Solar Energy

PEN : Lectures Solar - Part II

Solar Cell

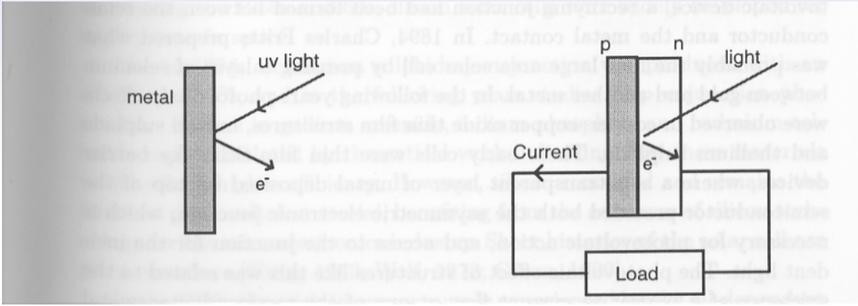

Figure: Solar Cell Basic

Solar Cell

- The above and following figures are from Nelson " The Physics of Solar Cells ." Imperial College Press.
- In ordinary matter, excited electrons relax back to their original state. In PV device, there is an *asymmetry* which pulls electrons away before they can relax and feeds them to an extenal circuit. The movement of charge generates a potential difference or e.m.f.
- The "asymmetry" is created by having two types of material, called p and n-type semiconductors.

Solar Module

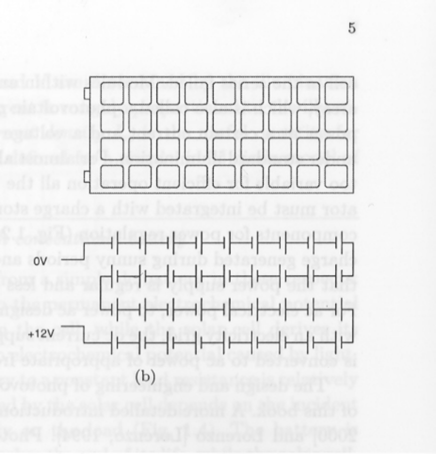

Figure: Solar Cells in series

Solar Cells, modules, arrays

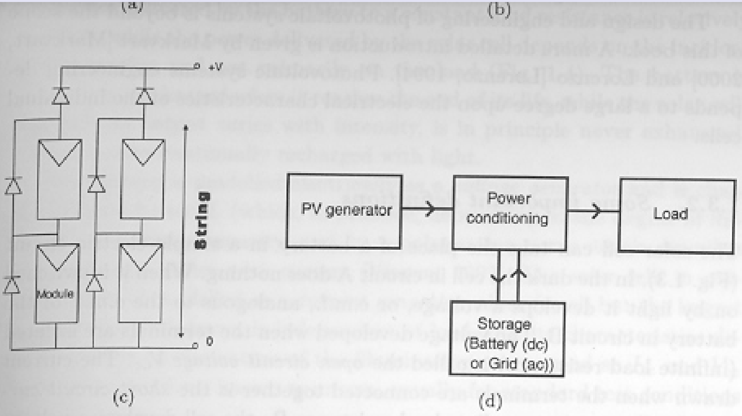

Fig. 1.2. (a) Photovoltaic cell showing surface contact patterns (b) In a module, cells are usually connected in series to give a standard dc voltage of 12 V (c) For any application, modules are connected in series into strings and then in parallel into an array, which produces sufficient current and voltage to meet the demand. (d) In most cases the photovoltaic array should be integrated with components for charge regulation and storage.

Band Structures : Metal , Insulator, Semi-conductor

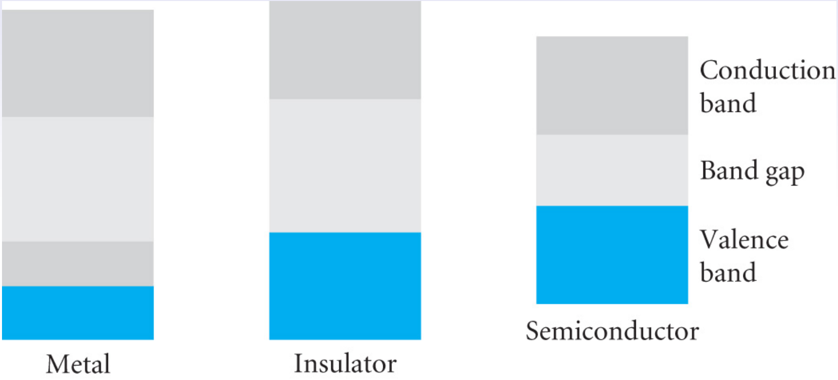

Figure:

Acceptors, Donors, Holes

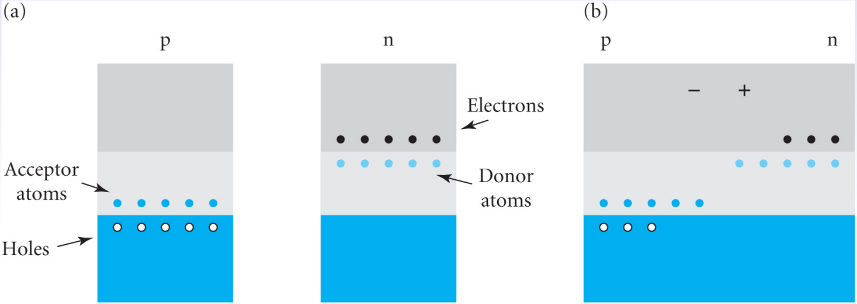

Figure: Diffusion and buildup of internal electric field at p-n junction

Note the build-up of positive charge on the n-side. When electrons in the depletion region are excited by photons, they move towards the n-side, due to the build-up of net positive charge on that side.

Effect of diffusion on bands

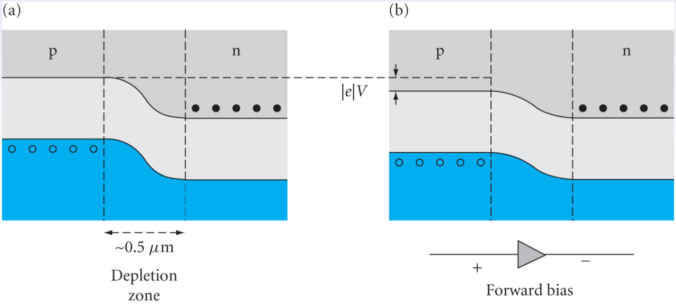

Figure: Net + charge in n-side lowers potential energy of electrons

Characteristic of Diode

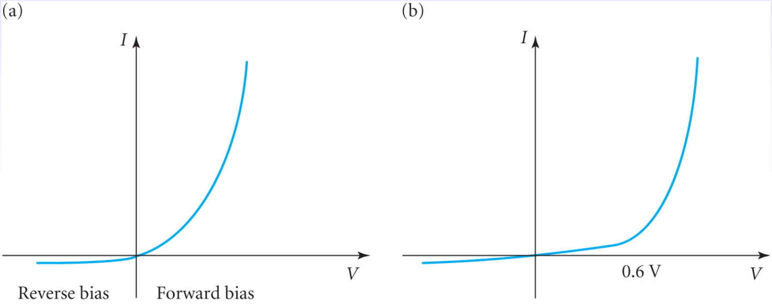

Figure: (a) Ideal diode (b) Lossy diode, with ohmic region

Operation of solar cell

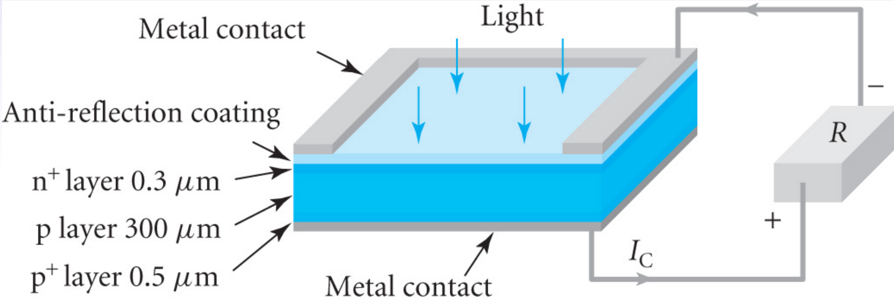

Figure: p-n junction, load and cell-current

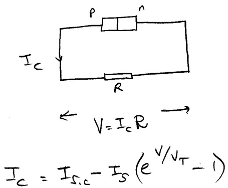

Figure: A simpler picture of p-n junction under illuminatiom

I-V characteristic of solar cell

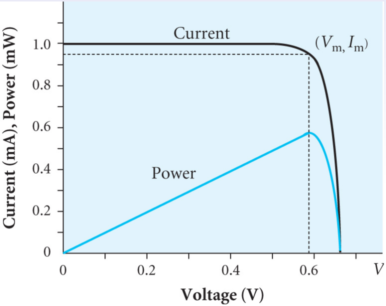

Figure: I-V characteristic

The ideal diode equation is

$$I = I_S(e^{\frac{V}{V_T}} - 1)$$

I_S is the saturation current, typically order $10^{-12} - 10^{-14}\mathrm{A}$. The quantity $V_T = \frac{k_B T}{|e|} = 0.026\mathrm{Volt}$.

A theoretical approximation to the current flowing in the p-n junction under illumnation is

$$I_C = I_{SC} - I_S(e^{\frac{V}{V_T}} - 1)$$

I_{SC} is the current generated due to electrons excited in the depletion region by the photons. Note that, under short-cricuit conditions, the load $R = 0$, and $I_C = I_{SC}$.

When we have an open circuit, $R \to \infty$, then $V = V_{OC}$. So

$$0 = I_{SC} - I_S(e^{\frac{V_{OC}}{V_T}} - 1)$$

This means that

$$V_{OC} = V_T \ln(1 + \frac{I_{SC}}{I_S}) \simeq V_T \ln(\frac{I_{SC}}{I_S}) \quad (1)$$

I_{SC} is typically of order several milliamps and we have $\frac{I_{SC}}{I_S} \gg 1$, hence the approximation $(1 + \frac{I_{SC}}{I_S}) \simeq \frac{I_{SC}}{I_S}$

Deriving formulae for (I_m, V_m) where Power is maximized.

$$\begin{aligned} P &= I_{SC}V - I_S V(e^{\frac{V}{V_T}} - 1) \\ \frac{dP}{dV} &= I_{SC} - I_S(e^{\frac{V}{V_T}} - 1) + \frac{I_S V}{V_T} e^{\frac{V}{V_T}} \end{aligned} \tag{2}$$

Setting derivative to zero :

$$\begin{aligned} I_{SC} + I_S &= I_S(1 + \frac{V}{V_T})e^{\frac{V}{V_T}} \\ (1 + \frac{I_{SC}}{I_S}) &= (1 + \frac{V}{V_T})e^{\frac{V}{V_T}} \end{aligned} \tag{3}$$

Approximate LHS by $\frac{I_{SC}}{I_S}$, since I_{SC} is typically of order a few mA, while $I_S \sim 10^{-14} - 10^{-12} A$. Use (1) to express the ratio in terms of $e^{\frac{V_{OC}}{V_T}}$ Also approx the linear factor on RHS with $\frac{V_{OC}}{V_T}$, but leave V as an unkown in the exponential.

Think through typical numbers to justify this

Hence obtain for $V = V_m$

$$e^{\frac{V_{OC}}{V_T}} = \frac{V_{OC}}{V_T} e^{\frac{V_m}{V_T}}$$

Solve for V_m

$$\frac{V_m - V_{OC}}{V_T} = ln\frac{V_T}{V_{OC}}$$
$$V_m = V_{OC} + V_T ln(\frac{V_T}{V_{OC}})$$
$$V_m = V_{OC}(1 + x_{OC} ln x_{OC})$$

where x_{OC} is defined as $\frac{V_T}{V_{OC}}$.
To get I_m,

$$I_m = I_{SC} - I_S(e^{\frac{V_m}{V_T}} - 1) \sim I_{SC} - I_S e^{\frac{V_m}{V_T}} = I_{SC} - I_S \frac{I_{SC}}{I_S} x_{OC} \qquad (4)$$

In last line we used (4). Hence

$$I_m = I_{SC}(1 - x_{OC})$$

Hence theoretical formula for fill factor

$$FF = \frac{I_m V_m}{I_{SC} V_{OC}} = (1 - x_{OC})(1 + x_{OC} ln\, x_{OC}) \tag{5}$$

Efficiency bounds

A simple physical bound comes from considering the Planck spectrum. Photons below the band gap cannot excite the electrons from valence band. Photons with higher energy excite electrons which lose some of their energy to phonons (lattice excitations) and relax to the bottom of the conduction band. Hence maximum useful energy available from each photon is E_g.

If E_g is too large, not enough photons excite electrons. If E_g is too small, a lot of energy is lost to phonons. An optimal band gap of around $1.1\mathrm{eV}$ leads to an *ultimate efficiency* of around 44%.

This is developed further in a homework problem. (homework 5).

Efficiency bounds

Consideration of radiative loss of energy, when electrons relax back to valence band emitting photons, reduces maximum theoretical efficiency to around 33%. This is also described as radiative recombination of electrons ans holes.

Other losses reduce practical efficiencies further. See Nelson (The Physics of solar cells) section 2.6 for further discussion

See Wikipedia article on “photovoltaics” for more info on best experimental efficiencies.