}$  is the cell output power in watts,  $S_a$  is the solar intensity incident on the entrance aperture of the concentrator, and  $A_a$  is the entrance aperture area in square meters. This is experimentally obtainable although care must be taken to assure accurate measurements of  $S_a$ .

Basically, there are five methods in which sunlight can be concentrated: refraction, reflection, wavelength conversion, diffraction, and laser action; with the first two cases being the most popular methods. Reflection is usually accomplished by the use of mirrors whereas refraction is done with lenses. In this experiment, Fresnel concentrator lenses will be used to refract the light although other types of lenses such as planoconvex, and biconvex can also be used.

### iii. Lifetime and Maintenance

In essence, solar cells have unlimited life and are practically maintenance free. However, since the cells are usually subject to various environmental effects, both fair and adverse, photovoltaic systems do require some periodic maintenance (especially for terrestrial applications) so that negligible cell or system degradation occurs.

Humidity is perhaps the major cause of most maintenance problems for solar arrays, causing the growth of fungus and the formation of a "sticky" surface film that tends to catch dust and dirt particles. This in turn leads to reduced cell output and lower efficiencies. Humidity, coupled with high temperatures is also very detrimental in that corrosion occurs.

In addition to humidity problems, other environmental effects on arrays that may require some preventive maintenance is that occurring by various forms of precipitation (especially hail, snow, and ice; rain has a beneficial effect), by wind damage, earthquakes, and unfortunately, vandalism.

### 8. Cost and Future Prospects

In general, solar cells appear to be the ultimate energy source of the future. They are simple to operate, simple to maintain, mechanically uncomplicated, reliable, safe (with no harmful by-products), and operate with a minimum lifetime of 20 years at a reasonable energy conversion efficiency. But they are also expensive. Therefore, the big question becomes, are solar cells practical enough to be feasibly employed as a major source of generated electrical energy? The answer is no, solar cells are generally not economically feasible for most electricity generating applications at this time; but sometime in the future, the prospects for solar generation of electricity are promising.

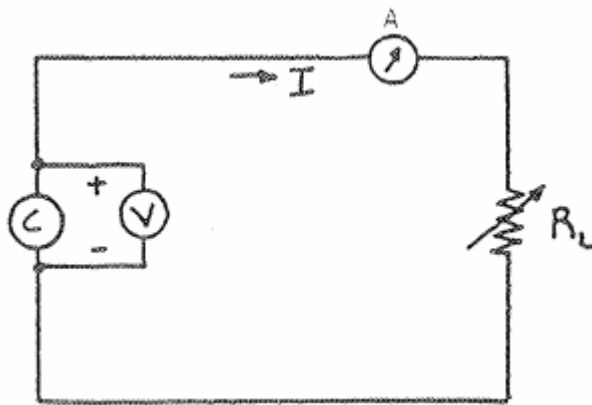


Figure 17



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## B. EXPERIMENT

### 1. Equipment List

- 1 Instrument rack with the usual test equipment
- 1 Mounted silicon solar cell (Solarex #42,270)
- 1 Radiometer
- 1 G.E. Quartzline Halogen lamp (Par Flood Lamp, Q150Par 38FL)
- 1 Mounted outdoor lamp fixture (Sarama 2953 - 15)
- 1 Variable autotransformer
- 1 Temperature probe
- 1 Roll masking tape
- 1 Meter stick
- ? such other equipment as may be needed

### 2. Preliminary Setup and Calibration

To assist the student in his endeavors, the solar cell has been mounted in a convenient box and suitable resistors permanently connected as shown in Fig. 18. Pay special attention to the two potentiometers which (a) increase resistance when their knobs are rotated in a clockwise direction and (b) together with the shunt constitute the load resistance  $R_L$ . Note that the contact resistance in each should be on the order of  $10\text{ m}\Omega$ . Electrical connections to the solar cell must be made as illustrated in Fig. 18; this is known as a 'four-wire connection' and minimizes the effects of lead and contact resistance in the measurements.

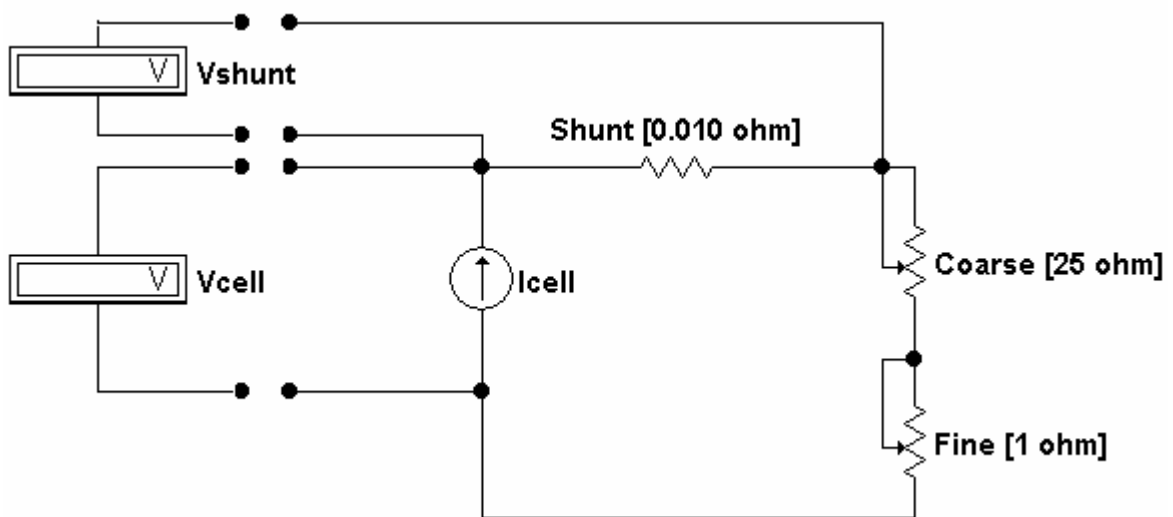


Figure 18  
Solar Cells -- 33

Use masking tape to mark a zero position for the front face of the solar cell box close to the equipment chassis and perpendicular to the edge of the bench. Lay down strips of masking tape from the zero position to the far end of the bench; these tape strips should be parallel to the edge of the bench. Calibrate the tape strips at 0, 100, 250, 500, 750, 1000, 1250, and 1500 mm. Note that the optical axis of the solar cell lies  $90 \pm 5$  mm above the bench top.

Connect the infrared (IR) sensor to the light meter to form a radiometer. Calibrate the radiometer in units of  $W/m^2$  per the calibration procedure using the coefficient shown on the IR sensor tab. Now tape the IR sensor to the back of the solar cell box, centered left to right,  $90 \pm 5$  mm above the bench top. Position the solar cell box with the IR sensor facing the flood lamp such that the IR sensor face is on the marked zero position

### 3. Incident IR Energy

Connect the flood lamp to a variable autotransformer and adjust the lamp voltage to the maximum that allows incident power readings to be taken at 100 mm without saturating the radiometer. Be sure that ambient IR energy is minimized by turning off all bench lights and closing all blinds. With the flood lamp off, record the ambient IR reading. Now turn the flood lamp back on and measure incident power density at the solar cell box position in  $kW/m^2$  as a function of radiometer to lamp spacing at each calibrated distance.

### 4. Solar Cell VI Characteristics

With the incident illumination set to a nominal<sup>#</sup>  $1 kW/m^2$  through adjustment of the lamp spacing only, face the solar cell box toward the flood lamp with its front at the zero position. Vary  $R_L$  and measure  $v(i)$  all the way<sup>▼</sup> from near-open-circuit to near-short-circuit conditions.

### 5. Solar Cell Sensitivity

Adjust  $R_L$  to yield three-quarter maximum current at the illumination of  $1 kW/m^2$ ; call this value  $R_L^*$ . Then determine  $v$  and  $i$  at  $R_L^*$ , at  $R_L = \textit{near-open-circuit}$ , and at  $R_L = \textit{near-short-circuit}$  for a number of different illuminations at the calibrated distances as the flood lamp position is varied all the way from 100 mm to 1500 mm.

<sup>#</sup> "nominal" is a superb weasel-word which should be mastered by all practicing engineers and scientists. What it means is that the quantity in question has been measured to the best of our ability but that we aren't prepared to say just how great our ability is. Presumably, (i) a sequence of nominal values will correlate well with the corresponding sequence of actual values. (ii) the absolute error of any measurement is within bounds considered tolerable by an experienced investigator in the area, and (iii) any given setting or measurement is repeatable.

<sup>▼</sup> In varying  $R_i$ , proceed with delicacy. You'll have a devilish time finding the power maximum unless you employ sharp ears and sensitive Fingertips to discern the winding-to-winding progress of the wiper over the coils of the rheostat.

**Note that the electronic properties of the cell can be a strong function of device temperature. The photocell should be maintained close to ambient temperature by interrupting the incident light except when a data point is actually being taken.** This can be done with a flat opaque object such as a notebook. This has proven to be a better alternative than switching the lamp off and on. Note that it takes a few seconds after illuminating the cell for the meters to settle and that the output from the cell then seems to drift slowly.

## 6. Temperature Effects on Cell Characteristics

Fix the source-cell spacing to yield  $1 \text{ kW/m}^2$ . Turn on the source and leave it on. For  $R_L = R_L^*$ , determine  $v$  and  $i$  and temperature for several temperatures of the front face of the photocell as it rises from ambient to its illuminated thermal equilibrium. **DO NOT EXCEED A FRONT FACE TEMPERATURE OF  $50^\circ\text{C}$ .** Repeat for  $R_L = \text{near-open-circuit}$ . The actual performance of this innocuous sounding experiment is difficult, and you may have to settle for less than ideal data.

## 7. Report

- Using Part 3 data, plot incident power density [ $\text{W/m}^2$ ] versus source-cell spacing [mm] in full logarithmic fashion, i.e., log vs. log. Find an equation for the power density in the form  $P_0/d^k$  where  $d$  is the source-cell spacing [mm] and  $P_0$  and  $k$  are constants. Comment cogently.
- Using Part 4 data, first, plot the  $v(i)$  characteristic for  $1 \text{ kW/m}^2$  illumination as  $R_L$  was varied from near-open-circuit to near-short-circuit conditions; second, use linear extrapolation to estimate the values of  $V_{oc}$  and  $I_{sc}$ ; third, calculate and plot the Thevenin resistance for each current; fourth, comment cogently concerning this quasi global Thevenin equivalent. Also, calculate the near-short-circuit and near-open-circuit values of  $R_L$  and explain what effect, if any, these non-ideal values would have had on the Thevenin equivalent circuit parameters.
- Using Part 5 data, plot on three separate graphs as a function of source-cell spacing: (i) the near-open-circuit voltage  $V_{noc}$ , (ii) the near-short-circuit current  $I_{nsc}$ , and (iii) the power  $P^*$  delivered to the load when  $R_L = R_L^*$ . Use a logarithmic scale for the distance (spacing) axis.
- Using Part 5 data, calculate and plot on a separate graph as a function of source-cell spacing the pseudo-fill-factor  $PFF = P^*/(V_{oc} I_{sc})$ . Comment on these results. Use a logarithmic scale for the distance (spacing) axis.

- e. Determine the efficiency of the solar cell at 200 mm source-cell spacing based on the measured IR energy from Part 3 and the  $v$  and  $i$  data at  $\mathbf{R}_L^*$  from Part 5. Assume the diameter of the solar cell is 2.75 inches. Comment on this value of efficiency.
- f. Using Part 6 data, reduce your results to produce curves of near open circuit voltage  $\mathbf{V}_{noc}$  and Thevenin resistance versus temperature. Comment cogently and concisely.
- g. Consider the simplified equivalent circuit shown in Fig. 19 for a solar cell under test. Presume that the current generator represents the solar current  $I_S$  [A] and that the diode current is given by

$$i_D = I_0[e^{\kappa} - 1]$$

where  $I_0$  is a constant scale current and, as might be expected,  $\kappa = eV_D/kT$ . Show that the short circuit current is the solar current, i.e.,  $I_{sc} = I_S$ , and that the open circuit voltage  $V_{oc}$  is given by

$$V_{oc} = \frac{kT}{e} \ln\left[\frac{I_S}{I_0} + 1\right]$$

- h. Next prove (or disprove) the assertion that the power to the load  $P_L$  is given by

$$P_L = V_D \{I_S - I_0[e^{\kappa} - 1]\}$$

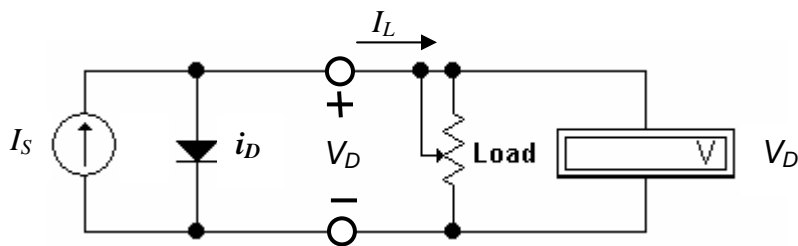


Figure 19.

- i. Derive a formula for the fill factor as a function of  $V_D$  and then differentiate it to find the value of  $V_D$  for which the fill factor is a maximum for a particular  $I_S$ .