CHAPTER II
FUNDAMENTAL OF SOLAR CELL

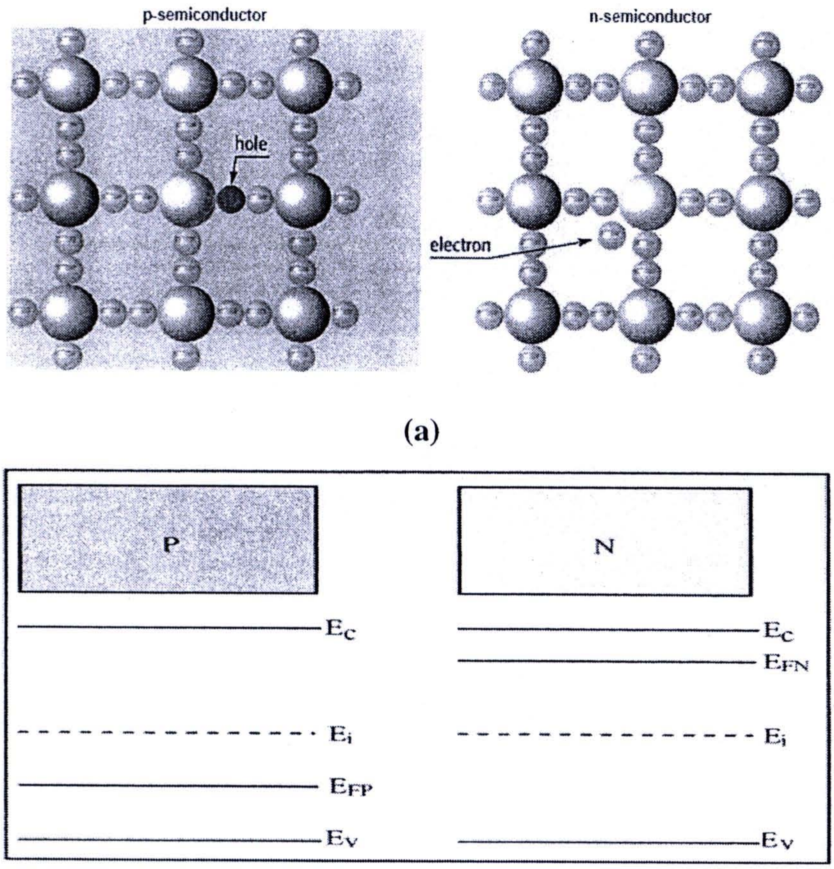
2.1 General

The objective of this chapter is mainly to elaborate on the knowledge and competencies of solar cells from many previous researchers who studied about the solar cells. Various researches were especially conducted in heterojunction solar cells, and most of them mostly delineated the knowledge and competencies of solar cells.

2.2 Fundamental definition, and operation of solar cells

To understand the photovoltaic effect, some basic theory about semiconductors and their use as photovoltaic energy conversion devices needs to be given as well as information on p-n junction [7]. The term photovoltaic means the direct conversion of light into electrical energy using solar cells. Semiconductor materials such as Silicon, Gallium Arsenide, Cadmium Telluride or Copper Indium Diselenide are used in these solar cells [7].

The semiconductor described so far is intrinsic; it is a perfect crystal containing no impurity. The one which has been doped to increase the density of electrons relative to holes is n-type semiconductor, and the one which is doped to increase the density of positive charge carriers relative to negative charge is p-type semiconductor. The schematic illustration of 2 dimensional structures of n and p type semiconductors and energy band diagram are shown in **figure 2.1 (a)** and **(b)**.



(b)

Figure 2.1 Schematic illustration of 2 dimensional crystal structure **(a)** and band diagram of n type and p type semiconductors **(b)** **[2]**.

The structure of solar cells is a p-n junction, as shown in **figure 2.2**. If the n- and p-type region is the same semiconductor material, the junction is a homojunction. If the semiconductor is different, we call heterojunction **[9]**.

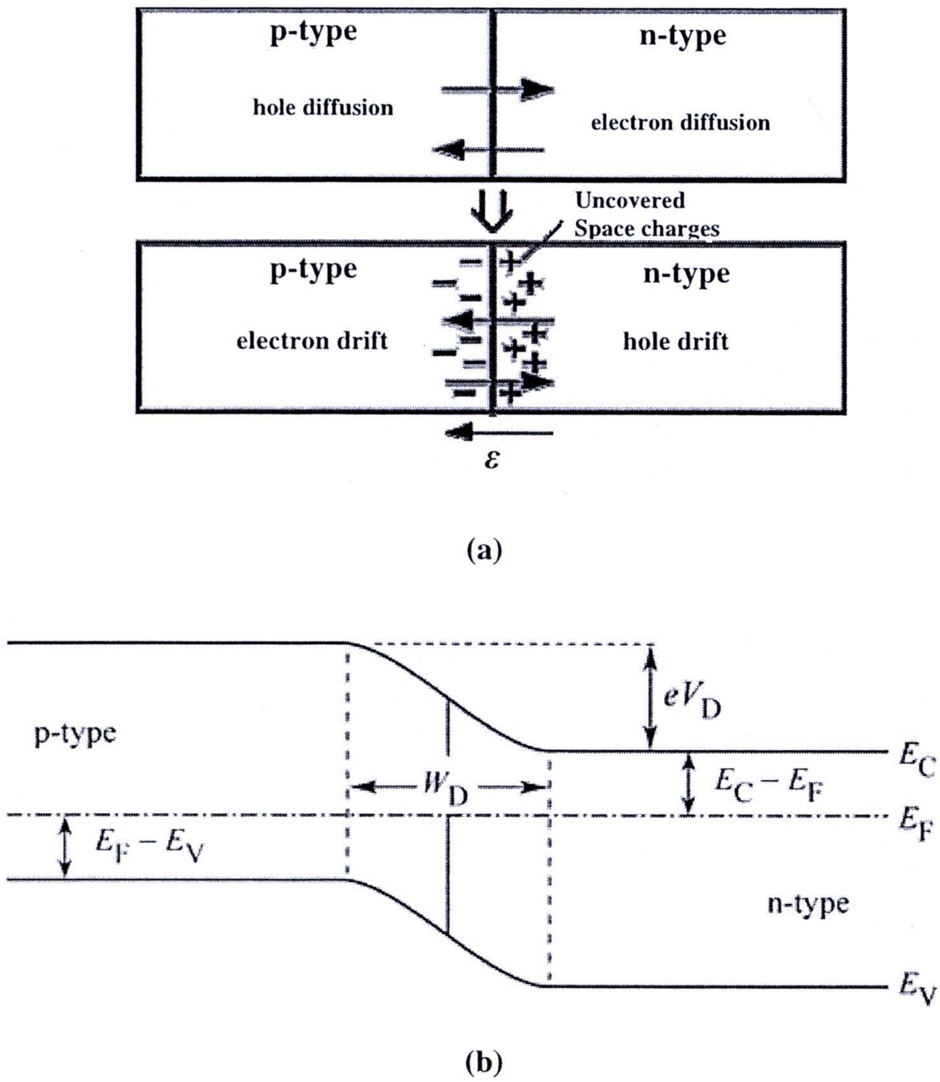


Figure 2.2 Schematic of n-p junction structure **(a)** and energy band diagram **(b) [2].**

2.2.1 Spectral response and collection efficiency

The photon is incident on solar cell panel, and then the solar cell generates the photocurrent. The photocurrent depends both on the spectral response of solar cell and spectral radiation of sunlight.

Spectral response is the rate of short circuit current J_{sc} (λ) per photon energy P (λ) absorbed by the panel, J_{sc} (λ) and P (λ) are the function of sunlight wavelength. The unit of spectral response is ampere per watt (A/W).

Collection efficiency is the amount of electrons that solar cells generate per amount of the photon absorbed.

There are two definition of collection efficiency:

(1) Internal collection efficiency, η_{in}.

In the case, there is no reflection from the solar cells panel.

(2) External collection efficiency, $\eta_{ext.}$

In the case, there is reflection from solar cells panel.

We can write the internal and external collection efficiency.

$$\eta_{In}(\lambda) = \frac{Jsc(\lambda)}{P(\lambda)} = \frac{Jsc(\lambda)}{qF(\lambda)[1 - R(\lambda)]} \tag{2.1}$$

$$\eta_{Ext}(\lambda) = \eta_{In}(\lambda)[1 - R(\lambda)] = \frac{Jsc(\lambda)}{qF(\lambda)} \tag{2.2}$$

R (λ): Reflection index of photon at solar cell surface.

F (λ): Photon flux, amount of photon per unit area and time unit is access on the cells.

q: Electron charge.

Actually, internal collection efficiency is greater than external collection efficiency, and both of them are less than one. Almost of external collection efficiency can calculate from **(2.2)**.

$$\eta_{Ext} = \frac{\sum Jsc(\lambda)}{q\sum F(\lambda)} \tag{2.3}$$

- **Collection Efficiency of p-n Junction Solar Cells**

We consider the collection efficiency of p-n junction solar cells as shown in the **figure 2.3**. Collection efficiency can be calculated by separating the layer of solar cells, n, depletion and p layer from each other; and short circuit current is calculated by solving diffusion equation.

In steady state, continuity equation of minority carrier hole is generated by photon in n-type in written as.

$$\frac{dJ_h}{dx} + \frac{Pn - Pno}{q\tau_h} - g(x) = 0 \tag{2.4}$$

$$J_h = q\mu_h p_n E - qD_h \frac{dp_n}{dx} \tag{2.5}$$

Continuity equation of minority carrier electron is generated by photon in p type is written as.

$$\frac{dJ_e}{dx} - \frac{n_p - n_{no}}{q\tau_e} + g(x) = 0 \tag{2.6}$$

$$J_e = q\mu_e n_p E + qD_e \frac{dn_p}{dx} \tag{2.7}$$

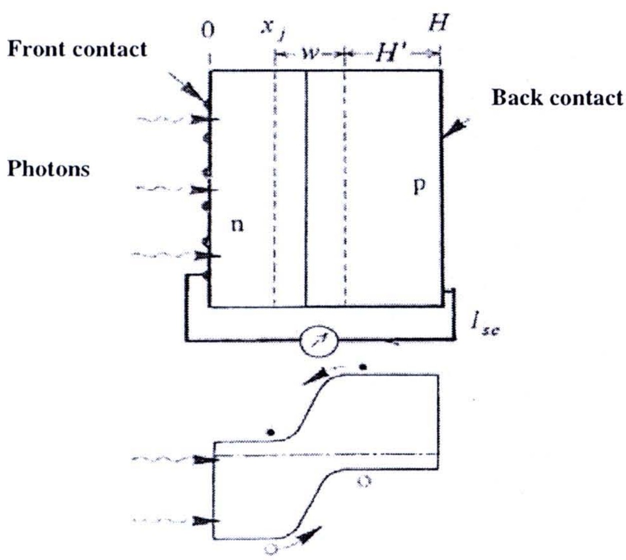


Figure 2.3 Structure and energy band of solar cell **[10]**.

J_e: Current of electron per unit area.

J_h: Current of hole per unit area.

τ_e: Lifetime of electron.

n_p: Number of electron per unit area in p layer.

D_e: Diffusion coefficient of electron.

g(x): generation rate of carrier per second.

q: Electron charge.

E: Electric field.

μ_e: Mobility of electron.

μ_h: Mobility of hole.

τ_h: Lifetime of hole.

p_n: Number of hole per unit area in n layer.

D_h: Diffusion coefficient of hole.

p_{n0}, n_{p0}: Carrier concentration at thermal equilibrium.

x: Distance from surface.

To solve equation of **2.4 ~2.7,** we will set up boundary condition as follow

$$p_n = p_{no} \exp(qV/kT) \quad \text{, at } x = x_J \qquad \textbf{(2.8)}$$

$$n_p = n_{po} \exp(qV/kT) \quad \text{, at } x = x_J + w \qquad \textbf{(2.9)}$$

$$S_h(p_n - p_{no}) = D_h \frac{dp_n}{dx} - \mu_h p_n E \quad \text{, at } x = 0 \qquad \textbf{(2.10)}$$

$$S_e(n_p - n_{po}) = D_e \frac{dn_p}{dx} - \mu_e n_p E \quad \text{, at } x = H \qquad \textbf{(2.11)}$$

S_e: Recombination velocity of electron at solar cells surface (x=H).

S_h: Recombination velocity of hole at solar cells surface.

W: Width of depletion layer.

In depletion layer, there are built-in potential generates from space charge, but in p and n layer, there are less built-in potential. If we are not considered the built-in potential in p and n, we can write the continuity equation in n layer by equation of **2.4** and **2.5**:

$$D_h \frac{d^2 p_n}{d x^2} + g(x) - \frac{p_n - p_{no}}{\tau_h} = 0 \qquad \textbf{(2.12)}$$

$$g(x) = \alpha F(1-R)\exp(-\alpha x) \qquad \textbf{(2.13)}$$

Then we solve the equation of **2.12**

$$p_n - p_{no} = A Cosh \frac{x}{L_h} + B \sinh \frac{x}{L_h} - \frac{\alpha F(1-R)\tau_h}{\alpha^2 L_h^2 - 1} \exp(-\alpha x) \qquad \textbf{(2.14)}$$

L_h: Diffusion distance of hole, $L_h = (D_h \tau_h)^{1/2}$.

α: Absorption coefficient.

R: Reflection coefficient.

A and B can calculate by two conditions:

1 $x = x_J$, there are negligible excess carriers

$$p_n - p_{no} = 0, \quad x = x_j \qquad \textbf{(2.15)}$$

2 On the front surface of solar cells, there is recombination.

$$D_h \frac{d(p_n - p_{no})}{dx} = S_h (p_n - p_{no}), \quad x = 0 \qquad \textbf{(2.16)}$$

After giving two conditions, we can write the equation of **2.14**.

$$P_n - P_{no} = \left[\frac{\alpha F(1-R)\tau_h}{\alpha^2 L_i^2 - 1}\right] \left[\frac{(\frac{S_h L_h}{D_h} + \alpha L_h) Sinh \frac{x_J - x}{L_h} + \exp(-\alpha x_J)(\frac{S_h L_h}{D_h} Cosh \frac{x_J}{L_h} + Sinh \frac{x_J}{L_h})}{\frac{S_h L_h}{D_h} Sinh \frac{x_J}{L_h} + Cosh \frac{x_J}{L_h}} - \alpha L_h \exp(-\alpha x_J) \right] \qquad \textbf{(2.17)}$$

$x = x_j$ is the edge of depletion layer. Photocurrent of hole (J_h) generates in n layer.

$$J_h = -qD_h \frac{dp_n}{dx}$$

$$= \left[\frac{qF(1-R)\alpha L_h}{\alpha^2 L_h^2 - 1}\right]\left[\frac{\frac{S_h L_h}{D_h} + \alpha L_h - \exp(-\alpha x_J)\left(\frac{S_h L_h}{D_h} Cosh \frac{x_J}{L_h} + Sinh \frac{x_J}{L_h}\right)}{\frac{S_h L_h}{D_h} Sinh \frac{x_J}{L_h} + Cosh \frac{x_J}{L_h}} - \alpha L_h \exp(-\alpha x_J)\right] \quad \textbf{(2.18)}$$

In the same case, photocurrent of electron (J_e) generates in n layer can be calculated from equation of **2.16** and **2.17** by giving two conditions.

1 $n_p - n_{po} = 0, \quad x = x + w$ **(2.19)**

2 $-D_e \frac{d(n_p - n_{po})}{dx} = S_e(n_p - n_{po})$, $x = H$ **(2.20)**

From two conditions, we get J_e:

$$J_e = qD_e \frac{dn_p}{dx} = \frac{qF(1-R)\alpha L_e}{\alpha^2 L_e^2 - 1} \exp[-\alpha(x_J + w)]$$

$$\times \left[\alpha L_e - \frac{\frac{S_e L_e}{D_e}\left(Cosh \frac{H'}{L_e} - \exp(-\alpha H')\right) + Sinh \frac{H'}{L_e} + \alpha L_e \exp(-\alpha H')}{\frac{S_e L_e}{D_e} Sinh \frac{H'}{L_e} + Cosh \frac{H'}{L_e}}\right] \quad \textbf{(2.21)}$$

For $\quad H' = H - (x_J + w)$

From equation of **2.18** and **2.21**, we get "the value of photocurrent of hole (J_h) and electron (J_e) correspond to absorption coefficient of photon (α) and diffusion distance of carriers (L_e, L_h)".

Next, we consider the photocurrent generates in depletion layer. The carrier is excited in depletion layer, and pull out of the external by electric field of p-n junction. Those carriers are not recombined or recombine a little. The current flow like this, called drift current (J_{dr}).

$$J_{dr} = qF(1-R)\exp(-\alpha x_J)[1 - \exp(-\alpha w)] \quad \textbf{(2.22)}$$

W: depletion thickness.

$$w = \left[\frac{2\varepsilon_s}{q} (v_d - v) \frac{N_a - N_d}{N_a N_d} \right]^{1/2} \qquad (2.23)$$

ε_s: Dielectric permittivity of semiconductor.

N_a, N_d: Density of acceptor, donor impurity atoms.

V_d: Voltage generates from p-n junction.

V: Bias voltage.

We can summarize, the short circuit photocurrent at each wavelength of photon in p-n junction ($J_{sc}(\lambda)$).

$$J_{sc} = J_h(\lambda) + J_e(\lambda) + J_{dr}(\lambda) \qquad (2.24)$$

η_{in} and η_{ext} can be calculated from equation of **2.1** and **2.2**. This equation can be used the photon access on the n layer. The photon access on the p layer also can be used, but there have to change the subscription **[10]**.

- **Collection efficiency of Schottky barrier and MIS (Metal Insulator Semiconductor) solar cells**

Figure 2.4 (a) and (b) demonstrate schematic structure and energy band diagram of Schottky barrier and MIS solar cells. Both of them, the access photon of the metal layer tunnels to semiconductor layer. Therefore, the carrier is excited by photon at depletion and semiconductor layer. So the photocurrent generates at depletion region is the same equation **2.22**

$$J_{dr} = qT(\lambda)F(\lambda)[1 - \exp(-\alpha w)] \qquad (2.25)$$

$T(\lambda)$: tunneling metal layer coefficient/Insulator of photon.

W: depletion thickness.

$$W = \left[\frac{2\varepsilon_s}{qN_d} \left(V_d - V \right) \right]^{1/2} \tag{2.26}$$

Next semiconductor layer generates photocurrent of holes.

$$J_h = \left(\frac{qF\alpha L_h}{\alpha L_h + 1} \right) T(\lambda) \exp(-\alpha w) \tag{2.27}$$

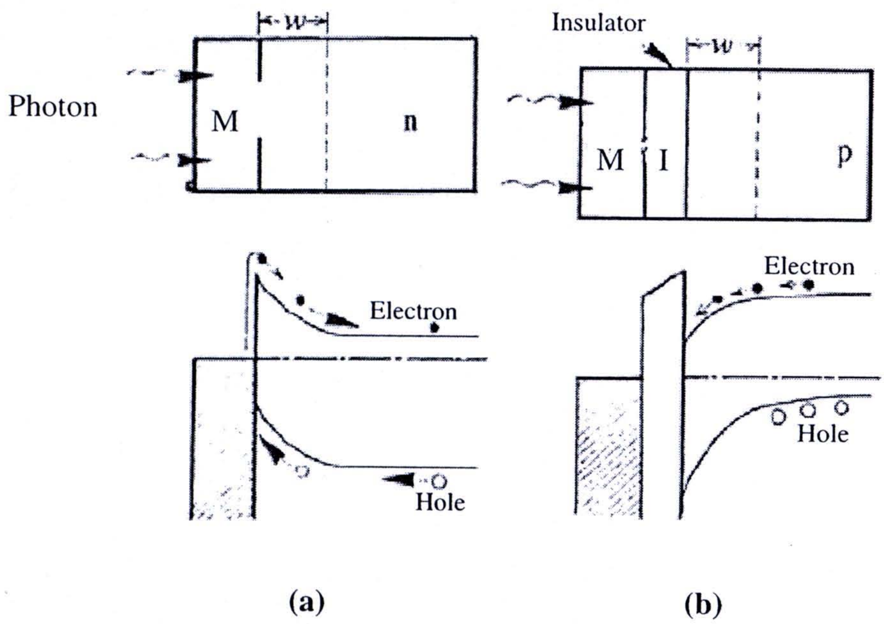


Figure 2.4 Energy band diagram and schematic structure of (a) Schottky barrier, and (b) MIS solar cell **[11]**.

To suppose that $\alpha L_h >> 1$

$$J_{sc}(\lambda) = J_{dr}(\lambda) + J_h(\lambda)$$

$$= T(\lambda) qF(\lambda) \left[1 - \exp(-\alpha w) \frac{\alpha L_h}{\alpha L_h + 1} \right] \tag{2.28}$$

Therefore, the collection efficiency $\eta_{In}(\lambda)$.

$$\eta_{In}(\lambda) = \frac{J_{sc}(\lambda)}{qF(\lambda)T(\lambda)} \tag{2.29}$$

Figure 2.5 shows the calculation of collection efficiency (η_{In}) of Schottky barrier solar cells. There is a bit influence from carrier recombination on the front surface. So collection efficiency of schottky barrier is greater than p-n junction **[11]**.

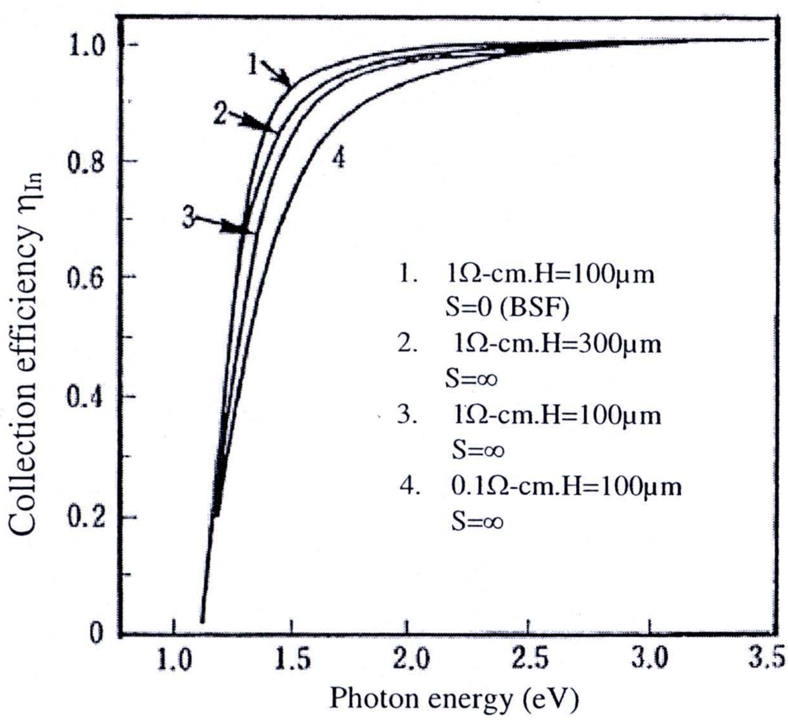


Figure 2.5 Calculation result of collection efficiency of schottky barrier solar cell **[11]**.

- **Collection efficiency of heterojunction solar cells**

Heterojunction solar cells are consisting of two different energy band semiconductors being contacted to be a p-n junction. **Figure 2.6** shows the sample of p-n heterojunction solar cells; n-type energy band diagram is wider than p-type, and the photon accesses on n-type surface. The carrier generates in p-type is more influence to efficiency. The electron current generates in p-type layer can be calculated from the equation **(2.6)**, **(2.7)**, **(2.9)** and **(2.20)**, by consideration some part of photon being absorbed in n-type.

$$J_e(\lambda) = \frac{qF(\lambda)\exp\left[-\alpha(x_j + w_1)\right]\exp(-\alpha_2 w_2)\alpha_2 L_{e2}(1-R)}{\alpha_2^2 L_{e2}^2 - 1} \times$$

$$\left[\alpha_2 L_{e2} - \frac{\frac{S_e L_{e2}}{D_{e2}}\left(\cosh\frac{H'}{L_{e2}} - ex(-\alpha H')\right) + \sinh\frac{H'}{L_{e2}} + \alpha_2 L_{e2}\exp(-\alpha H')}{\frac{S_e L_{e2}}{D_{e2}}\sinh\frac{H'}{L_{e2}} + \cosh\frac{H'}{L_{e2}}}\right] \quad \textbf{(2.30)}$$

In this p-n heterojunction, there are two depletion regions w_1 and w_2 as shown in **figure 2.6**. Hole current is generated in n-type layer, calculates by using equation **2.18**. And $J_{dr}(\lambda)$ equal to $J_{w1}+J_{w2}$, J_{w1} can be calculated by equation **2.22** and J_{w2} also can be calculated by equation **2.22** but using x_j+w_1 instead of x_j.

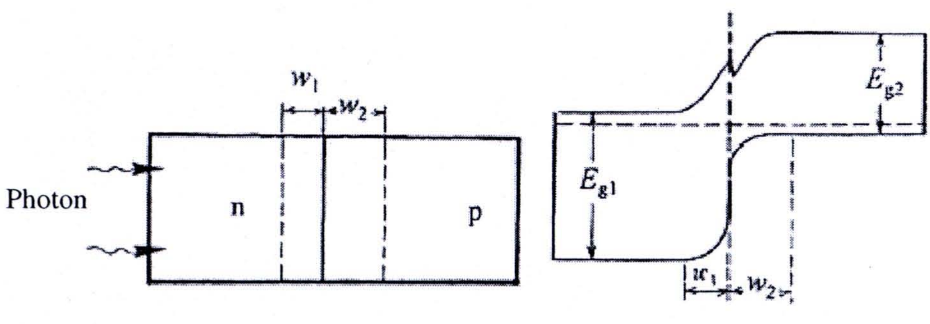


Figure 2.6 Structure of solar cells where n-type energy band diagram is greater than p-type **[11]**.

2.3 Output characteristics of solar cells

The following electrical and optical characteristics are used to explain the performance of solar cells.

2.3.1 Energy conversion efficiency

It means the ratio between maximum output power per sunlight energy incident on the solar cells and simply written by η.

$$\eta = \frac{P_{\max}(w)}{Area(m^2) \times P_{in}(w)} \times 100\% \qquad \textbf{(2.31)}$$

2.3.2 Short circuit current

If solar cells output terminals are in short circuit, we call the current flows on the circuit "Short circuit current (I_{sc})".

Figure 2.7 demonstrates the equivalent circuit of solar cells. If the solar cells is in the dark, the relation between dark current (I) and voltage (V) of solar cells is the same as the current equation of diode.

$$I = I_o\left[\exp(qV / nkT) - 1\right] \qquad \textbf{(2.32)}$$

$$I_0 = qA\left[\frac{D_h P_n}{L_h} + \frac{D_e n_p}{L_e}\right]$$

I_0 is called saturation current and n is ideality factor of diode.

So I_{out} flows to external, this current is different between dark current I and I_{ph} (=I_{sc}).

$$I_{out} = I - I_{ph} \qquad \textbf{(2.33)}$$

I_{ph}(=I_{sc}) from equation of **2.2**, A is area of the photon access.

$$I_{sc} = qA\int_{0}^{\infty} F(\lambda)\eta_{ext}(\lambda)d\lambda \qquad \textbf{(2.34)}$$

To consider the resistance inside of solar cells such as series resistance (R_s) and shunt resistance (R_{sh}), so we can write I_{out}.

$$I_{out} = I_0\{\exp\left[\frac{q(V - IRs)}{nkT}\right] - 1\} + \frac{V - IRs}{R_{sh}} - I_{ph} \qquad \textbf{(2.33')}$$

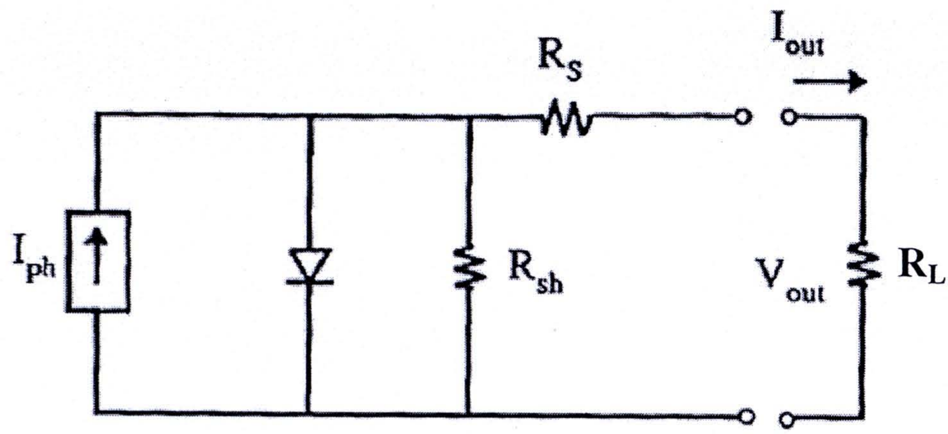


Figure 2.7 Equivalent circuits of solar cells **[12]**.

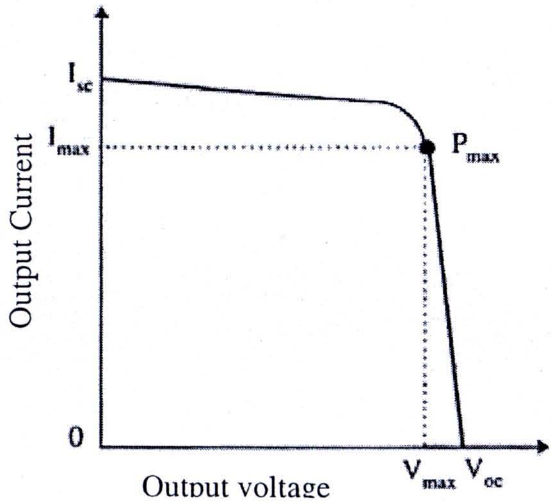
2.3.3 Open circuit voltage (V_{oc})

If output of solar cells is in open circuit, the voltage that we measure, calls "Open circuit voltage (V_{oc})". V_{oc} can be calculated from equation of **2.33** by giving $I_{out} = 0$.

$$V_{oc} = \frac{nkT}{q}\ln(\frac{I_{sc}}{I_0} + 1) \qquad \textbf{(2.35)}$$

The **figure 2.8** demonstrates the output characteristics of solar cells. The point of graph intersect voltage axis, is called open circuit voltage (V_{oc}). The point of graph intersect current axis, is called short circuit current (I_{sc}). Then the maximum power (P_{max}) is equal to the area of square being calculated by V_{max} and I_{max}. On the **figure**

2.8 also shows the parameter of maximum voltage (V_{max}), and maximum current (I_{max}).



I_{sc}: Short circuit current.

I_{max}: Maximum current.

V_{oc}: Open circuit voltage.

V_{max}: Maximum voltage.

P_{max}: Maximum power.

Figure 2.8 Maximum outputs of solar cells **[12]**.

$$P_{max} = V_{max} \times I_{max} \quad \textbf{(2.36)}$$

We can calculate V_{max} by finding the derivative of maximum power (P_{max}) with respect to maximum voltage (V_{max}) and let

$$\frac{\partial P_{max}}{\partial V_{max}} = 0$$

The solution is

$$\exp\left(\frac{qV_{max}}{nkT}\right)\left(1+\frac{qV_{max}}{nkT}\right) = \left(\frac{I_{sc}}{I_0}+1\right) \quad \textbf{(2.37)}$$

It is the same case, we can calculate maximum current (I_{max}).

$$I_{max} = \frac{(I_{sc}+I_0)\dfrac{qV_{max}}{nkT}}{1+\dfrac{qV_{max}}{nkT}} \quad \textbf{(2.38)}$$

2.3.4 Fill Factor

An other important output parameter is the fill factor which is defined as ratio between $V_{max}\times I_{max}$ and $V_{oc}\times I_{sc}$.

$$FF = \frac{P_{max}}{V_{oc}\times I_{sc}} = \frac{V_{max}\times I_{max}}{V_{oc}\times I_{sc}} \tag{2.39}$$

$$= \frac{V_{max}}{V_{oc}}\left[1-\frac{\exp(qV_{max}/nkT)-1}{\exp(qV_{oc}/nkT)-1}\right] \tag{2.40}$$

If series resistance (R_s) is less, the fill factor (FF) is great.

If we know the parameter output above, we calculate the efficiency of solar cells.

$$\eta = \frac{P_{max}}{P_{in}}\times 100\% = \frac{V_{max}\times I_{max}}{P_{in}} = \frac{V_{oc}\times I_{sc}\times FF}{P_{in}}\times 100\% \tag{2.41}$$

$$= FF\times(nkT/q)\ln[(I_{sc}/I_0)+1]\times q\times\frac{\int_0^\infty F(\lambda)\eta_{ext}(\lambda)d\lambda}{\int_0^\infty F(\lambda)\times(hc/\lambda)d\lambda} \tag{2.42}$$

2.4 Application of heterojunction solar cells or window effect

The junction which is made form two different type semiconductors called heterojunction. If two type of semiconductors is the same such as n-n and p-p, called isotype junction. Otherwise, if they are different such as p-n or n-p, called anisotype.

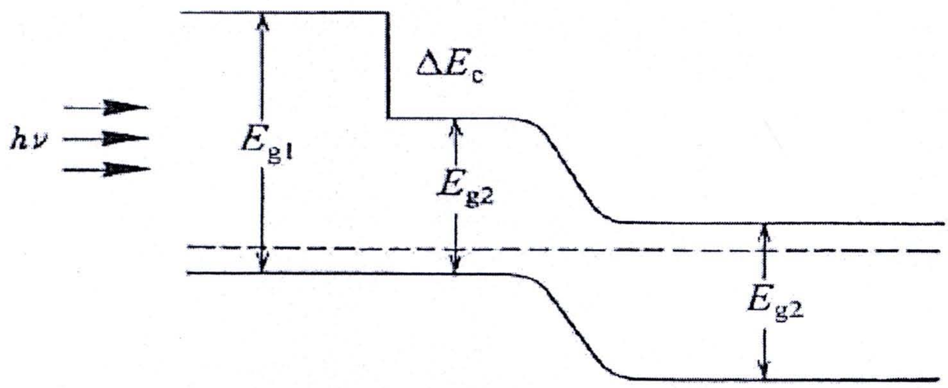


Figure 2.9 Band diagrams of AlGaAs/GaAs homojunction solar cells **[12]**.

Isotype junction is more important for homojunction solar cells. **Figure 2.9** demonstrates solar cells band diagram of p-$Ga_{1-x}Al_xAs$/p-GaAs/n-GaAs. If there is no layer of p-$Ga_{1-x}Al_xAs$, the rate recombination of electrons of solar cells at p-GaAs surface will be greater than 10^6 cm/s. So there is less electrons flowing out of n-GaAs, because the electrons recombine at p-GaAs.

If we grow the p-$Ga_{1-x}Al_xAs$ layer on p-GaAs, the electrons recombination at p-GaAs is lower than 10^4 cm/s. and p-$Ga_{1-x}Al_xAs$ generates ΔE_C to reflect more electrons flowing to n-GaAs. Then the efficiency is high.

Energy band gap of $Ga_{1-x}Al_xAs$ depends on the content of Al, if x=0.7 the energy gap is 2.5eV. It is suitable for wavelength of photons of solar spectrum. So if we increase thickness about 10μm, the sheet resistance of $Ga_{1-x}Al_xAs$ is decreased.

Heterojunction solar cells consist of n and p type semiconductor. P or n type has wide band gap semiconductor on the top. The photon with energy less than band gap of top layer can pass through, so called this layer as " window layer " and this phenomena is called " window effect ".

The photon can pass through the window layer, and then is absorbed at the next layer which has lower energy band gap generates electron and hole pair. The heterostructure solar cells have high spectral response with photon energy in between band gap energy of both semiconductors. We can reduce the sheet resistance of solar cells by growing thick window layer and this window can protect other radiation in space.

Hence, to design heterojunction solar cells, they have to select approximate band gaps of both semiconductors material relate to the spectral response of sunlight.

On the **table 2.1** shows the lattice mismatch and band discontinuity of semiconductor pair formed heterojunction. The definition of lattice match is the difference of lattice constant of two type semiconductors contacted **[12]**.

Table 2.1 Lattice mismatches and band discontinuity of semiconductor that we make the heterojunction anisotype.

Semiconductors	**Lattice mismatch** (%)	**Band discontinuity**
p-$Ga_{0.4}Al_{0.6}As$/n-GaAs	0.08	$\Delta E_v \approx 0$ eV
n-CdS/p-InP	0.9	$\Delta E_c \approx 0.12$ eV
n-CdS/p-CdTe	9.7	$\Delta E_c \approx 0.22$ eV
n-CdS/p-Cu_2S	4.6	$\Delta E_c \approx 0.2$ eV