

Lecture 19: Solar cells

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1 Introduction

Solar cells and photodetectors are devices that convert an optical input into current. A solar cell is an example of a *photovoltaic device*, i.e., a device *that generates voltage when exposed to light*. The photovoltaic effect was discovered by Alexander-Edmond Becquerel in 1839, in a junction formed between an electrode (platinum) and an electrolyte (silver chloride). The first solid state photovoltaic device was built, using a Si *pn* junction, by Russell Ohl in 1939. The functioning of a solar cell is similar to the photodiode (photodetector). It is a photodiode that is unbiased and connected to a load (impedence). There are three qualitative differences between a solar cell and photodetector

1. A photodiode works on a narrow range of wavelength while solar cells need to work over a broad spectral range (solar spectrum).
2. Solar cells are typically wide area devices to maximize exposure.
3. In photodiodes the metric is quantum efficiency, which defines the signal to noise ratio, while for solar cells, it is the power conversion efficiency, which is the power delivered per incident solar energy. Usually,

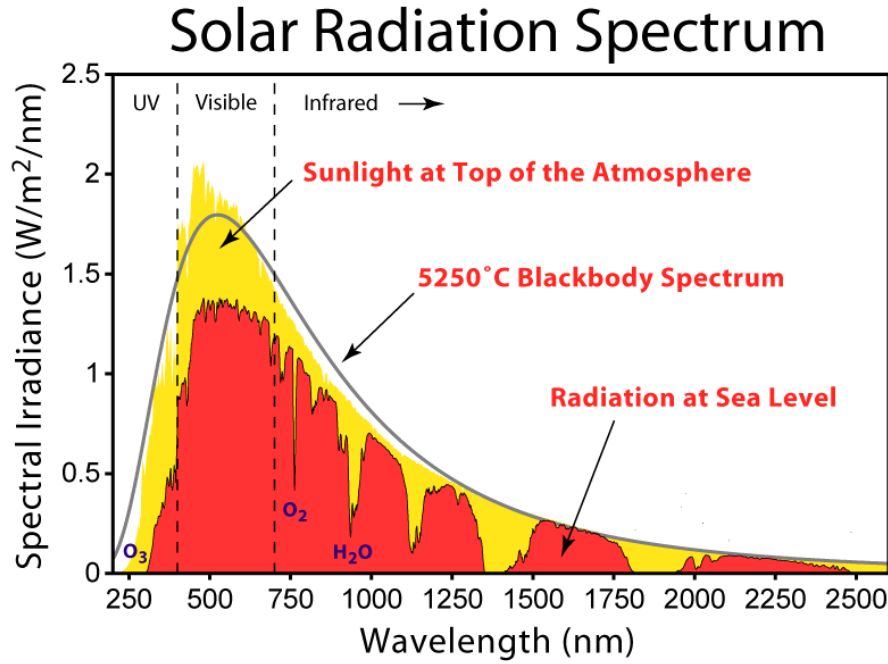


Figure 1: Typical solar spectrum at the top of the atmosphere and at sea level. The difference is the radiation absorbed/scattered by the atmosphere. The spectrum of a black body at 5250 °C is also superimposed and used for modeling. Modified from <http://en.wikipedia.org/wiki/Sunlight>

solar cells and the external load they are connected to are designed to maximize the delivered power.

2 Solar spectrum

The solar spectrum typically extends from the IR to the UV region, wavelength range from $3 \mu m$ to $0.2 \mu m$. But the intensity is not uniform. A typical solar spectrum, as a plot of spectral irradiance vs. wavelength, is shown in figure 1. The area under the curve gives the *total areal intensity* and this is approximately $1.35 kW m^{-2}$. The solar spectrum can be approximated by a black body radiation curve at temperature of approximately 5250 °C. There is also a difference in the spectra measured at the top of the atmosphere and at the surface, due to atmospheric scattering and absorption.

The path length of the light in the atmosphere depends on the angle, which will vary with the time of day. This is given by the *air mass number* (AM), which is the *secant* of the angle between the sun and the zenith ($\sec \theta$). AM0

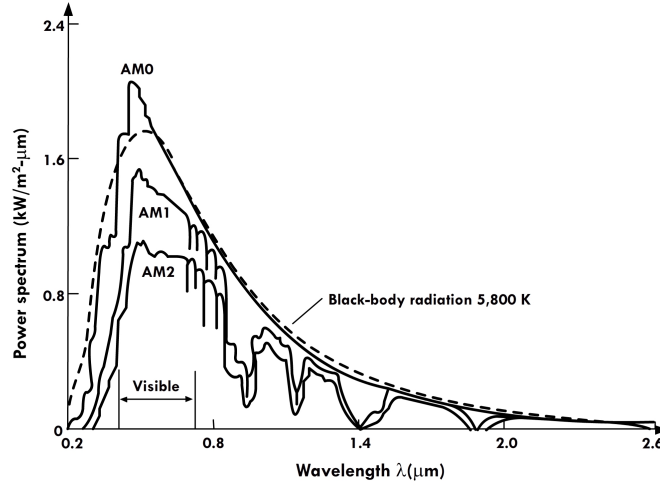


Figure 2: Typical solar spectrum for different air mass conditions. The plot shows AM0 (spectrum outside the atmosphere), AM1 (at the zenith), and AM2 (at an angle of 60°). This again can be modeled by black body spectrum, at various temperatures. Adapted from *Physics of semiconductor devices* - S.M. Sze.

represents the solar spectrum outside the earth's atmosphere. AM1 is when the angle is zero, i.e. sun is at the zenith and it has an intensity of 0.925 kW m^{-2} . AM2 is when sun is at angle of 60° and its intensity is 0.691 kW m^{-2} . The different spectra are plotted in figure 2. The data can also be plotted as a photon flux density i.e. no. of photons per unit energy per unit area per unit time. This is shown in figure 3.

3 Solar cell working principle

A simple solar cell is a pn junction diode. The schematic of the device is shown in figure 4. The n region is heavily doped and thin so that the light can penetrate through it easily. The p region is lightly doped so that most of the depletion region lies in the p side. The penetration depends on the wavelength and the absorption coefficient increases as the wavelength decreases. Electron hole pairs (EHPs) are mainly created in the depletion region and due to the built-in potential and electric field, electrons move to the n region and the holes to the p region. When an external load is applied, the excess electrons travel through the load to recombine with the excess holes. Electrons and holes are also generated with the p and n regions, as seen from figure 4.

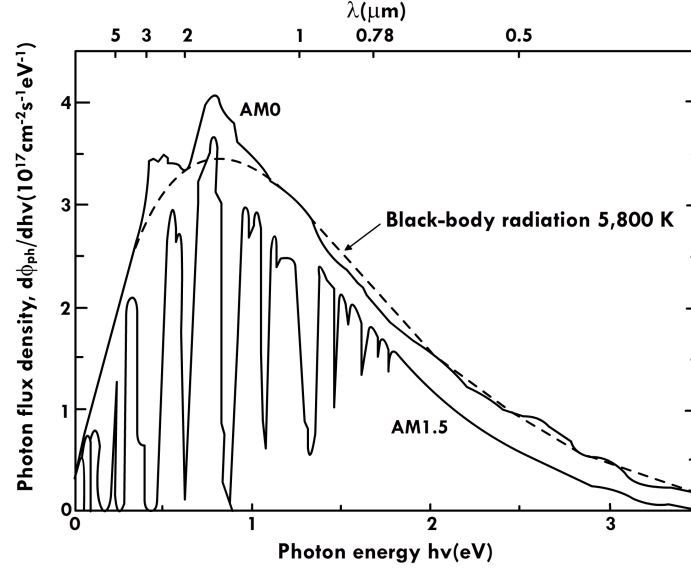


Figure 3: Solar spectrum plotted as photon flux density vs. energy for AM0 and AM1.5. The difference in the spectra is due to the absorption/scattering by the atmosphere. Adapted from *Physics of semiconductor devices* - S.M. Sze.

The shorter wavelengths (higher absorption coefficient) are absorbed in the n region and the longer wavelengths are absorbed in the bulk of the p region. Some of the EHPs generated in these regions can also contribute to the current. Typically, these are EHPs that are generated within the minority carrier diffusion length, L_e for electrons in the p side and L_h for holes in the n side. Carriers produced in this region can also diffuse into the depletion region and contribute to the current. Thus, the total width of the region that contributes to the solar cell current is $w_d + L_e + L_h$, where w_d is the depletion width. This is shown in figure 5. The carriers are extracted by metal electrodes on either side. A finger electrode is used on the top to make the electrical contact, so that there is sufficient surface for the light to penetrate. The arrangement of the top electrode is shown in figure 6.

Consider a solar cell made of Si. The band gap, E_g , is 1.1 eV so that wavelength above 1.1 μm is not absorbed since the energy is lower than the band gap. Thus any λ greater than 1.1 μm has negligible absorption. For λ much smaller than 1.1 μm the absorption coefficient is very high and the EHPs are generated near the surface and can get trapped near the surface defects. So there is an optimum range of wavelengths where EHPs can contribute to photocurrent, shown in figure 5.

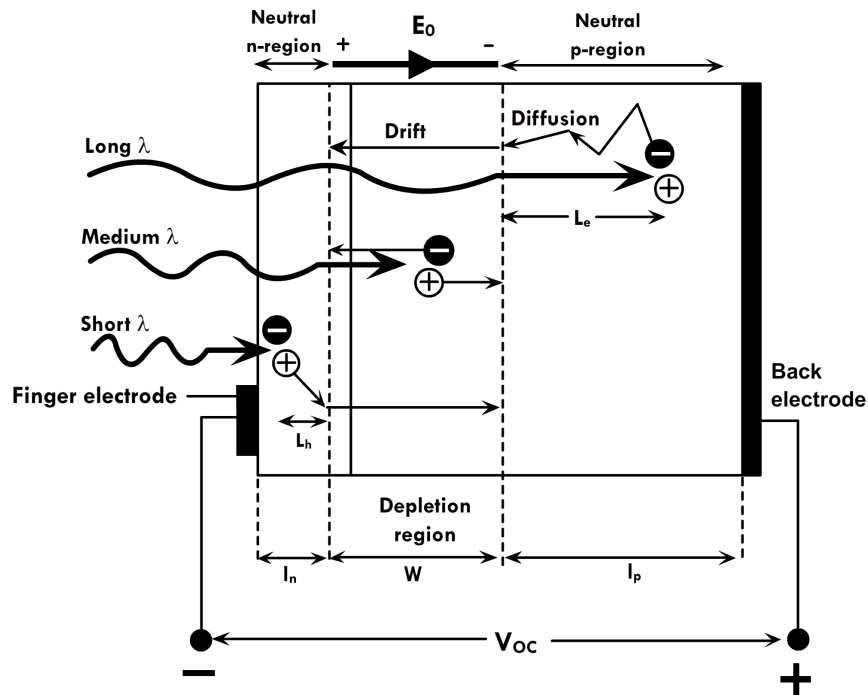


Figure 4: Principle of operation of a pn junction solar cell. Radiation is absorbed in the depletion region and produces electrons and holes. These are separated by the built-in potential. Depending on the wavelength and the thickness different parts of the device can absorb different regions of the solar spectrum. Adapted from *Principles of Electronic Materials* - S.O. Kasap

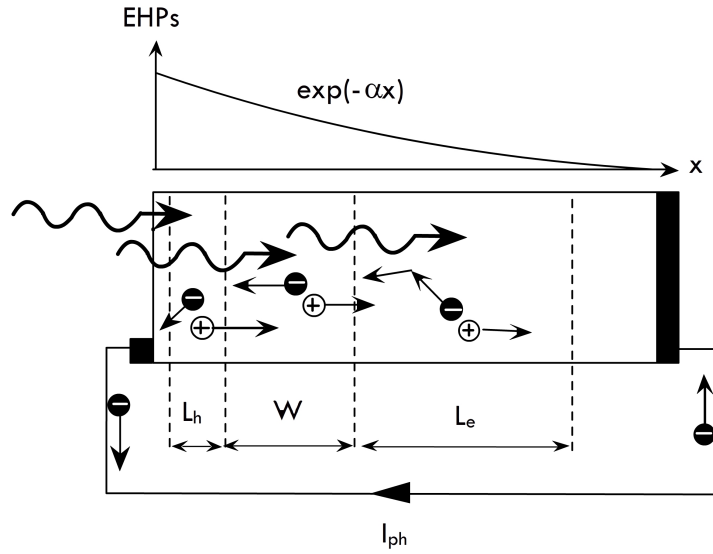


Figure 5: Photogenerated carriers in a solar cell due to absorption of light. w is the width of the depletion region, while L_h and L_e are minority carrier diffusion lengths in the n and p regions. The amount of absorption reduces with depth and hence the depletion region must be close to the surface to maximize absorption. This is achieved by having a thin n region. Adapted from *Principles of Electronic Materials* - S.O. Kasap

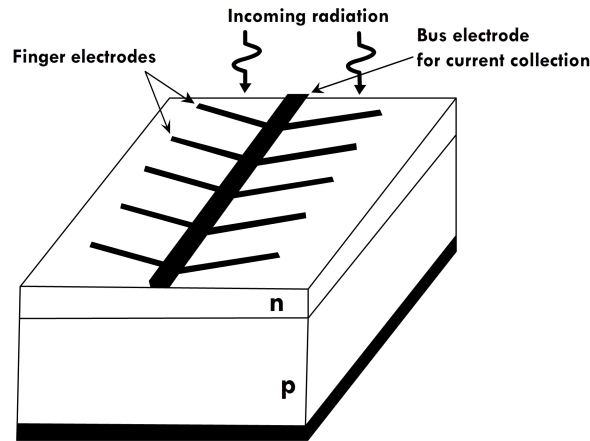


Figure 6: Finger electrodes on a pn junction solar cell. The design consists of a single bus electrode for carrying current and finger electrodes that are thin enough so that sufficient light can be absorbed by the solar cell. Adapted from *Principles of Electronic Materials* - S.O. Kasap

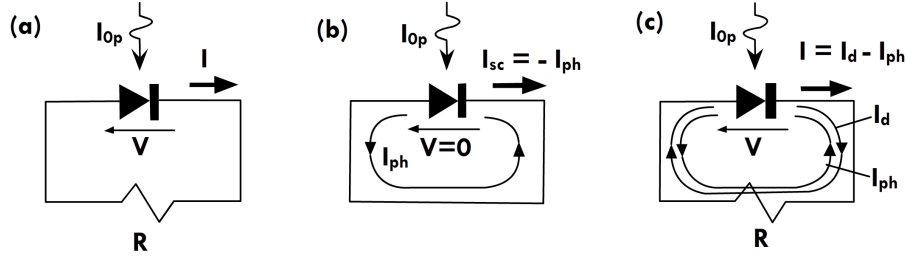


Figure 7: (a) pn junction solar cell under illumination with an external load. The equivalent circuit (b) without and (c) with an external load. The illumination causes a photocurrent to flow through the external circuit. When an external load is applied the potential drop across it creates a forward bias current that opposes the photocurrent. Adapted from *Principles of Electronic Materials* - S.O. Kasap

4 Solar cell I-V characteristics

It is possible to calculate the I-V characteristics of the solar cell by considering its equivalent circuit. The I-V characteristics depend on the intensity of the incident radiation and also the operating point (external load) of the cell. Consider a pn junction solar cell under illumination, as shown in figure 7. If the external circuit is a short circuit (external load resistance is zero) then the only current is due to the generated EHPs by the incident light. This is called the photocurrent, denoted by I_{ph} . Another name for this is the *short circuit current*, I_{sc} . By definition of current, this is opposite to the photocurrent and is related to the intensity of the incident radiation, I_{op} , by

$$I_{sc} = -I_{ph} = -kI_{op} \quad (1)$$

where k is a constant and depends on the particular device. k is equivalent to an efficiency metric that measures the conversion of light into EHPs.

Consider the case when there is an external load R , as shown in figure 7. The equivalent circuit for this case is shown in figure 8. There is a voltage across the external load, given by $V = IR$. This voltage opposes the built-in potential and reduces the barrier for carrier injection across the junction. This is similar to a pn junction in forward bias, where the external bias causes injection of minority carriers and increased current. This forward bias current opposes the photo current generated within the device due to the solar radiation. This is because I_{ph} is generated due to electrons going to the n side and holes to the p side due to the electric field within the device, i.e. *drift current* while the forward bias current is due to *diffusion current*.

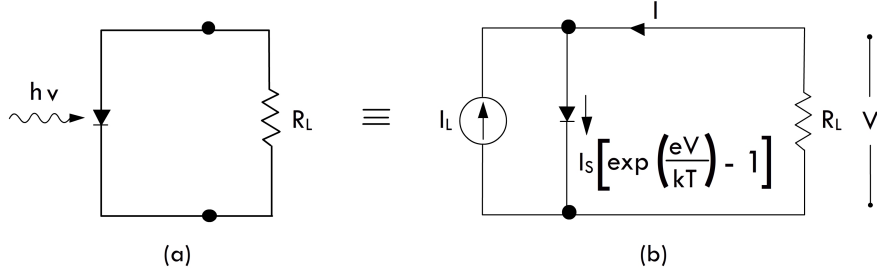


Figure 8: (a) A solar cell connected to an external load (b) Equivalent circuit, with a constant current source, a forward biased pn junction and the external load. The current from the forward biased pn junction opposes the constant current source. Adapted from *Physics of semiconductor devices - S.M. Sze*.

caused by the injection of minority carriers. Thus, the net current can be written as

$$\begin{aligned}
 I &= -I_{ph} + I_d \\
 I_d &= I_{s0} \left[\exp\left(\frac{eV}{k_B T}\right) - 1 \right] \\
 I &= -I_{ph} + I_{s0} \left[\exp\left(\frac{eV}{k_B T}\right) - 1 \right]
 \end{aligned} \tag{2}$$

where I_d is the forward bias current and can be written in terms of the reverse saturation current, I_{s0} and external voltage, V .

Consider a Si pn junction solar cell at room temperature. The donor concentration is 10^{15} cm^{-3} and the acceptor concentration is 10^{16} cm^{-3} . Using values of mobility for pure Si and electron and hole lifetimes of 50 ns and 100 ns respectively, it is possible to plot the forward bias I-V characteristics for this junction. This constitutes a dark current. The pn junction can then be illuminated with light of a given intensity. For simplicity the wavelength is assumed to be 400 nm and the intensity is given in Wm^{-2} . For 100% conversion efficiency, this translates directly into a photo generated current, I_{ph} . This photocurrent opposes the forward bias dark current and has the effect of shifting the I-V curve into the negative current axis. With increasing light intensity, the downward shift is higher. Solar cell I-V characteristics for three values of light intensity is plotted in figure 9.

In the absence of light, the *dark characteristics* is similar to a pn junction I-V curve. The presence of light (I_{ph}) has the effect of shifting the I-V curve down. From figure 9, it is possible to define a photo current I_{ph} , which is the current when the external voltage is zero and an *open circuit voltage*, V_{oc} , which is the voltage when the net current in the circuit is zero. Using

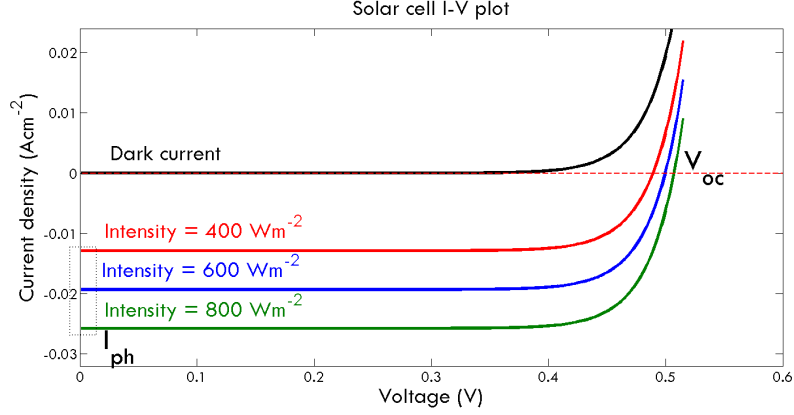


Figure 9: $I - V$ characteristics of Si pn junction solar cell under dark conditions and under illumination with light of increasing intensity. Short circuit current and open circuit voltage both increase with increasing intensity. The plot was made in MATLAB and the pn junction and pn junction and illumination parameters are given in the text. The open circuit voltage, V_{oc} , and short circuit current, I_{ph} , are marked.

equation 2, V_{oc} can be calculated as

$$\begin{aligned} I_{ph} &= I_{s0} \left[\exp\left(\frac{eV_{oc}}{k_B T}\right) - 1 \right] \\ V_{oc} &\approx \frac{k_B T}{e} \ln\left[\frac{I_{ph}}{I_{s0}}\right] \end{aligned} \quad (3)$$

Higher the photon flux, higher is the value of I_{ph} (by equation 1), and higher the value of V_{oc} . Similarly, lower I_{s0} can also cause higher V_{oc} . Since I_{s0} is the reverse saturation current for the pn junction it is given by

$$I_{s0} = n_i^2 e \left[\frac{D_e}{L_e N_A} + \frac{D_h}{L_h N_D} \right] \quad (4)$$

The reverse saturation current can be lowered by choosing a material with a higher band gap, E_g , which will cause n_i to be lower. But this will also reduce the range of wavelengths that can be absorbed by the material, which will have the effect of lowering I_{ph} .

The total power in the solar cell circuit is given by

$$P = IV = I_{s0} V \left[\exp\left(\frac{eV}{k_B T}\right) - 1 \right] - I_{ph} V \quad (5)$$

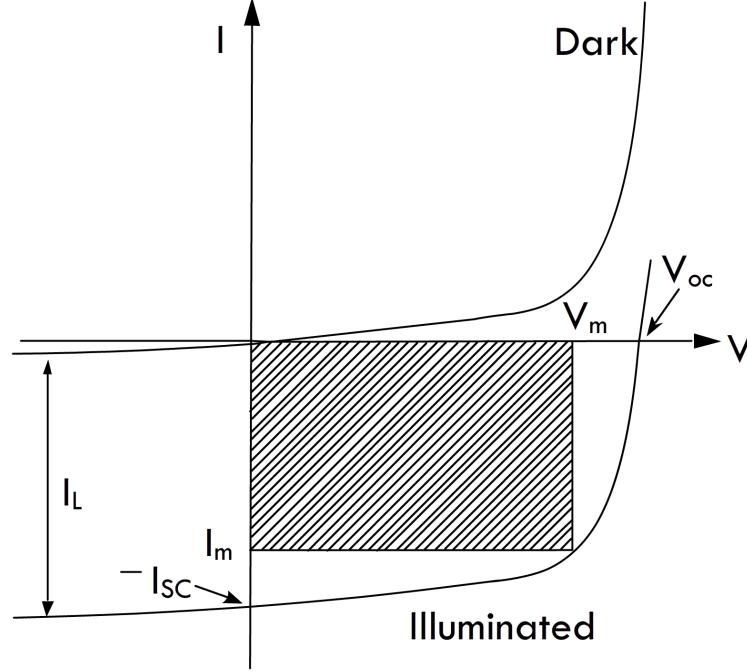


Figure 10: I-V curve for a solar cell with maximum power indicated by the shaded area. The corresponding voltage and current are V_m and I_m . The value depends on the external load applied. Adapted from *Physics of semiconductor devices* - S.M. Sze.

For maximum power, its derivative with respect to voltage should be zero. This gives a recursive relation in current and voltage.

$$\begin{aligned}
 \frac{dP}{dV} &= 0 \\
 I_m &\approx I_{ph} \left(1 - \frac{k_B T}{e V_m}\right) \\
 V_m &\approx V_{oc} - \frac{k_B T}{e} \ln\left(1 + \frac{e V_m}{k_B T}\right) \\
 P_m = I_m V_m &\approx I_{ph} \left[V_{oc} - \frac{k_B T}{e} \ln\left(1 + \frac{e V_m}{k_B T}\right) - \frac{k_B T}{e}\right]
 \end{aligned} \tag{6}$$

This can be seen from figure 10. The area under the curve, corresponding to I_m and V_m , gives the maximum power. From equation 6 it can be seen that the maximum power is directly proportional to V_{oc} and can be increased by

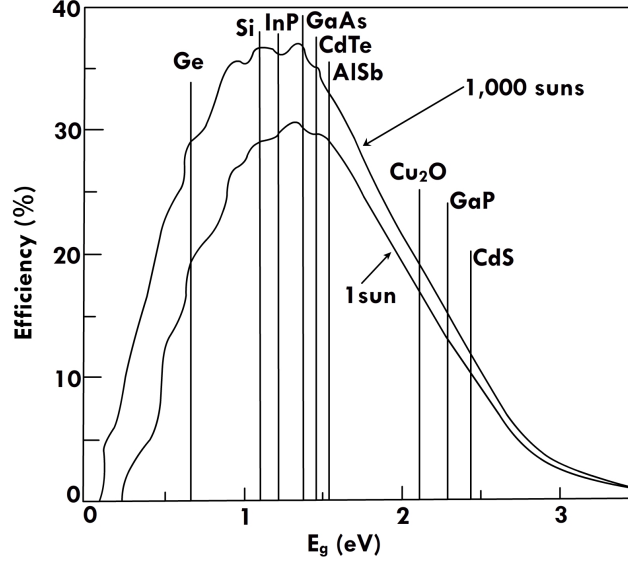


Figure 11: Solar cell efficiency as a function of band gap of the semiconductor material. There is an particular band gap range where the efficiency is maximum. Adapted from *Physics of semiconductor devices* - S.M. Sze.

decreasing I_{s0} . This means that smaller n_i and a larger E_g are favorable but the trade off is that less radiation is absorbed.

5 Solar cell materials and efficiency

Conventional solar cells are made of Si single crystal and have an efficiency of around 22-24%, while polycrystalline Si cells have an efficiency of 18%. A schematic representation of such a cell is shown in figure 6. The efficiency of the solar cell depends on the band gap of the material and this is shown in figure 11. Polycrystalline solar cells are cheaper to manufacture but have a lower efficiency since the microstructure introduces defects in the material that can trap carriers. Amorphous solar cells have an even lower efficiency but can be grown directly on glass substrates by techniques like sputtering so that the overall cost of manufacturing is lowered. There are also design improvements in the solar cell that can enhance the efficiency. PERL (passivated emitter rear locally diffused) cells, shown in figure 12, have an efficiency of 24% due to the inverted pyramid structure etched on the surface that enhances absorption.

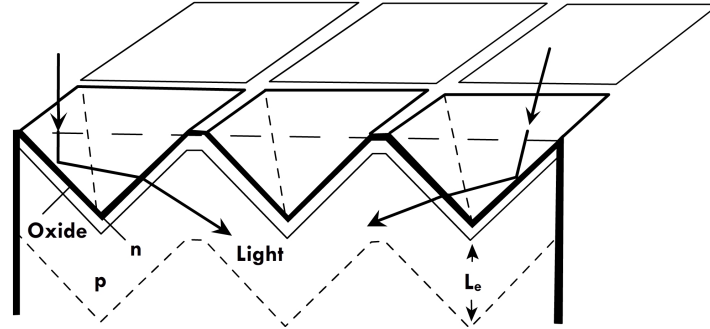


Figure 12: Si solar cell with an inverted pyramid structure to enhance absorption of the incoming radiation. These are called PERL cells. The inverted pyramid structure causes multiple reflections at the surface, which help in absorption of the incoming radiation. Adapted from *Principles of Electronic Materials* - S.O. Kasap

Typical solar cells are made of the same material so that the pn junction is a homojunction. Some solar cell materials and their efficiencies are summarized in table 1. A comprehensive state of current research in different solar cell technologies and their efficiency is available in figure 13. Heterojunction solar cells are also possible and they have the advantage of minimizing absorption in regions other than the depletion region, but overall cost increases because of the use of different materials and the tight processing conditions needed to produce defect free interfaces. A schematic of such a cell based on GaAs/AlGaAs is shown in figure 14. The shorter wavelengths are absorbed by the AlGaAs layers while the longer wavelengths, with higher penetration depths, are absorbed by the GaAs layer. This leads to an overall efficiency of around 25%, see table 1. It is also possible to have a homojunction solar cell but with a passivating layer of another material at the surface to reduce defects. This is shown in figure 15. The surface passivating layer removes the dangling bonds and minimizes carrier trapping. The passivation layer is a thin layer of a higher band gap material to minimize absorption. Similarly, amorphous semiconductor materials like Si and Ge also have a passivating layer of H, a-Si:H or a-Ge:H, to reduce dangling bonds.

Another way of improving solar cell efficiency is to have more than one cell in tandem. These are called *tandem solar cells* and a schematic is shown in figure 16. These consist of two pn junction solar cells, with the first one having a higher band gap than the second. Thus, the shorter wavelengths can be absorbed in cell 1, see figure 16, while the longer wavelengths are absorbed in cell 2. The advantage is that a larger portion of the solar radiation

Table 1: Some common solar cell materials and their characteristics. Adapted from *Principles of Electronic Materials - S.O. Kasap*

Semi-conductor	E_g (eV)	V_{oc} (V)	J_{sc} ($mA\ cm^{-2}$)	$\eta(\%)$	Comments
Si, single crystal	1.1	0.5-0.7	42	16-24	Single crystal, PERL
Si, poly-crystalline	1.1	0.5-0.65	38	12-19	
Amorphous Si:Ge:H film				8-13	Amorphous films with tandem structure, large-area fabrication
GaAs, single crystal	1.42	1.02	28	24-25	
GaAlAs/GaAs, tandem		1.03	27.9	25	Different band gap materials in tandem increases absorption efficiency
GaInP/GaAs, tandem		2.5	14	25-30	Different band gap materials in tandem increases absorption efficiency
CdTe, thin film	1.5	0.84	26	15-16	
InP, single crystal	1.34	0.87	29	21-22	
CuInSe ₂	1.0			12-13	

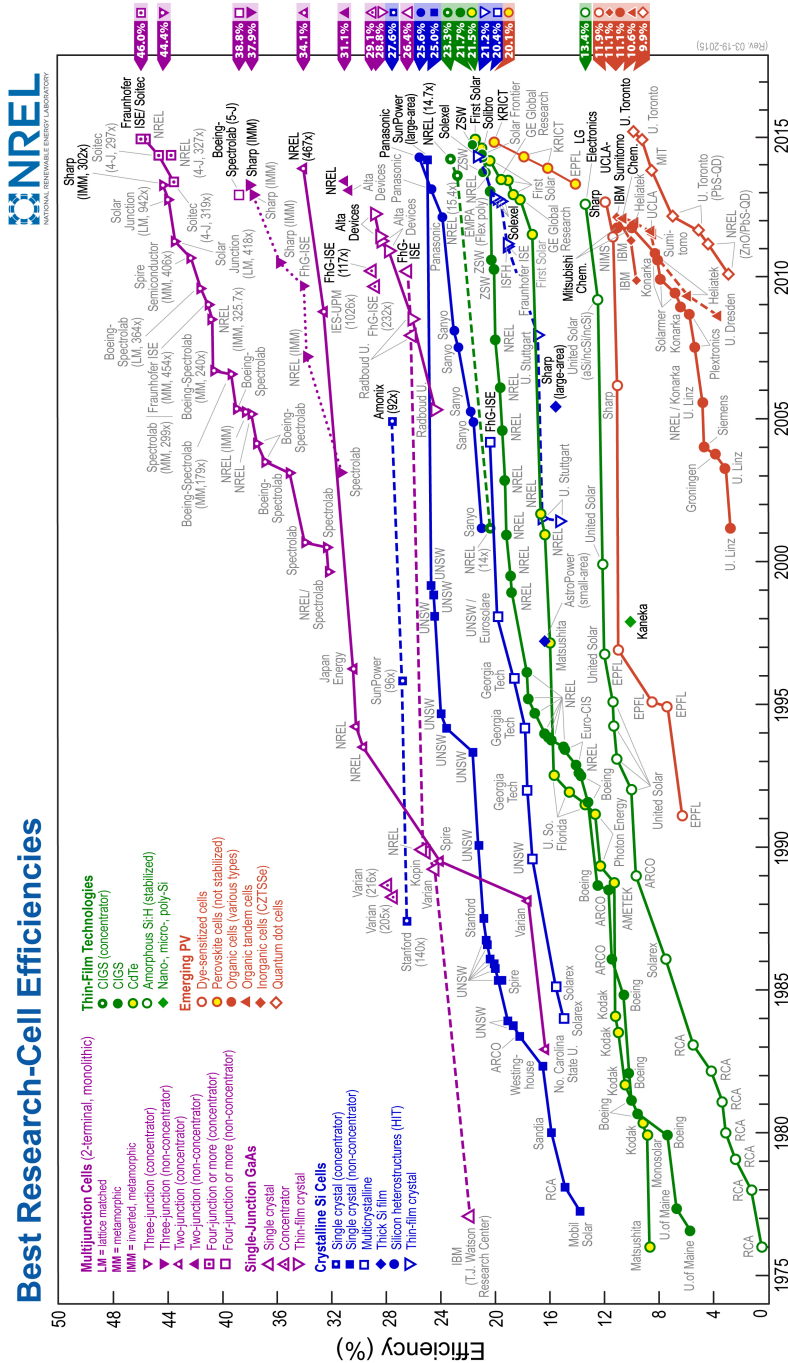


Figure 13: Efficiency of various research solar cells. The latest diagram is available at <http://www.nrel.gov/ncpv/>

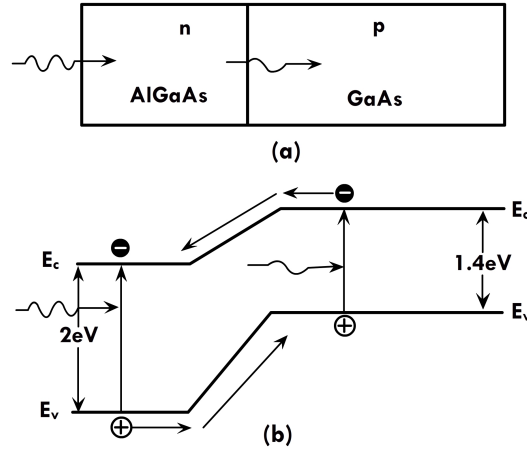


Figure 14: (a) GaAs/AlGaAs based heterojunction solar cell. (b) Energy band alignment across the junction. AlGaAs has the higher band gap and can absorb higher energy radiation while GaAs can absorb the lower energy portion of the solar spectrum. Adapted from *Principles of Electronic Materials* - S.O. Kasap

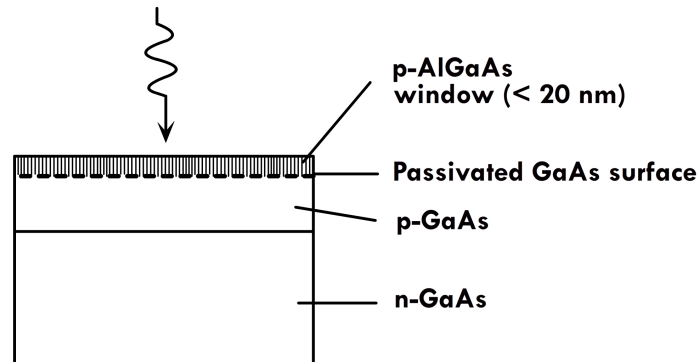


Figure 15: Schematic of a GaAs based homojunction solar cell with a surface passivating layer to minimize surface recombination. This layer should be thin and have a high band gap to minimize absorption. Adapted from *Principles of Electronic Materials* - S.O. Kasap

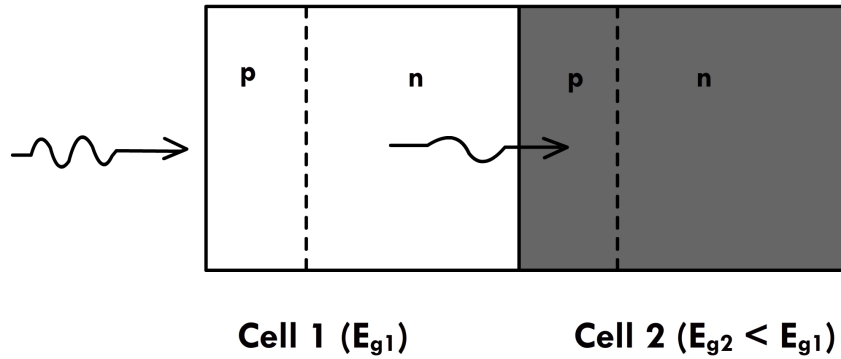


Figure 16: Tandem solar cells. The higher band gap cell is closer to the illuminating surface to absorb the short wavelengths and the smaller band gap cell is at the interior to absorb the longer wavelengths. Adapted from *Principles of Electronic Materials* - S.O. Kasap

is used so that tandem cells have high efficiency, see table1, but it also adds a layer of complexity in growth and increases cost. Tandem cells can also be made using amorphous Si:H and Ge:H. These are cheaper to make and more efficient than individual amorphous solar cell devices.