CHAPTER II

GENERAL THEORY OF SOLAR CELLS

2.1 Introduction.

Photovoltaic effect is the phenomena of converting solar or radiant energy directly into electrical energy. It is briefly described in sections 2.2 and 2.3 of this chapter. The last section is devoted to an analysis of internal parameters affecting the output power of solar cells. These parameters are the photocurrent, I_{ph}, the reverse saturation current, I_s, the ideality factor, n, series resistance, R_s and shunt resistance, R_{sh}.

2.2 Optical Absorption in a Semiconductor.

Photons, $h\nu$, may or may not be absorbed in an illuminated semiconductor, depending on photon energy and the energy gap, Eg, of that material, that is (3)

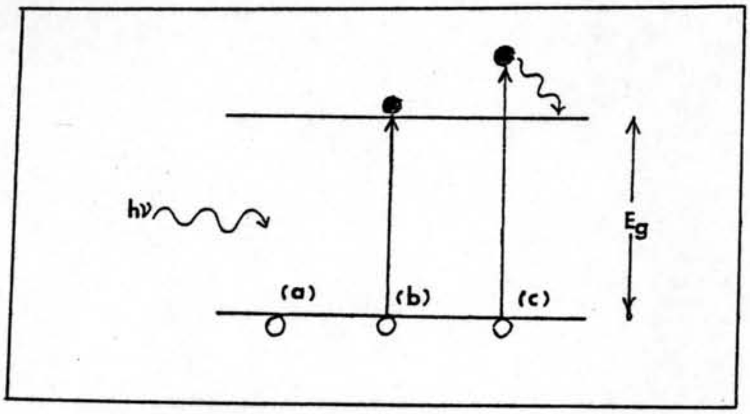

Fig 1. Optically generated electron-hole pairs in a semiconductor.(3)

If $h\nu < Eg$, photons are not absorbed by a semiconductor, and the light is transmitted through the material as shown in Fig. 1, case (a);

If $h\nu = Eg$, photons are absorbed to create electron-hole pairs, as shown in Fig. 1 case (b);

If $h\nu > Eg$, the electron-hole pairs are generated, besides, the excess energy is dissipated as heat, as shown in Fig. 1, case (c).

The fraction of light is transmitted through a semiconductor by the Lambert law.

$$F(x) = F_o \exp(-\alpha x) \qquad (1)$$

where x is distance from the surface

F_o is the number of photons at the surface

α is the absorption coefficient of a semiconductor for a given wavelength of incident photons.

A variation of absorption coefficient, α with wavelength, λ, for silicon is shown in Fig. 2. In fact, it varies with temperature(4)

From Eq. (1), when every absorbed photon generates electron-hole pairs, the genation rate is

$$G(x) = -\frac{dF}{dx} = \alpha F_o \exp(-\alpha x) \qquad (2)$$

When surface reflectivity is included, Eq. (2) becomes

$$G(x) = \alpha F_o (1-R) \exp(-\alpha x) \qquad (3)$$

where R is the reflectivity.

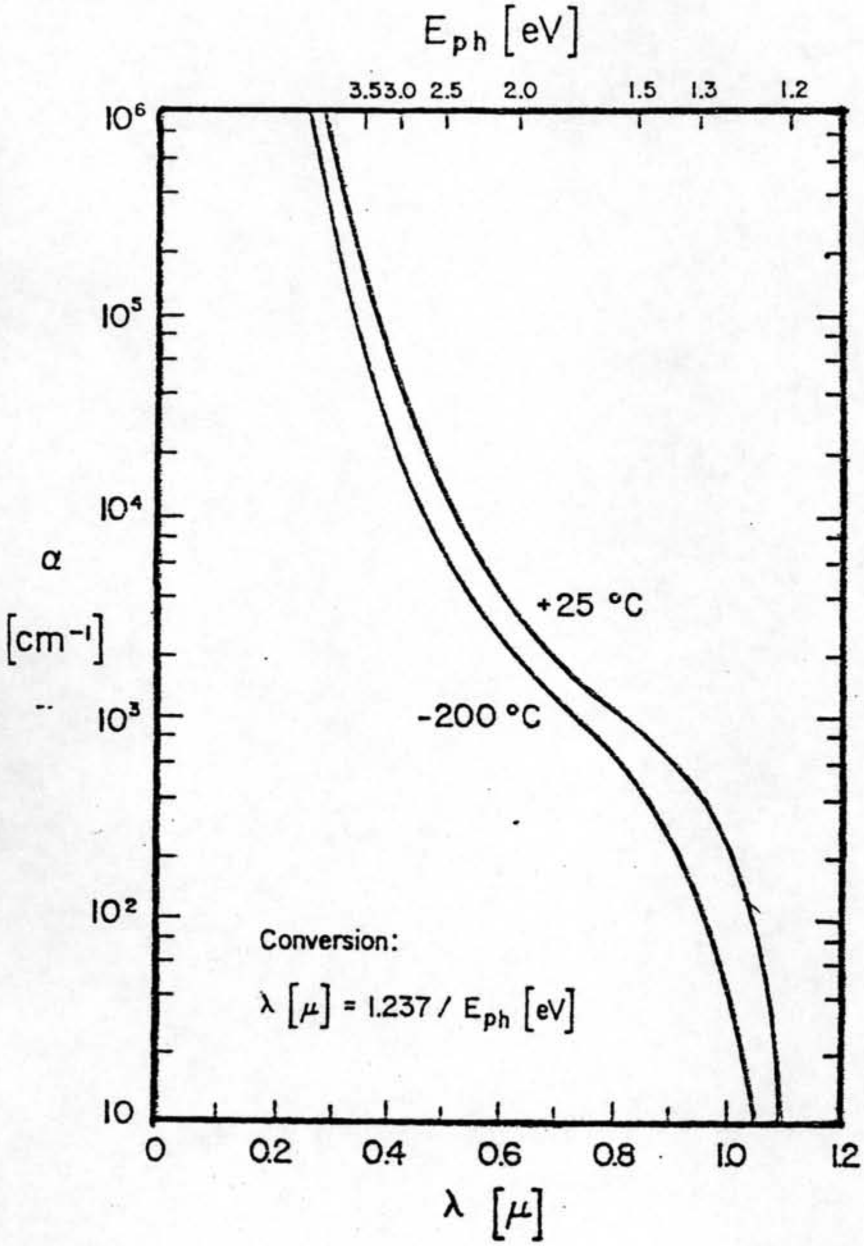

Fig.2 Absorption coefficient vs. wavelength.

2.3 Principle of Photovoltaic Energy Conversion.

The process of converting radiant energy into electrical energy in an n-on-p junction involves the following steps[(3)], see Fig. 3.

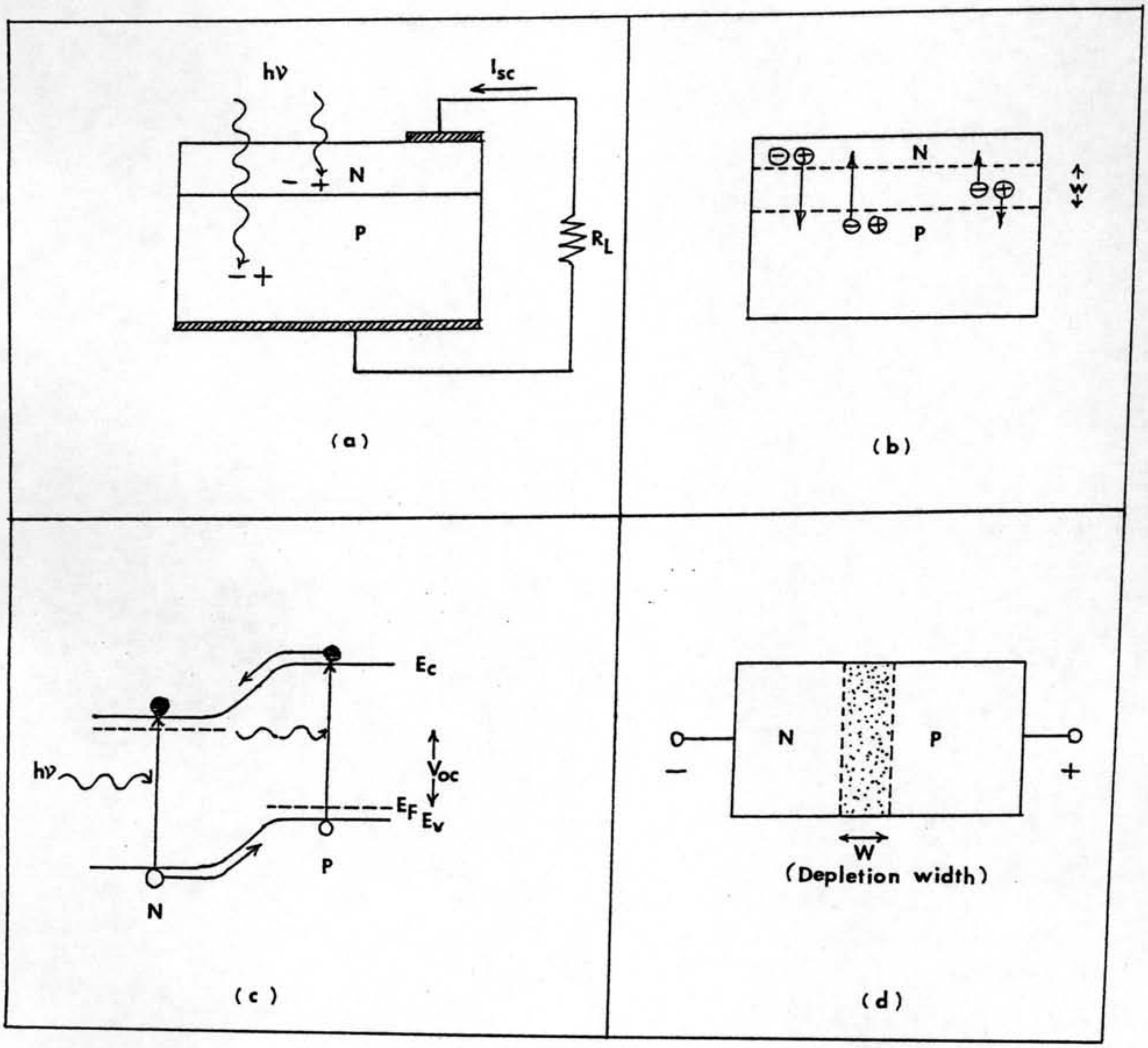

Fig. 3. The process of energy conversion.

Firstly, photons are absorbed, so that, electron-hole pairs are both created in the n and p sides of the junction as shown in Fig. 3, case (a). Secondly, by diffusion, the excess minority carriers, electrons, on the p-side and holes on the n-side of the junction reach the space charge region as shown in Fig. 3 case(b). Thirdly, electron-hole pairs are then separated by the strong electric field; thus, electrons in the p-side slide down the potential to move to the n-side and holes go in the opposite direction as shown in Fig. 3, case(c). Finally, if the junction is open-circuited, the accumulation of electrons and holes on the two sides of the junction produces an open-circuited voltage, V_{oc} as shown in Fig. 3, case(d). When terminals are short-circuited, a current will conduct in the circuit as shown in Fig. 3, case(a). This current is called short-circuit current, I_{sc}.

The amount of collected electron-hole pairs are those survived from loss processes. These loss processes are described as the following.(1)

Bulk recombination can occur by direct mutual annihilation through an intermediate centers; usually the intermediate recombination is the dominant mechanism. Then, the hole lifetime on the n-side of the junction (for an n-on-p junction) is approximately given by

$$\tau_p = (\sigma_p v_{th} N_r)^{-1}$$

where σ_p is the hole capture cross section. (cm^2)

v_{th} is the thermal velocity, $v_{th} = \sqrt{3kT/m} \cong 10^7$ cm/scc at 300 °K.

and N_r is the recombination center densities. (cm^{-3})

Surface recombination takes place at the surfaces of the material due to the presence of surface states which arise from dangling bond, chemical residues, metal precipitates, nature oxides and the like. The rate at which carriers are lost at a surface is described by the surface recombination velocity, S, which is given by the minority carrier current towards the surface, J_s. That is

$$\begin{aligned} J_s &= qS_p(P_n - P_{no}) && \text{for n-type material} \\ &= qS_n(n_p - n_{po}) && \text{for p-type material} \end{aligned} \tag{4}$$

where J_s is the minority carrier current towards the surface.

q is the electronic charge.

S_p, S_n are the surface recombination velocity of hole and electron, respectively

P_n is the hole density in n-type material.

n_p is the electron density in p-type material.

P_{no} is the hole density in equilibrium.

and n_{po} is the electron density in equilibrium.

2.4 Simple Analytical Model of Eletrical Characteristics of Solar Cells.

The electrical characteristics of p-n junction solar cells can be understood by the simplified equivalent circuit in Fig.4.

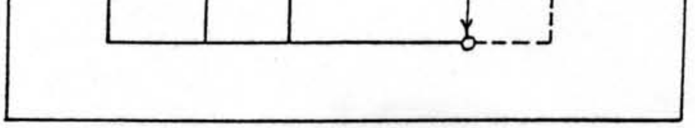

Fig.4. Simplified equivalent circuit of solar cells

An equivalent circuit for the solar cell is shown in Fig.4.

where R_s is the series resistance of the cell.

R_{sh} is the shunt resistance of the cell.

R_L is the load resistance.

I_{ph} is the photocurrent of the cell.

I_1 is the current through shunt resistance.

and I_o is the output current when the circuit is connected to an external load, R_L.

These parameters are decribed as the following. R_s can be arised from contact resistance to the front and the back, the resistance of diffused layer and the resistance of the base region. R_{sh} can be caused by surface leakage along the edges of the cell, by diffusion spikes along dislocations or grain boundaries, or possibly by fine metallic bridges along microcracks, grain boundaries, or crystal defects such as stacking faults after the contact metallization has been applied. I_{ph}, is the amount of collected electron-hole pairs under illumination minus surface and bulk recombination or the photocurrent. And I_D is the diode forward bias current without illumination or dark current.

In case of $R_s=0$, $R_{sh}=\infty$ (i.e, an ideal solar cell), the photocurrent, I_{ph} is equal to the short-circuit current, I_{sc}, when the terminals are short-circuited. If the load, R_L, does not equal zero, there produces the output voltage V_o. The amount of this voltage biases the cell and gives rise to I_D and I_1. Therefore, the current supplying to the load is the photocurrent minus these two currents. That is

$$I_o = I_{ph} - (I_D + I_l) \qquad (5)$$

Practically, the dark current, I_D, in Eq. (5) can be written as

$$I_D = I_s \left[\exp\left(\frac{V_o + I_o R_s}{nV_T}\right) - 1 \right] \qquad (6)$$

Where I_s is the reverse saturation current without illumination.

V_o, I_o are the output voltage and current, respectively.

V_T is the thermal voltage which is equal to $\frac{kT}{q}$ or 26 mV at 300°K (k is Boltzmann constant, 1.381×10^{-23} J/°K, q is electronic charge, 1.602×10^{-19} C and T is the temperature) and n is the ideality factor of diode.

In case where $V_o \gg V_T$, Eq. (6) can be approximated as

$$I_D = I_s \exp\left(\frac{V_o + I_o R_s}{nV_T}\right) \qquad (7)$$

Substitute I_D and I_l in Eq. (5), I_o becomes

$$I_o = I_{ph} - I_s \exp\left(\frac{V_o + I_o R_s}{nV_T}\right) - \frac{V_o + I_o R_s}{R_{sh}} \qquad (8)$$

Then, it is clearly seen that the ability of converting radiant energy into electrical energy of solar cells depends on I_{ph}, I_s, n, R_s and R_{sh}. In order to study the influence of these parameters to the output power, Eq. (8) can be rewritten as

$$I_o = I_{ph} - I_s \exp\left(\frac{V_D}{nV_T}\right) - \frac{V_D}{R_{sh}} \qquad (9)$$

Where V_D is the voltage drop across the diode. And

$$V_o = V_D - I_o R_s \qquad (10)$$

2.4.1 The Photocurrent, I_{ph}

The effects of photocurrent, I_{ph}, on the solar cell performance are investigated by numerical calculation $^{(5)}$. It is shown in Fig.5.

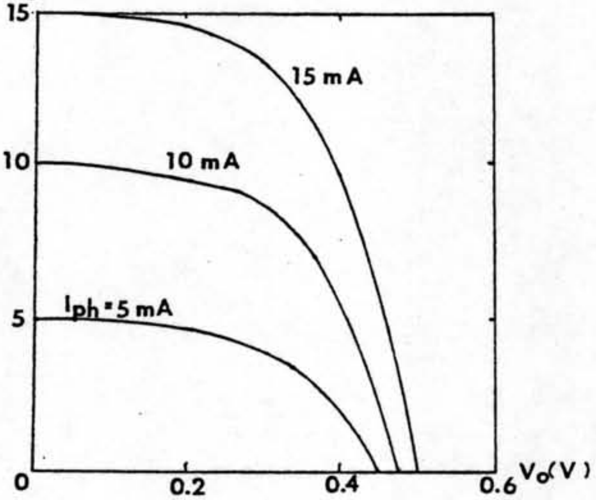

Fig.5. Calculated results of solar cell curves with different photocurrents. Given that $I_s = 1\mu A$, $R_s = 5\ \Omega$, $R_{sh} = 1K\ \Omega$, n=2 and $V_T =$ 0.026 mV.

It can be seen that the higher values of I_{ph} results in the higher output power. The amount of electron-hole pairs generated depends mainly on the intensity and the spectral characteristic of the incident light source.

The corresponding photocurrent is the result of minority carrier extraction ability of the cell. Hence, the spectral response of the light source must be carefully investigated. The spectral characteristic depends on the following parameters: the optical absorption coefficient, α, the junction depth, X_j, the depletion region width, W, the lifetime, τ, or diffusion length, L, on both sides of the junction, reflection coefficient, R, surface recombination velocity, S and the quality of contact. The analysis of photocurrent via spectral response will be given in the next two chapters.

2.4.2 The Reverse Saturation Current, I_s and the Ideality Factor, n.

The effects of reverse saturation current, I_s and ideality factor, n on the solar cell performance are investigated by numerical simulation. They are shown in Figures 6 and 7.

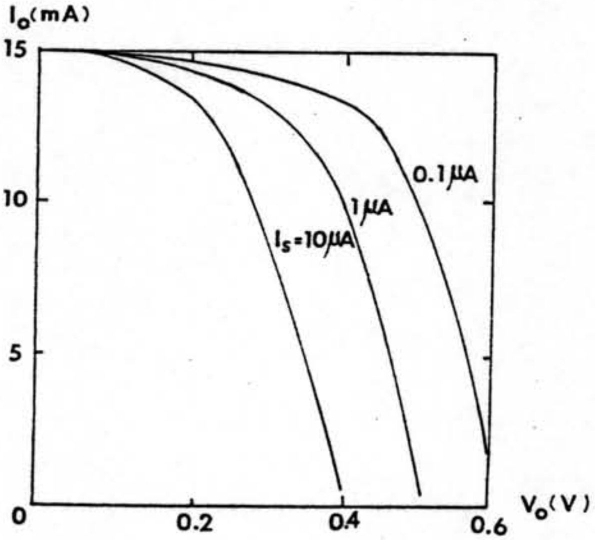

Fig.6 Calculated results of solar cell curves with difterent reverse saturation current, I_s. Given that I_{ph}=15 mA, R_s=5 Ω, R_{sh}=1 KΩ, n=2 and V_T=0.026 v$^{(5)}$.

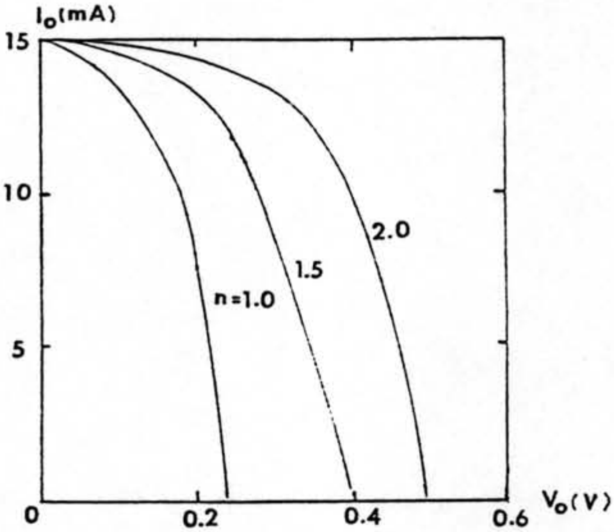

Fig.7 Calculated results of solar cell curves with different ideality factors,n. Given that I_{ph}=15 mA,I_s= 1 μA,R_s=5 Ω , R_{sh}=1K Ω and V_T=0.026 V.(5)

It can be seen from Figures 6 and 7 that the increase in the values of ideality factor, n,and the decrease in the values of reverse saturation current, I_s, result in a higher output power.

When a solar cell supplies power to the load, R_L, there produces the voltage drop across the p-n junction. In this case, the potential at p-side is higher than n-side so that the p-n junction is forward-biased. The current is produced through the diode of the cell. This current is divided into two components,i.e. the Schockley's diffusion current and the Sah-Noyce-Schockley's recombination current as follows(6).

$$I_D = qAn_i^2 \;(D_p/L_pN_d+D_n/L_nN_a)\left[\;\exp\left(\frac{V_o+I_oR_s}{V_T}\right)-1\;\right] +qAn_i\;\; W/2\,\tau_o\left[\;\exp\left(\frac{V_o+I_oR_s}{2V_T}\right)\;-1\right] \qquad (9)$$

or

$$I_D = I_{s1}\left[\;\exp\;\left(\frac{V_o+I_oR_s}{V_T}\right)-1\;\right] + I_{s2}\;\left[\quad \exp\;\left(\frac{V_o+I_oR_s}{2V_T}\right)\; - 1\;\right] \qquad (10)$$

where

$$I_s = I_{s1} + I_{s2}$$

$$= qAn_i^2\; (D_p/L_pN_d+D_n/L_nN_a) \;\; + qA\; n_i\; W/2\; \tau_o \qquad (11)$$

where q is the electronic charge.

n_i is the intrinsic carrier density.

D_p ,D_n are diffusion coefficient of hole and electron, respectively.

N_d, N_a are concentration of donor and acceptor impurity.

L_p,L_n are diffusion length of hole and electron,respectively.

A is the cross-sectional area of a p-n junction.

W is the depletion region width.

τ_o is the minority carrier lifetime.

I_{s1},I_{s2} are the preexponential reverse saturation currents due to diffusion and recombination effect respectively.

and I_s is the reverse saturation current.

The first terms and the last terms of right-hand-side of Equations(9), (10) and (11) corresponds to the currents due to the diffusion and recombination effect, respectively. As shown in Fig.8,I_s of Eq.(11) can be practically reduced by doping higher level of impurity concentrations of N_a and N_d. This results in the decrease in D_p, D_n, L_p, L_n and W because diffusion coefficient and diffusion length are strong function of carrier concentration(22). A higher N_d and N_a yield a lower D_p, D_n, L_p, L_n and W as will be seen in Figs. 13 and 14 and Eq. 24 in chapterIII. Therefore, both the diffusion and the recombination currents, I_{s1} and I_{s2} are reduced.

As shown in Fig. 8, the ideality factor, n, is dependent on the mode of operation. For the low bias voltage, $I_D \approx I_{s2} \exp(V/2V_T)$. That is, the value of n is 2. On the contrary, the value of n is 1 for the high bias voltage, $I_D \approx I_{s1} \exp(V/V_T)$.

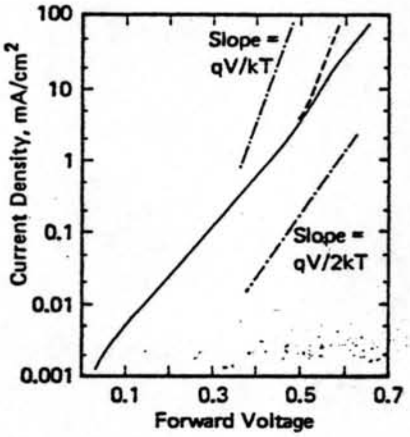

Fig.8 Double-exponential regions of dark I-V characteristics of silicon solar cells at 300 °K and the effect of series resistance.(1)

It can be noticed from Fig.8 that for the high bias voltage, the curve deviates from slope = qV/k_T due to the voltage drop in series resistance, R_s of solar cells.

2.4.3 Series Resistance, R_s and Shunt Resistance, R_{sh}

The effects of series resistance, R_s on the solar cell performance are investigated by numerical calculation. They are shown in Figures 9 and 10 .

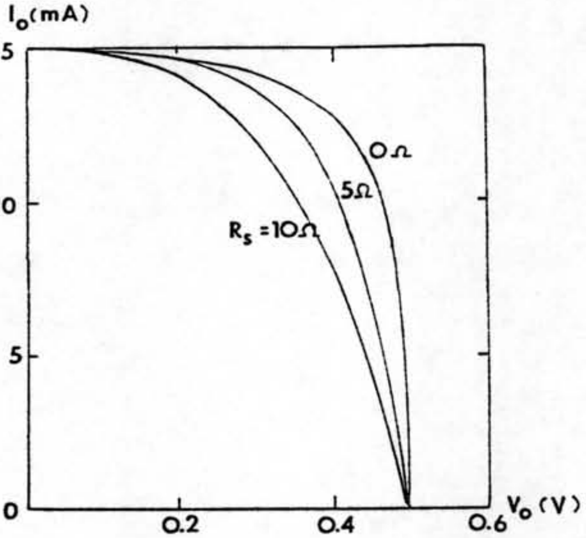

Fig.9 Calculated results of solar cell curves with different series resistance, R_s. Given that I_{Ph}=15 mA, I_s=1 μA,R_{sh}=1K Ω ,n=2 and V_T= 0.026 V .(5)

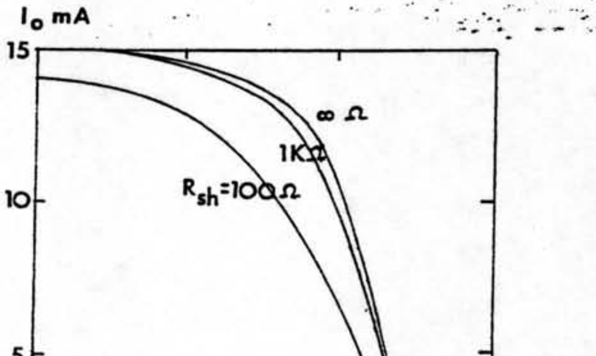

Fig.10 Calculated results of solar cell curve with different shunt resistance, R_{sh}. Given that I_{ph}=15mA,I_s=1 μA, R_s=5Ω ,n=2 snd V_T=0.026V.(5)

It can be seen from Figures 9 and 10 that the maximum power output are resulted from the minimum series resistance, R_s and the maximum shunt resistance, R_{sh}.

The series resistance, R_s can be reduced by decreasing the bulk resistance of silicon wafer, i.e. high doping impurity concentration in substrate or choosing the lower resistivity substrates. However, the top (illuminated) surface of semiconductor has much more contribution to series resistance. To design an optimum grid contact, junction depth and the improved contact quality is the way to reduce this resistance.

The shunt resistance, R_{sh} can be increased by improving the fabrication technique, i.e. to improve diffusion process for better diffusion uniformity and better control of contaminations of the process.