August Cote
ELE 432

Solar Cells: The Renewable Energy Source

How They Work: The P-N Junction, Light and Photovoltaics

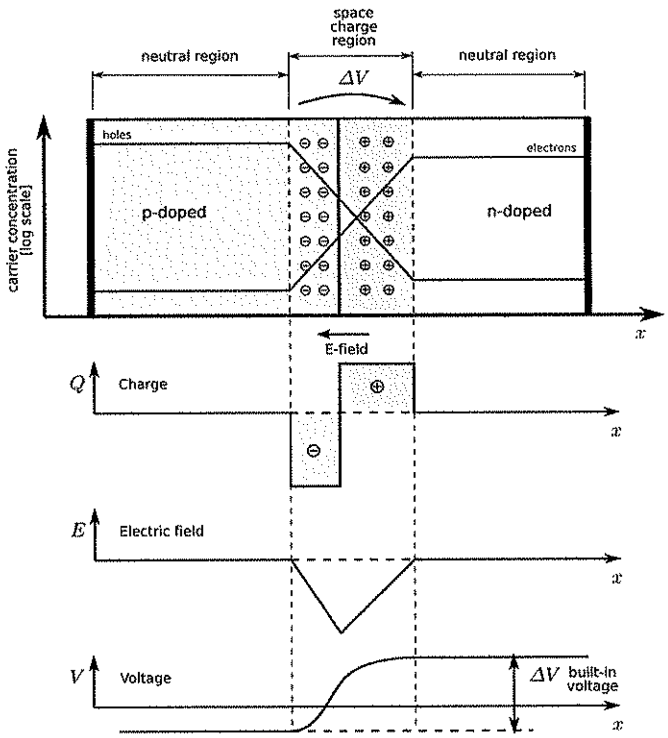


Figure 1: PN junction at thermal equilibrium and no bias voltage.

The basic component all solar cells are based on is the p-n junction. Basically, a p-n junction consists of a p-type and n-type semiconductor that, when in contact, allow current to flow in one direction and not the other. Near the junction, electrons from the n-type material diffuse into the p-type materials valence band to recombine with the holes. This region is normally referred to as the depletion region, which inhibits further electron diffusion into the p-type material unless there is a forward bias applied across the junction. Across the depletion region, an electric field forms from the n-type to the p-type which, in the presence of a bias voltage, will allow electrons to flow from the n-type material to the p-type and prevent electrons from flowing in the opposite direction. The difference in energy between the conduction and valence bands is referred to as the bandgap energy of the material. A diagram describing the Fermi energy and equilibrium conditions of the p-n junction is shown in Figure 1.

The energy of a photon is inversely proportional to the wavelength of the light scaled by Planck's constant and the speed of light, $E = \frac{hc}{\lambda}$ (5). Given a designed energy bandgap for the p-n junction, all photons with that energy or more will be absorbed and contribute to the current. Lower energy photons pass through the solar cell, not making any contribution to the current and those with higher energy that are absorbed generally create heat to dissipate the additional energy over the bandgap energy. When a photon is absorbed, it transfers its energy to an electron (usually in the valence band) and excites it into the conduction band where it is free to move in the semiconductor. The excitation of this electron into the conduction band also creates a hole in the valence band, which is why a photon normally creates an electron-hole pair when it is absorbed.

Ideally, a solar cell would be modeled as a current source in parallel with a diode however, there are some non-ideal characteristics. As the free electron must now travel through the semiconductor to the metal contact, through the load and then back to the valence band to fill the hole it left after being excited by a photon, there is some energy loss that is modeled as a parallel shunt resistance to ground (8). There is also a series resistance added before the load due to the resistance of the bottom and top contacts which can be significant depending on design. The equivalent model for a solar cell is shown in Figure 2.

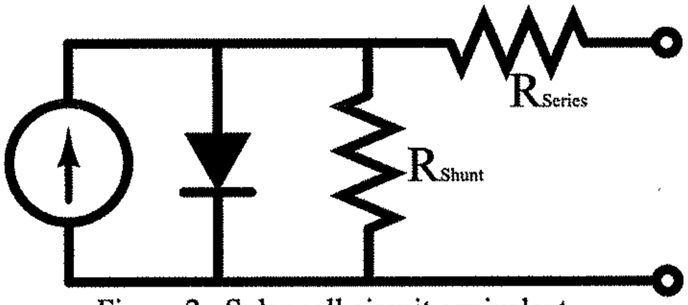


Figure 2: Solar cell circuit equivalent.

Perhaps the most important characterization parameter of a solar cell is its energy conversion efficiency, η. This term is the percentage of power converted from absorbed light when a solar cell is connected to an electrical circuit. It is calculated as the ratio of the maximum power point, P_m, divided by the input light irradiance (E) multiplied by the surface area of the solar cell (A_c), $\eta = \frac{P_m}{E \times A_c}$ (8). Light irradiance is found under standard test conditions (STC), which are defined as at a temperature of 25°C with 1000W/m^2 irradiance and air mass of 1.5(8). Although this efficiency factor is the industry standard, there are other efficiency losses that make up the overall loss of the solar cell, reflective loss, thermodynamic efficiency, recombination losses and resistive electrical losses. A timeline describing the evolution of solar cells and efficiency breakthrough's is shown in Figure 3 below.

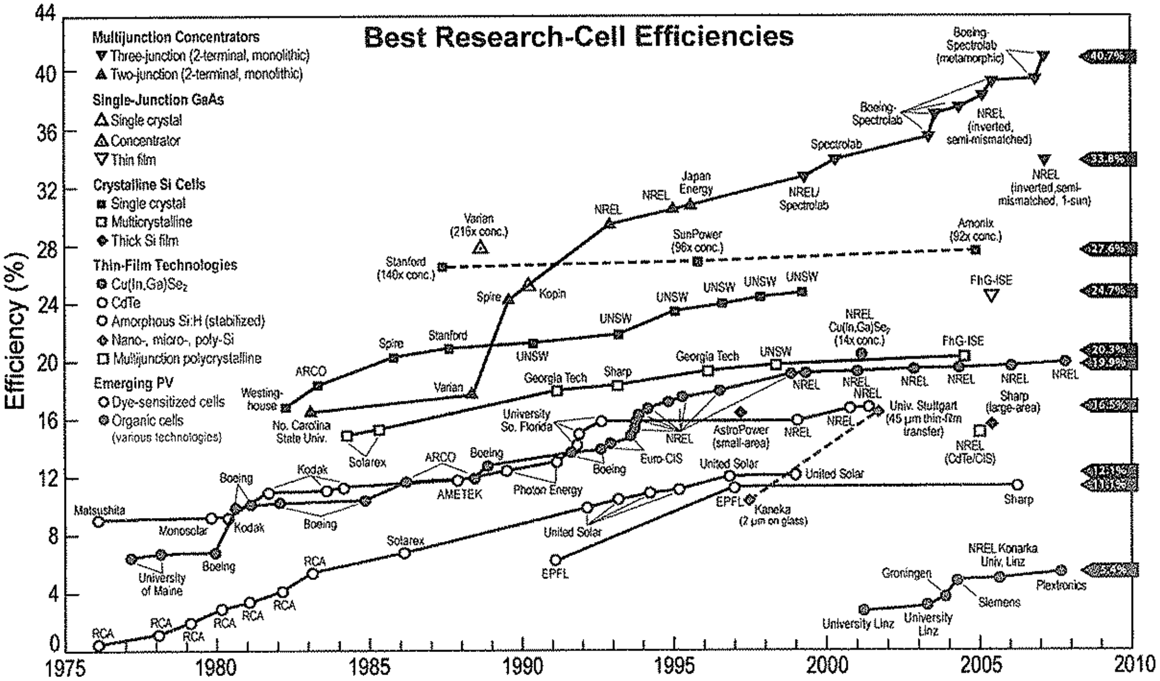
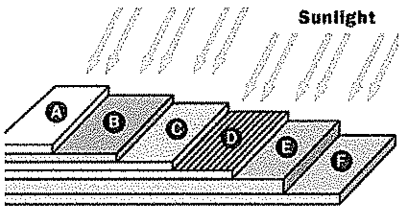


Figure 3: Timeline of research solar cell efficiencies.

How They're Made: Single Junction Needs Six Layers

The basic element of the solar cell is the p-n junction which, in the case of a Si based single junction cell, begins as a p-type doped Si ingot. The ingot is usually grown using the Czochralski process which basically involves suspending a small, highly purified Si crystal in a molten Si filled crucible and slowly drawing the crystal out. Once an ingot has been drawn, it is cut into wafers and an n-type dopant diffused into the wafer to form the p-n junction. A metal contact is then deposited on the bottom p-type side of the junction to serve as the negative terminal of the solar cell. There are several means to deposit this contact, but the most widely used is by sputtering. Similarly, a positive contact grid is deposited on the n-type side of the Si wafer using photolithography and sputtering. In order to eliminate reflection off the surface of the wafer, an anti-reflective coating is sputtered over the wafer and contact grid. Finally, the solar cell is finalized by covering the anti-reflective coating with glass to protect it from the elements. An overall cross section of a standard single junction solar cell is shown in Figure 4.



A = Glass cover B = Anti reflective coating C = Contact grid
D = N-type Silicon E P-type silicon F = Back contact

Figure 4: Standard commercial solar cell cross section.

Several variations of this general form are used including polycrystalline or amorphous Si as opposed to single crystal to reduce fabrication costs. Although these types of substrates result in lower efficiencies, the kW/H versus cost is better for most applications. Additionally, the contact grid can utilize "transparent conductors" to add efficiency by reducing reflection and maximizing the surface area exposed to the sun.

Applications: Need Power?

Solar cells could ultimately be used in any application requiring power, but has predominantly been used in remote locations where power is not available and to ease the growing cost of energy produced by fossil fuels around the world. A solar cell can be substituted for a voltage source in almost all applications and the electrical symbol is shown in Figure 5. The single junction Si solar cell explained previously is predominantly utilized in the construction of large panel arrays for utility power, but is also used in much smaller arrays for solar calculators, battery chargers and almost all consumer solar cell goods as it is the most inexpensive and commonly available. However, there are several other types of solar cells that have specific applications that are extremely useful and will be discussed in the next section.

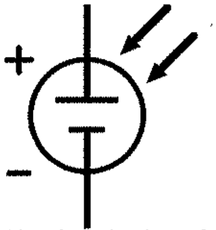


Figure 5: Electrical circuit symbol for solar cell.

The Alternatives: Multijunctions, Plastics and Dyes? Oh my!

The most efficient solar cells to date are multijunction cells that contain several P-N junctions with varying band gaps that cover the entire light spectrum. The highest efficiency achieved to date was by Boeing and was a three junction concentrator cell that peaked at 40.7% efficiency (8). These cells are solely utilized on the Mars rover missions and have well outlived their expected lifetime and efficiency longevity. Similar two junction concentrator cells are utilized on most satellite's currently in orbit and have reached peak efficiencies of approximately 30% (1). Although these cells are significantly more efficient than the single junction cell, they are also far more expensive to produce and are usually impractical from a cost versus yield standpoint.

Polymer based solar cells are much lighter, more flexible, disposable and far cheaper to fabricate than its single junction equivalent. Unfortunately, polymer cells have significantly less efficiency, only around 5% and also suffer dramatic degradation effects from ultraviolet and infrared light (7). Most polymer based solar cells consist of four layers, the bottom electrode normally PolyEthyleneTerephtalate (PET) foil, the two polaron reagents indium tin oxide (ITO) and PolyEthyleneDiOxyThiophene (PEDOT) and the top electrode (Alluminum) (7). Illuminating the polymer leads to electron transfer from the polymer chain to a fullerene molecule and creation of a polaron (+) particle on a polymer chain and fullerene ion-radical (-) (7).

Dye sensitized solar cells are a relatively new type of solar cell that is based on a photoelectrochemical system that utilizes a photo-sensitized anode and an electrolyte. Similar to polymer based cells, dye sensitized cells are significantly cheaper to produce and have several applications where flexible and disposable characteristics are preferred. However, they also share the drawback that the dye and electrolyte are quite sensitive to temperature and UV light exposure. The negative terminal of the semiconductor is a transparent conductor; normally fluorine doped tin oxide, which seals the dye and electrolyte with the bottom electrode. Light enters the electrolyte, hits the dye, which causes an electron to 'jump' into the conduction band of the molecule carrying the dye (normally TiO_2) (3). Once this electron has 'jumped' to the conduction band, the electron then diffuses into the electrolyte to form tri-iodide and quickly diffuses the electron to the bottom contact to return to equilibrium. A cross sectional diagram of a common dye sensitized solar cell and an actual commercial cell are shown below in Figure 6.

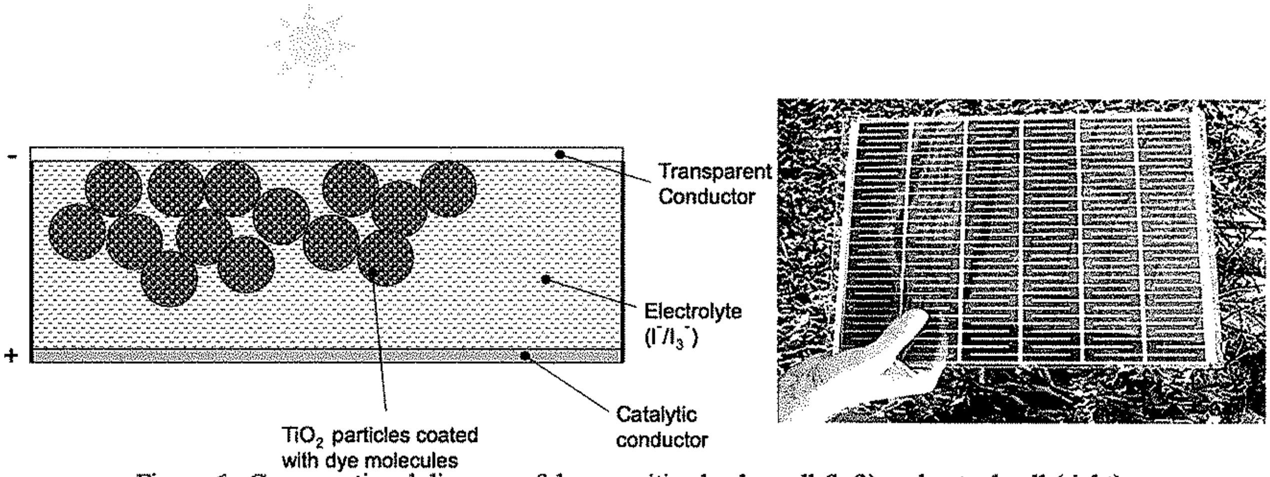


Figure 6: Cross sectional diagram of dye-sensitized solar cell (left) and actual cell (right).

References:

1. Knier, Gil. "How do Photovoltaics Work?"
   http://science.nasa.gov/headlines/y2002/solarcells.htm

2. Solar Navigator. "How Solar Cells Work." 2005.
   http://www.solarnavigator.net/how_solar_cells_work.htm

3. Wikipedia.org. "Dye-Sensitized Solar Cells." April 20th, 2008.
   http://en.wikipedia.org/wiki/Dye-sensitized_solar_cells

4. Wikipedia.org. "Indium Nitride." April 10th, 2008.
   http://en.wikipedia.org/wiki/Indium_nitride

5. Wikipedia.org. "Light." April 17th, 2008.
   http://en.wikipedia.org/wiki/Light

6. Wikipedia.org. "p-n Junction." April 6th, 2008.
   http://en.wikipedia.org/wiki/P-n_junction

7. Wikipedia.org. "Polymer Solar Cells." February 28th, 2008.
   http://en.wikipedia.org/wiki/Polymer_solar_cells

8. Wikipedia.org. "Solar Cells." April 22nd, 2008.
   http://en.wikipedia.org/wiki/Solar_cell