4.8. Solar cells

Solar cells are p-i-n photodiodes which are operated under forward bias. The intention is to convert the incoming optical power into electrical power with maximum efficiency

4.8.1. The solar spectrum

The solar spectrum is shown in Figure 4.8.1. The spectrum as seen from a satellite is referred to as the AM0 spectrum (where AM stands for air mass) and closely fits the spectrum of a black body at 5800 K. The total power density is 1353 W/m^2.

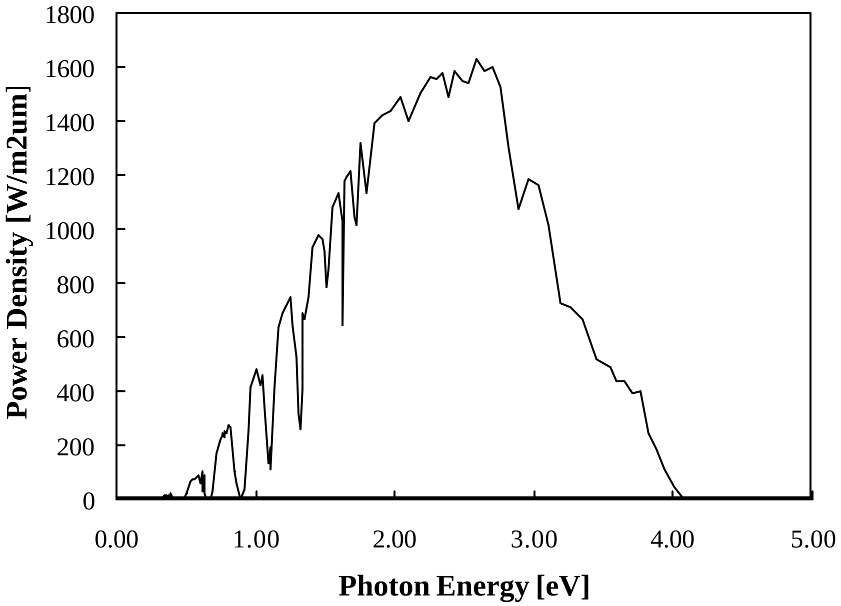

Figure 4.8.1 The solar spectrum under of AM1 conditions

The solar spectrum as observed on earth is modified due to absorption in the atmosphere. For AM1 (normal incidence) the power density is reduced to 925 W/cm^2 whereas for AM1.5 (45° above the horizon) the power density is 844 W/m^2. The irregularities in the spectrum are due to the absorption, which occurs at specific photon energies.

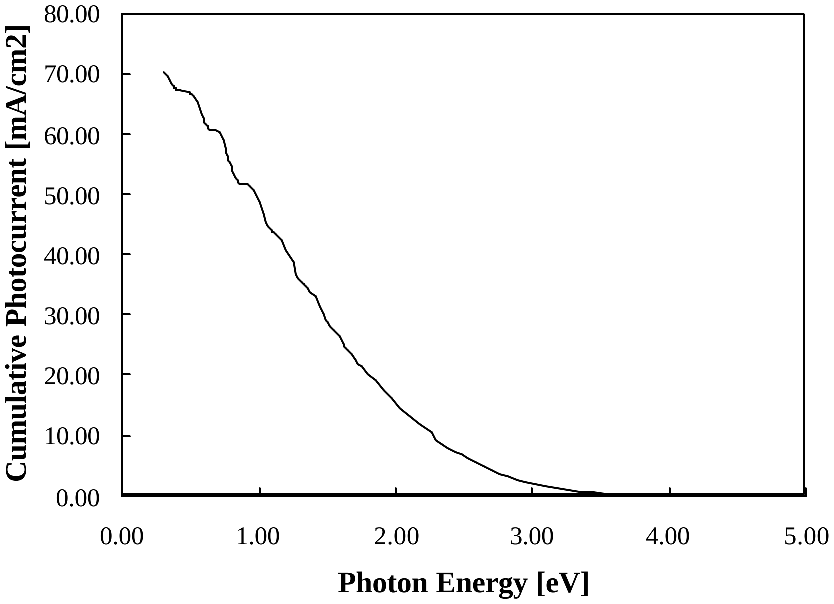

Figure 4.8.2 Cumulative Photocurrent versus Photon Energy under AM1 conditions

4.8.2. Calculation of maximum power

The current through the solar cell can be written as:

$$I = I_s (\mathrm{e}^{V_a / V_t} - 1) - I_{ph} \tag{4.8.1}$$

where I_s is the saturation current of the diode and I_{ph} is the photo current (which is assumed to be independent of the applied voltage V_a). This expression only includes the ideal diode current of the diode, thereby ignoring recombination in the depletion region. The short circuit current, I_{sc}, is the current at zero voltage equals $I_{sc} = -I_{ph}$ and the open circuit voltage equals:

$$V_{oc} = V_a (I = 0) = V_t \ln(\frac{I_{ph}}{I_s} + 1) \cong V_t \ln \frac{I_{ph}}{I_s} \tag{4.8.2}$$

The total power is then:

$$P = V_a I = I_s V_a (\mathrm{e}^{V_a / V_t} - 1) - I_{ph} V_a \tag{4.8.3}$$

The maximum power occurs at $\frac{dP}{dV_a} = 0$. The voltage and current corresponding to the maximal power point are V_m and I_m.

$$\frac{dP}{dV_a} = 0 = I_s(\mathrm{e}^{V_m/V_t} - 1) - I_{ph} + \frac{I_s V_m}{V_t}\mathrm{e}^{V_m/V_t} \tag{4.8.4}$$

This equation can be rewritten as:

$$V_m = V_t \ln[\frac{I_{ph} + I_s}{I_s}\frac{1}{1 + \frac{V_m}{V_t}}] \cong V_t[\frac{V_{oc}}{V_t} - \ln(1 + \frac{V_m}{V_t})] \tag{4.8.5}$$

Using equation [5.3.2] for the open circuit voltage V_{oc}. The most accurate solution is obtained by solving this transcendental equation and substituting into equations [5.3.1] and [5.3.3]. The maximum power can be approximated by:

$$P_m = I_m V_m \cong -I_{ph}(1 - \frac{V_t}{V_m})(V_{oc} - V_t \ln(1 + \frac{V_m}{V_t})) \tag{4.8.6}$$

$$P_m \cong -I_{ph}(V_{oc} - V_t \ln(1 + \frac{V_m}{V_t}) - \frac{V_{oc} V_t}{V_m}) \tag{4.8.7}$$

or

$$P_m = -I_{ph}\frac{E_m}{q} \tag{4.8.8}$$

where

$$E_m = q(V_{oc} - V_t \ln(1 + \frac{V_m}{V_t}) - \frac{V_{oc} V_t}{V_m}) \tag{4.8.9}$$

The energy E_m is the energy of one photon, which is converted to electrical energy at the maximum power point. The total photo current is calculated as (for a given bandgap E_g)

$$J_{ph}(E_g) = q \tag{4.8.10}$$

and the efficiency equals:

$$h = \frac{P_m}{P_{in}} = \frac{I_{ph} E_m}{q P_{in}} \tag{4.8.11}$$

4.8.3. Conversion efficiency for monochromatic illumination

This first order model provides an analytic approximation for the efficiency of a solar cell under monochromatic illumination. Starting from the result of the previous paragraph:

$$h = \frac{P_m}{P_{in}} = \frac{I_{ph}}{P_{in}}(V_{oc} - V_t \ln(1 + \frac{V_m}{V_t}) - \frac{V_{oc} V_t}{V_m}) \tag{4.8.12}$$

We replace V_{oc} by the largest possible open circuit voltage, $\frac{E_g}{q}$, yielding:

$$V_m = \frac{E_g}{q} - V_t \ln(1 + \frac{E_g}{kT}) \tag{4.8.13}$$

and

$$h = \frac{I_{ph} V_m}{P_{in}} = [1 - \frac{2kT}{E_g} \ln(1 + \frac{E_g}{kT})] \tag{4.8.14}$$

for a GaAs solar cell at 300K, $\frac{E_g}{q}$ = 55 so that the efficiency equals η = 85%

4.8.4. Effect of diffusion and recombination in a solar cell

4.8.4.1.Photo current versus voltage

The photo current is obtained by first solving the continuity equation for electrons

$$0 = D_n \frac{d^2 n}{dx^2} + m_n E \frac{dn}{dx} - \frac{n}{t} + g_{op} \tag{4.8.15}$$

as well as a similar equation for holes. The photo current is obtained from

$$I_{ph}(V_a) = \frac{qA}{d^2}(f_i - V_a) \int_0^d (m_n n + m_p p) dx \tag{4.8.16}$$

Once this photocurrent is obtained the total current is obtained from:

$$I = I_s (e^{V_a / V_t} - 1) - I_{ph}(V_a) \tag{4.8.17}$$

To obtain the corresponding maximum power one has to repeat the derivation of section 5.3.2.

4.8.5. Spectral response

Because of the wavelength dependence of the absorption coefficient one expects the shorter wavelengths to be absorbed closer to the surface while the longer wavelengths are absorbed deep in the bulk. Surface recombination will therefore be more important for short wavelengths while recombination in the quasi-neutral region is more important for long wavelengths.

4.8.6. Influence of the series resistance

$$V_{ext} = V_a + IR_s \tag{4.8.18}$$

$$I = I_s(\mathrm{e}^{V_a/V_t} - 1) - I_{ph} \tag{4.8.19}$$

$$P = V_{ext} I \tag{4.8.20}$$

Repeating the derivation of section 5.3.2 one can shown that the maximum power condition is given by the following set of transcendental equations:

$$V_m = V_t \ln[\frac{I_{ph} + I_s}{I_s} \frac{1}{1 + \frac{V_m}{V_t} + \frac{2I_m R_s}{V_t}}] \tag{4.8.21}$$

$$I_m = I_s(\mathrm{e}^{V_m/V_t} - 1) - I_{ph} \tag{4.8.22}$$

while the maximum external power equals: $P_{m,ext} = I_m\ (V_m + I_m R_s)$