Photovoltaic Devices

The semiconductor pn junction enables us to convert the power from sunlight into electrical power in an amazingly direct and simple fashion. The pn junction structure, or diode, absorbs light over most of the solar spectrum and provides the directionality to separate electrons and holes generated by the absorption of individual photons. In principle, we only need to attach wires to provide electrical power. However, to provide reasonable efficiency and reliability, a number of important issues and possibilities need to be explored. Once the basic photovoltaic cell has been constructed, secondary and tertiary concepts concerning the implementation of photovoltaic power require attention as well. The secondary level includes packing of individual solar cells into arrays and the orientation of the arrays with respect to the ever changing direction of sunlight. The tertiary level includes conversion to convenient AC power, storage and connection to the electrical power grid. Finally, the economic, environmental and social impacts of photovoltaic power will determine its place among electrical power sources in this country.

Photovoltaic Cells

The simple PV or solar cell consists of a base semiconductor material, a pn junction constructed to absorb as much of the solar radiation as possible and electrical contacts. The semiconductor is selected for its band gap energy, low electrical losses (resistance) and ease of fabrication. Figure 1 displays the conceptual design of a cell.

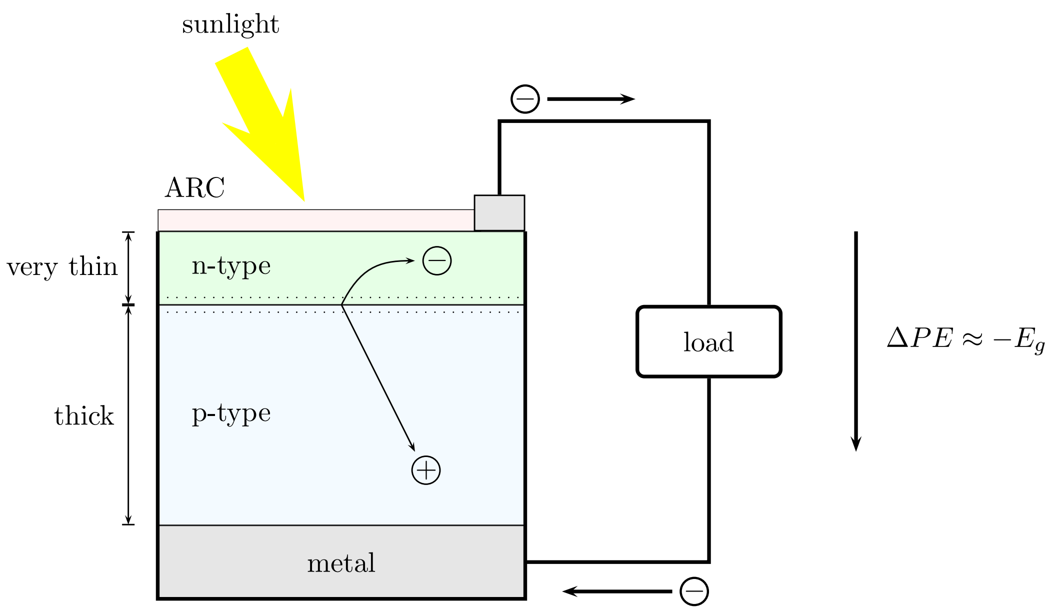

Figure 1: Photovoltaic or solar cell. The ARC is an anti-reflection coating.

Since the goal is to capture all the photons which strike the surface, there are several design considerations. Reducing the amount of light reflected from the surface, supplying a route for the electrons to flow out and making sure the photons are absorbed only in the pn junction depletion region are the major issues.

An anti-reflection coating (ARC) is applied to the surface because the reflectivity of a semiconductor can be 30%. The ARC cannot be entirely effective because even an expensive mult-layer film cannot eliminate reflection for the entire solar spectrum over a wide range of incident angle. There will be significant loss of conversion efficiency due to simple reflection from the surface.

To channel the electrons out toward the electrical load, a metal contact must be applied to the surface, but it cannot shade too much of the surface from the light. Often, the entire surface is actually covered with a conducting, transparent layer of Indium Tin Oxide (ITO), and the metal contact is connected to this layer. Electrons returning to the cell to complete the electrical circuit enter through the thick layer of metal at the bottom. Some of the energy of the photo-generated electrons will be dissipated at the junctions between different materials, thereby reducing the efficiency a bit and leading to slight heating.

In Figure 1, the depletion region in which the photons must be absorbed so that the electrons and holes will be automatically separated is indicated by the thin dotted lines. Since the n-type material will absorb photons, the thickness of this layer must be as thin as possible. The p-type section thick enough for structural integrity but thin enough to keep the resistance low. Resistance leads to loss of energy as heat. One important type of loss that occurs in the pn junction region is recombination of electrons and holes before they are swept in opposite directions from the depletion region. Upon recombination, the energy is lost as heat to the crystal.

For each electron that makes it through the electrical circuit, the change in potential energy will be equal to approximately the negative of the band gap energy, or $\Delta PE = -E_g$. The photon absorbed to create the mobile electron may have had an energy greater than E_g, but the difference would be lost as heat to the crystal. Thus, each electron passing through the electrical load can provide the energy E_g. Since electrostatic potential energy is charge $\times$ potential difference, the potential difference, or voltage, provided by the cell is $\Delta\Phi = E_g/e$, where e is the absolute value of the charge of the electron. If the band gap for the semiconductor is 2.4 eV, then the potential difference across the load will be 2.4 V.

Power Delivered by a Cell

The electrical power delivered by the solar cell is determined by the number of electrons passing through the load per second multiplied by the energy provided by each electron. Thus, $P = I\Delta\Phi$, where I is the current flowing from the cell in units of the *Ampere (A)*. One Ampere is the flow of one *Coulomb (C)* of charge per second. It takes 6×10^{18} electrons to achieve a charge of $-1C$.

To determine the number of electrons generated per second, one must know the power per unit area (S) of the light of energy greater than the band gap, the spectrum of the light, the area of the cell and the band gap energy. Consider the simple case of only green light of wavelength 500 nm striking the cell. Using the formula $u = h\nu = hc/\lambda$, the energy of a green photon is found to be $2.492eV \approx 2.5eV$. Since $1eV = 1.6 \times 10^{-19}J$, then $u = 4.0 \times 10^{-19}J$. For a beam of light with a power of $1W$ and and *intensity (S)* of $1W/m^2$, the number of photons per second per square meter would be $S/u = 2.5 \times 10^{18} photons/s/m^2$. Assuming that the cell has an area of 1 m_2, the number of photons striking the surface per unit time is $2.5 \times 10^{18} photons/s$. Now factor in efficiencies: the fraction of the incoming light absorbed $\eta_a = 0.9$ and the efficiency due to all other considerations $\eta_o = 0.9$. The incident power of 1 W now yields $\eta_a \eta_o S/u = 2.03 \times 10^{18}$ electrons/s, which is the current $I = 2.03 \times 10^{18} e/s \times 1.6 \times 10{-}19 C/e = 0.325A$. Furthermore, if the band gap is only 2.0 eV, then the efficiency of usage of each photon absorbed would be $\eta_p = 2.0/2.5 = 0.8$, or, alternatively, the potential created by the cell is only 2.0 V. Thus, the power delivered by the cell is $P = 0.325A \times 2.0V = 0.65W$. One would conclude that the efficiency of the cell for converting green light to electrical power is $P_{out}/P_{in} = 0.65W/1W = 0.65$.

Performing the same calculation using sunlight of all wavelengths is difficult because the photons of different wavelengths have different energies. So, for each type of semiconductor a theoretical solar spectrum efficiency η_s is defined for the conversion of the power of the solar spectrum into electrical power, exclusive of other efficiencies. Then, a theoretical maximum efficiency η_{max} is calculated by multiplying η_s by other inherent efficiencies. Even in developmental laboratory settings, η_{max} is not achieved because real materials and real electrical connections are not as perfect as theoretical models assume. And solar cells out in the real world exhibit even lower efficiencies. Thus, $\eta_{real} < \eta_{lab} < \eta_{max}$.

The major factor in η_{max} is η_s, a consequence of the fact that the band gap energy of a semiconductor may be too low to use the solar spectrum with much efficiency or too high to use any of the spectrum at all. Figure 2 shows the approximate solar spectrum at the surface of the earth in blue and a series of curves which represent the portion of the solar spectrum absorbed by semiconductors of different band gaps, each curve including an efficiency factor for the photons at every wavelength. A more useful graph is shown in Figure 3, which plots the same information along an energy axis. Now the relative η_s values for the different semiconductors can be determined by measuring the areas beneath the curves. The red curve, for the 1.5 eV band gap material, has the greatest area. The brown curve is for the silicon with a 1.14 eV bandgap.

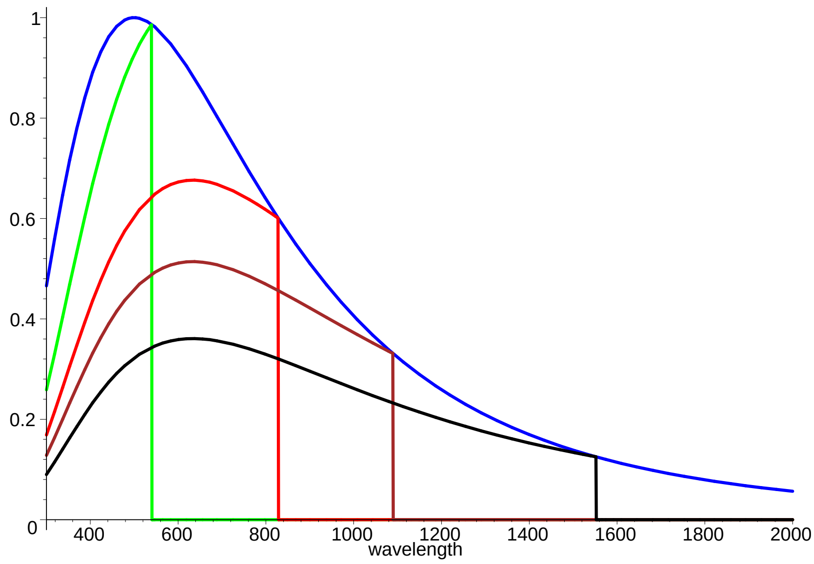

Figure 2: The solar spectrum (blue), and spectra of the light converted to electrical power by photovoltaic cells of different band gap energies. Color code: black is for $E_g = 0.8$ eV, brown is for $E_g = 1.14$ eV, red is for $E_g = 1.5$ eV and green is for $E_g = 2.3eV$.

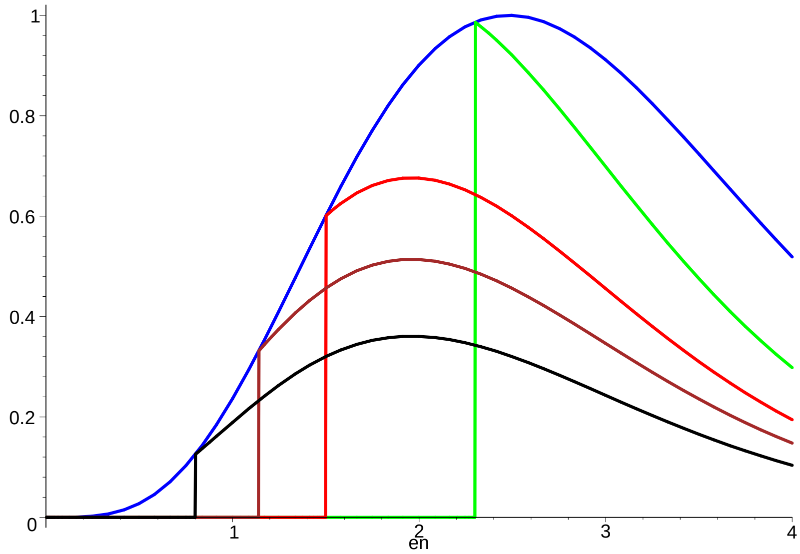

Figure 3: The same spectra displayed as function of energy in eV. The area underneath each curve is a measure of the relative power produced by the cell. The brown curve, for $E_g = 1.5eV$, has the greatest area.

Types of Photovoltaic Cells

Silicon has historically received the most attention as a photovoltaic material because of the extensive fabrication experience gained from the developments in the electronics industry. There are materials which have some characteristics surpassing those of silicon, but research and development has been miniscule compared to the efforts in the electronics industry to improve silicon-based integrated circuits. Four major categories of photovoltaic material have been defined: single crystal, polycrystalline, amorphous and thin film. Table lists the most common semiconductors and relevant photovoltaic properties.

	Band Gap	efficiency (%)				
semiconductor	in eV	commercial	laboratory	target	theoretical	comment
Si	1.14	15	24	30	31	crystal, $$$
Si	1.14	10	14	18		polycrystal, $$
Ge	0.67					crystal, $$$
GaAs	1.4	20	26	40	45	crystal, $$$$
AlGaAs	1.5		30		45	crystal, $$$$
GaInP	1.85		30			crystal, $$$$
GaInNAs	1.0					crystal, $$$$
a-Si:H	1.75	9	15	20	20	amorphous, $
a-Si,C:H	2.0	9	15	20	20	amorphous, $
a-Si,Ge:H	1.3	9	15	20	20	amorphous, $
CdTe	2.3	9	16.4	20	28	thin film, $$
$CuInSe_2$	2.0	11	18	20	21	thin film, $$
$CuInGaSe_2$	2.0	11	19			thin film, $$

Multi-Junction Cells

To avoid the inefficiency of turning some of the energy of an absorbed photon into heat, one can imagine passing sunlight through a stack of photovoltaic cells made from semiconductors with different band gap energies. Such a scheme is depicted in Figure 4. In this four cell version, the light first encounters the highest band gap material which absorbs only light of wavelength less than or equal to that of blue light. Alternatively, a photon is absorbed only if its energy is greater than or equal to the energy of a blue photon. Light of longer wavelength, or of lesser photon energy, passes through. The second cell absorbs green light as well as any blue light that makes it through the first cell. The third cell absorbs yellow, green and blue, and the fourth cell absorbs everything. All the energy of a blue photon is converted into useful electrical energy in the first cell, whereas in the fourth cell half of the energy would be wasted as heat.

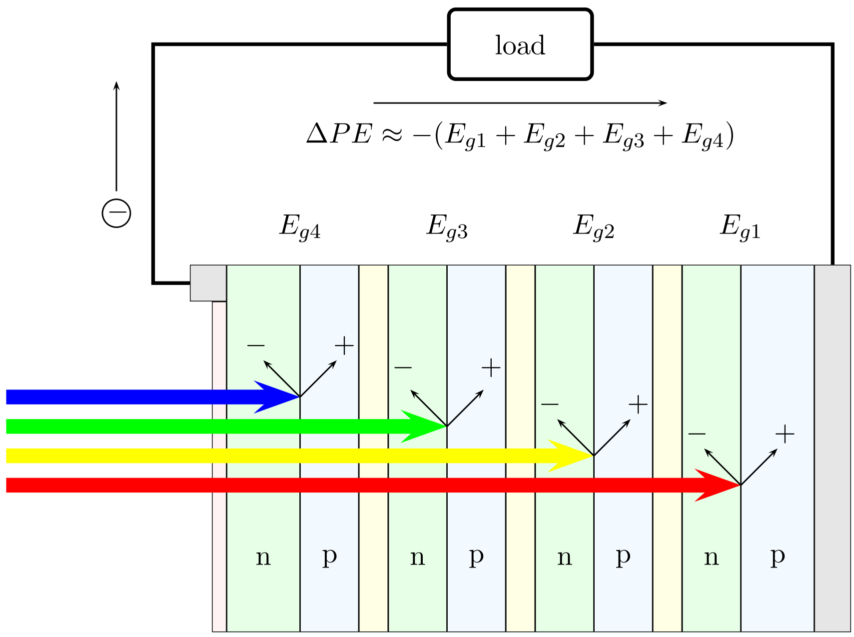

Figure 4: Multi-junction photovoltaic cell.

The generation of one electron at the top of the multi-junction cell requires the absorption of a photon in each level. The electron generated in the fourth level fills the hole in the third level, the electron in the third level fills the hole in the second and the electron in the second level fills the hole in the first level. The electron from the first level traverses the circuit, expends its energy and combines with the hole in the fourth level. An important point is that the energy of the electron is approximately $E_{g1} + E_{g2} + E_{g3} + E_{g4}$.

The efficiency of a multi-junction cell can certainly be greater than that of a single cell if no new losses are introduced. It is difficult to build, however. For instance, the pale layers separating the pn junctions in Figure 4 are specially designed to allow an electron to *tunnel* through to the next junction. And growing layers of different materials upon each other is fraught with problems.

The most promising multiple-junction devices are the following:

triple-junction a-Si;

two-junction GaInP on top of GaAs with a theoretical efficiency of 32%;

quadruple-junction GaInP/GaAs/GaInAs/Ge with a theoretical efficiency of 52% under conditions of AM1.5 and a concentration ratio of sunlight of up to 500.