# INTRODUCTION TO PHOTOVOLTAIC SOLAR ENERGY CONVERSION

by

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## Introduction

Among the most promising routes for converting solar energy into large-scale electric power are the thermal and photovoltaic conversion.

In the thermal conversion route, solar energy is utilized to produce steam or other vapor which could then be used as working fluid for a thermodynamic engine. Much of the work in this area has been directed towards the use of reflecting surfaces to concentrate solar radiation onto a small receiver or boiler. The need for very high temperature practically rules out the use of flat plate collectors, and current R & D efforts are directed towards the development of concentrators in the form of paraboloids, parabolic cylinders (troughs) and other similar geometrical shapes. The most extensively studied scheme in the United States is the so-called "power tower" concept. In this scheme, a large array of mirror concentrators (heliostats) on the ground focus the solar radiation onto a high-pressure steam boiler. The boiler is located on top of a high tower, having a turbogenerator at its base.

In photovoltaic conversion, on the other hand, electric power is obtained through the separation of charge carriers in semiconductors by a semiconductor junction. A photovoltaic device, which is now known as solar cell, behaves very much like a low-voltage battery whose charge is continuously being replenished at a rate proportional to the intensity of the illumination. When connected into series-parallel configurations, it is possible to extract from such a solar panel high currents and voltages.

From the theoretical point of view, photovoltaic conversion is more attractive than thermal conversion. This is because of the theoretical limit imposed by the Carnot cycle on the efficiency of the intermediate thermodynamic cycle. With photovoltaic conversion, no such theoretical limit exists. The conversion efficiencies of solar cells are limited only by the parameters and properties of the material used. Our previous experience with materials technology indicate that it is always possible to fabricate materials with any specified properties, given sufficient time and money.

At present, photovoltaic conversion cannot compete with other means of generating electricity for terrestial use. This is because of the tremen-

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dous expense, both in terms of money and energy, that is necessary in the fabrication and manufacture of solar cells.

Figure 1 shows graphically the cost involved in the manufacture of silicon solar cells. The Fig. shows that the fabrication of Si solar cells should be about an order of magnitude cheaper than the cost of producing Si semiconductors. However, the present technology is such that we do not know how to obtain solar grade Si from the metallurgical grade Si. The actual fabrication involves the purification of metallurgical grade Si to semiconductor grade. Impurities are then added to the semiconductor grade Si under controlled conditions to obtain the desired impurity level. It is obvious that we need a more direct way of obtaining solar grade Si.

## History of the Development of Photovoltaic Cells

Photovoltaic effect was first discovered in the 19th century by Becquerel. He first described the effect in electrolytic solutions in an article published in 1839. (Becquerel, 1839) In 1877, Adams and Day (Adams et al., 1877) observed the photovoltage which was developed across a selenium-metal junction when the junction was exposed to sunlight. Fifty years later, Grondhal (Grondhal et al.. 1927) obtained an electric power output of one watt at an efficiency of 0.2% using copper on copper oxide diode, one square meter in area.

The first practical solar cell was developed at Bell Laboratories by Chapin, Fuller and Pearson (Chapin et al., 1954). In an article in the Journal of Applied Physics, they described a silicon p-n junction photocell with an efficiency of 6%. Since that time, applications of photocells have been restricted to light-meters and space applications.

During the last two decades, researches on solar cells have been mainly concerned with space applications. Solar panels with typical efficiencies of from 10% to 12% are the predominant source of power for space satellites.

## Theory of the p-n Junction Photovoltaic Effect

Photovoltaic effect can be best described for a p-n junction. A p-n junction is formed when a p-type semiconductor is joined to a u-type semiconductor. In silicon, for example, a p-type semiconductor is formed when boron is introduced in Si as impurity. This results in an excess of free holes which will move freely in the crystal lattice. On the other hand, a u-type semiconductor is formed by introducing impurity atoms of arsenic or phosphorus in Si, thus creating an excess of free electrons.

When p-n junction is formed, electrons will flow from the u-type semiconductors side into the p-type due to the difference in concentration of electrons in these regions. Similarly, holes will flow from the p-to the n-side of the semiconductor. As a result of these redistribution of free charge carriers, an electric field will be set-up within the space charge region of the junction which will prevent further flow of charges across the junction. Letting $\Phi_p$ be the hole diffusion potential, and $\Phi_a$ the electron hole diffusion potential, the equilibrium potential set up at the junction will be given by

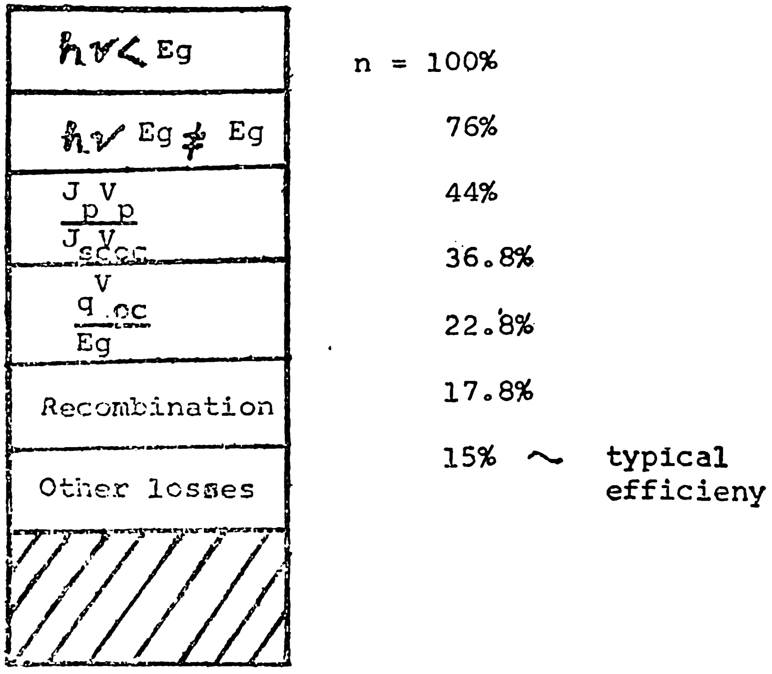
$$V_d = \phi_p + \phi_n \tag{3.1}$$

The resulting shift in the bands across the junction is shown schematically in Fig. 2.

Suppose now that photons are incident on the p-side of the junction. If the frequency of a photon is such that

$$h\nu > E_g \tag{3.2}$$

Where $E_g$ is the handgap, an electron in the valence band absorbing this photon will be promoted into the conduction band, leaving behind in the valence band a positively-charged hole· The resulting electronhole pair will then diffuse around the p-region until they either recombine or reach the space charge region. In the space charge region, the electron will see a potential which tends to attract it to the n-side of the junction. The hole, on the other hand, sees a potential which tends to pull it in the other direction. This charge separation will create an electric field which will tend



to oppose the diffusion potential $V_d$. If the number of photons absorbed is large enough, these two fields will cancel each other, leading to an open circuit voltage between the two ends of the junction. Current will then flow when these ends are connected to an external load.

## Conversion Efficiencies of p-n Junction Solar Cells

Let us consider a planar p-n semiconductor junction exposed to solar radiation. Fig. 3 shows an accounting of the various losses resulting in the reduction in the conversion efficiency of this system.

About 24% is lost due to the unabsorbed long wavelength photons (transparency loss). Figure 4 shows the distribution of solar photons versus the wavelength $\Lambda$ at sea level. It peaks around $.1\mu$ and falls off on either side

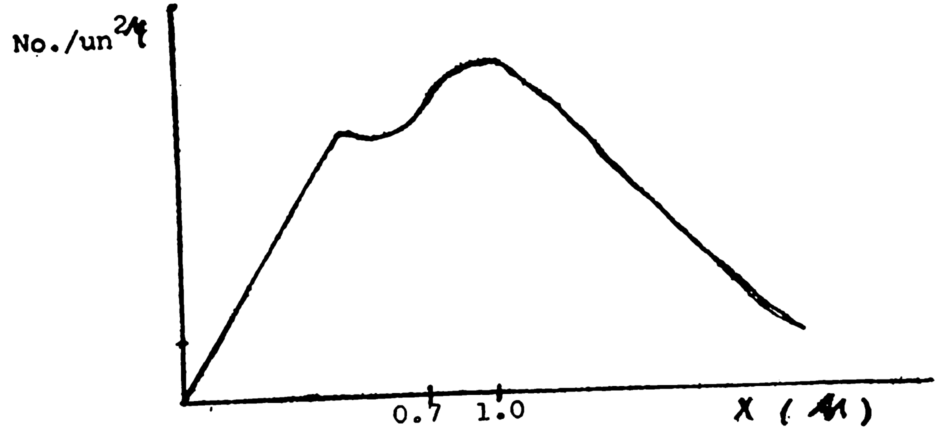


Fig. 4

It is clear that one would like to have a material with energy gap that is close to the peak of this distribution. In general, photons with wavelengths

$$\lambda > \frac{hc}{E_g}$$

will not be absorbed and will simply be lost.

The difference between the energy of the photons and the bandgap is also lost and accounts for a 32% reduction in efficiency. Photons with energy in excess of the bandgap lift the electron-hole pair away from the band edges, giving off the excess energy in the form of low-quality heat. This effect is particularly severe when the bandgap is far from the peak of the solar distribution.

The next type of loss, which accounts for about 8%, arises from the deviation of the current-voltage characteristic from a rectangular shape. Fig. 5 shows a typical current-voltage characteristic of a solar cell. The maximum power output corresponds to the maximum area rectangle which may be inscribed in this J-V characteristic curve.

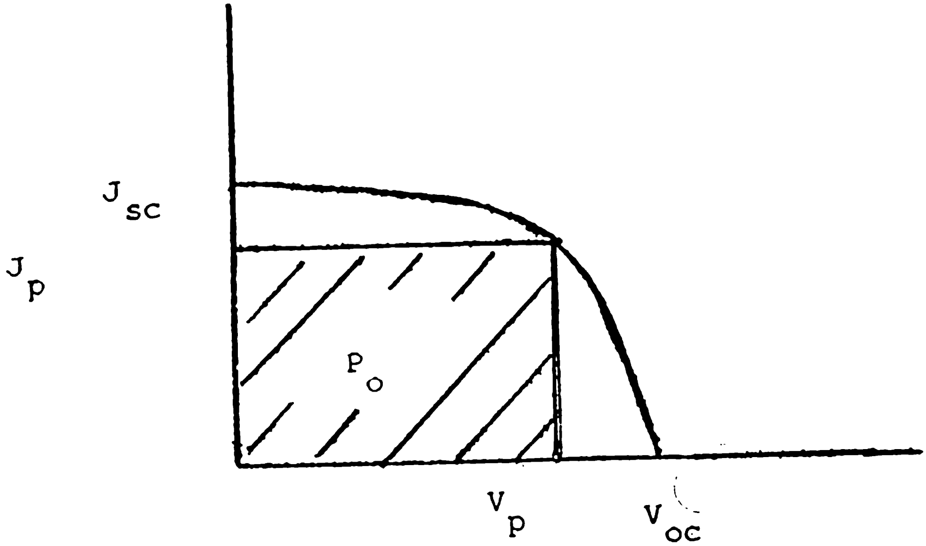


Fig. 5

The fourth type of loss is due to the fact that the open circuit voltage is typically less than the bandgap. The maximum available voltage, the open circuit voltage, is the diffusion potential $v_d$. At high doping levels, the lower band edge of the conduction band in the n-type semiconductor of the junction is depressed almost to the top of the valence band, making $V_d \simeq E_g$. In practice, one gets only 50% of the bandgap at high illumination.

Recombination losses arise from those photons absorbed far from the depletion region. Here, the electron-hole pair, once generated, recombine without contributing to the external current.

Other losses are principally due to the reflection of photons from the semiconductor surface, transmission of high energy photons due to large absorption length of the material, leakage and internal resistance. All these account to only about 3% of the loss in efficiency of the cell.

Recombination cannot only occur in the semi-conductor bulk, but also in the space charge region and at semiconductor surface. Also, oppositely charged carriers generated by different photons may recombine.

## Derivation of the Theoretical Efficiency of a p — u junction Solar Cell

We will now derive an expression for the conversion efficiency of 1 solar cell paying particular attention to the role played by the bandgap. In general, we can expect that high output voltage will be developed in materials with large bandgaps. Unfortunately, semiconductors with large Eg utilize only a small part of the incident photons. This results in a very low current output.

Thus one has to pick an optimum value of the bandgap. This Eg has to be chosen so as to maximize the power output (per unit area)

$$P_o = V_p J_p \qquad (5\text{-}1)$$

where $V_p$ and $J_p$ are the voltage and current density at matched load condition.

Consider a semiconductor junction which is kept in the dark. Then the current density is given by the usual p — n junction diode current-voltage characteristic.

$$J = -J_o \left(\exp \frac{qV}{k_BT} - 1\right) \qquad (5\text{-}2)$$

where V is the voltage applied to the P region of the junction.

If we now illuminate the junction,

$$J = J_D + J_S \qquad (5\text{-}3)$$

where

$$J_D = J_o \left(\exp \frac{qV}{k_BT} - 1\right) \qquad (5\text{-}4)$$

In Eq (5-3), $J_s$ is the photocurrent. Short-circuiting the cell (i.e., $V = O$), one finds that

$$Js = Jsc$$

where $J_{sc}$ is the short circuit current density. Hence

$$J - J_{sc} - J_D \qquad (5\text{-}5)$$

The equivalent circuit described by Eq (5-5) is shown in Fig. 6

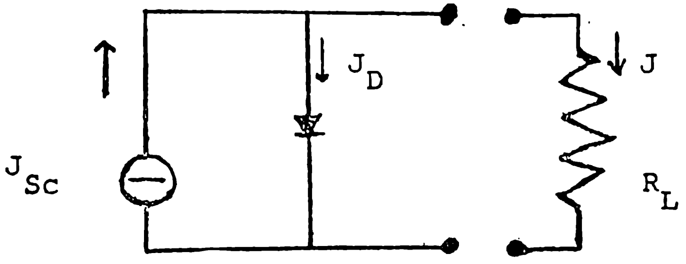


Fig. 6

In actual practice, one has to take into account the junction leakage and internal resistance. A more realistic equivalent circuit will then be as in Fig. 7

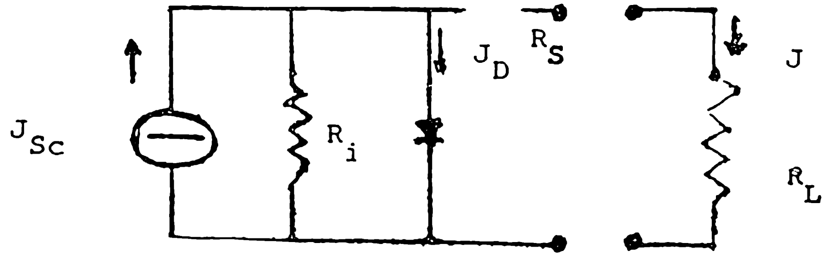


Fig. 7

with the current equation

$$J_{sc} = J_D + J\,(R_S + R_L)/R_i \qquad (5\text{-}6)$$

Both $R_i$ and $R_s$ are engineering and fabrication parameters. With the present technology, it is possible to obtain cells with $R_i \longrightarrow \infty$ and $R_s \longrightarrow$ o. Thus we will restrict our treatment to the ideal case. Fig. 6

Putting $J = O$ in Eq. (5-5), one finds the open-circuit voltage to be given by

$$V_{oc} = \frac{k_B T}{q} \ln \left| 1 + \frac{J_{sc}}{J_o} \right| \qquad (5\text{-}7)$$

For high intensity light, $J_{sc}$ greater than $J_o$ so that essentially

$$V_{oc} = \frac{k_B T}{q} \ln \frac{J_{sc}}{J_o} \qquad (5\text{-}8)$$

At first glance, it might appear that the open-circuit voltage increases linearly with temperature. Actually, the temperature dependence of $V_{oc}$ is rather complicated since $J_o$ also depends on the temperature in a complex manner. In fact, $V_{oc}$ decreases with increasing T for the most common semiconductors.

Fig. 8 shows the plot of the typical current-voltage characteristic of the solar cell as given by Eq (5-5)

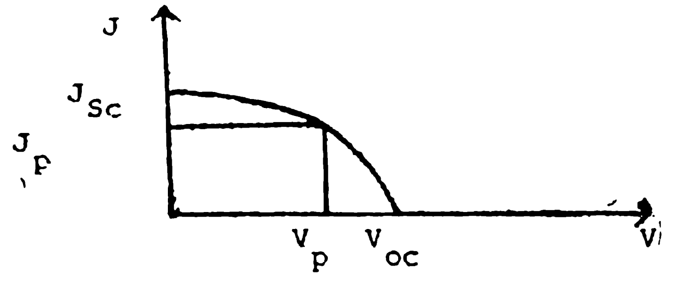


Fig. 8

together with the maximum power rectangle.

The short-circuit current $J_{sc}$ will obviously depend on the intensity of the incident solar radiation. In the ideal case where each photon having Eg generates a useful electronhole pair, one can show

$$J_{sc} = \int_{0}^{\tau_g} P_i\,(\tau)\; q \frac{\tau}{uc}\, d\tau \qquad (5\text{-}9)$$

where

$$\tau_g = \frac{hc}{E_g} \qquad (5\text{-}10)$$

$P_i\,(\tau)$ = **luminous power per unit area per unit at wavelength**

Notice that the value of $J_{sc}$ increases as g increases, i.e., as the bandgap $E_g$ decreases. The behavior is shown in Fig. 9

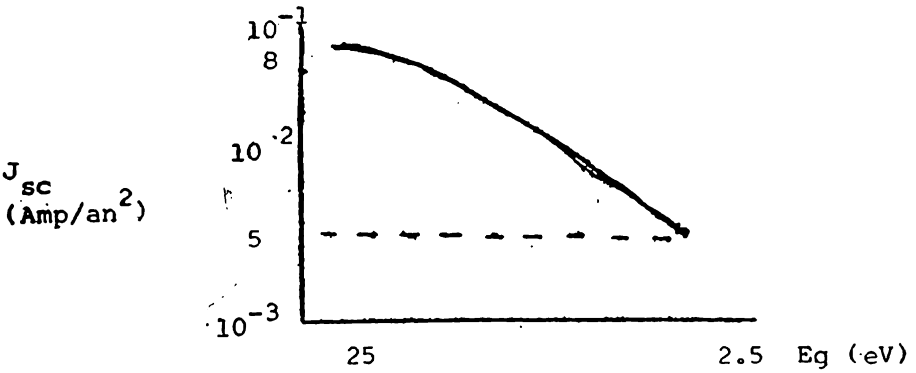


Fig. 9

Notice the logarithmic scale on the $J_{sc}$ axis.

Therefore, considered as a function of the bandgap alone, we have competing effect with voltage and current: Increasing V with increasing $E_g$, but decreasing J. One can obtain the optimum values of the current and voltage by maximizing the power, hence by solving the equation

$$\frac{\partial p}{\partial V} = 0$$

which gives us

$$V_p = V_{oc} - \frac{k_B T}{q}\; \text{lu}\,\left(1 + \frac{q V_p}{k_B T}\right). \qquad (5\text{-}11)$$

$$J_p = J_{sc} - J_o \left(\exp \frac{qV_p}{k_B T} - 1\right) \qquad (5\text{-}12)$$

The efficiency will then be given by

$$i = \frac{V_p J_p}{\text{incident power}}$$

$$= \frac{\left[V_{oc} - \frac{k_B T}{q} \,\mathrm{lu}\, \left(1 + \frac{qV_p}{k_B T}\right)\right]\left[(J_{sc} - J_o(\exp\frac{qV_p}{k_B T} - 1)\right]}{\int_u^{\alpha} P_i\,(\tau)\,d\tau} \qquad (5\text{-}13)$$

Effects of Recombination

The absorption coefficient $\alpha$ and the lifetime of minority carriers, as well as the other parameters which characterize each semiconductor material, have large influence on solar cell efficiency, in fact the $J_{sc}$ is in practice much lower than that calculated from Eq. (5-9)

The parameter which best influences the efficiency of solar cell is the recombination current. This, in turn, depends on:

1. The *lifetime* of the generated minority carriers: as $\tau$ becomes lower, the possibility of recombination increases.
2. The variation of the absorption coefficient with the photon wavelength: not all of the useful photons are absorbed at the same depths. The least energetic photons are absorbed near the surface while the more energetic ones penetrate the semiconductor bulk. Photons which are absorbed too far away from the junction do generate electron-hole pairs, but they recombine before they could diffuse into the depletion region without contributing to the external current. As a consequence of this, the surface to junction distance should not be very large. This distance in fact should only be of the order of the diffusion length of the material.
3. The crystal damage at the cells' surface which increases the recombination of the minority carriers.

Let us now determine the effects of recombination on the efficiency. Consider the solar cell shown in Fig. 10. We will assume that the space

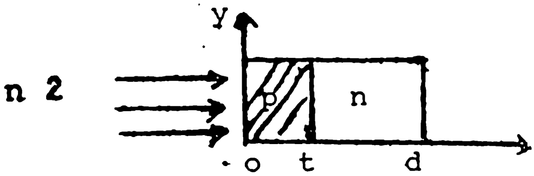


Fig. 10

charge region around the junction is very thin, relative to t. Thus, the generation and recombination of carriers in this region could be neglected. Its only effect will be to sweep away from the junction the charges arriving at this region.

This assumption is essentially satisfied by highly doped semiconductor materials typically used for solar cells.

We will also neglect the thermal generation of carriers. This is usually negligible compared to the photocurrent generation.

Under these assumptions, one can write for the p-side of the semiconductor (which we assume to be the side facing sunlight):

$$g(x) - \frac{n(x)}{t_n} + D_h \frac{d^2n(x)}{dx^2} \qquad (6\text{-}1)$$

where

$g(x)$ is the rate of generation of carriers at a depth $x$

$u(x)$ is the minority carrier density at the same depth.

$D_n$ = diffusion constant

$T_n$ = lifetime

Let No ($\tau$) be the number of photons having energy nc/ which are absorbed by the semiconductor, let N ($\tau$, x) be the number absorbed at a depth x, then

$$N(\tau, \chi) = No(\tau)(1 - e^{-\alpha x}) \qquad (6\text{-}2)$$

where $\alpha$ is the absorption coefficient. Assuming that each photon with energy higher than the bandgap generates an electron-hole pair, i.e., quantum efficiency equal to unity,

$$\begin{aligned} g(\tau, \chi) &= No(\tau)\, e^{-\alpha x} & \tau < \tau_g \\ &= 0 & \tau < \tau_g \end{aligned} \qquad (6\text{-}3)$$

Substituting Eq. (16) into Eq. (14), with

$$L_n = \sqrt{t_n D_n} \qquad (6\text{-}4)$$

We have the current at x = O to be the diffusion current given by

$$J_n\ (\tau) = q\ D_n \frac{dn(x)}{dx} = S_n\ (0) \qquad (6\text{-}5)$$

while for x = t

$$n(t) = n_o\ (\exp \frac{qV}{k_B T} - 1) \qquad (6\text{-}6)$$

where S is the surface recombination velocity, n(O) is the minority carrier concentration

With these boundary conditions, we find the solution to Eq (6-1) to be

$$J_n\ (\tau) = q \frac{D_n}{L_n} n_o\ (\exp \frac{qV}{k_B T} - 1) + \frac{\alpha N_o L_n e^{-\alpha t}}{\alpha^2 L_n^2 - 1} \text{tgh}(M + \frac{t}{L_n}) -$$

$$\frac{\dfrac{\alpha N_o L_n}{-q\alpha^2 L_n^2 - 1} (\text{tgh } M + L_n)}{\cos h \dfrac{t}{L_n} + \text{tgh } M \sin h \dfrac{t}{L_n}} + \frac{q\alpha^2 N_o L_n^2 \exp - t}{\alpha^2 L_n^2 - 1} \qquad (6\text{-}7)$$

$$\text{where tgh } M = \frac{SL_n}{D_n} \qquad (6\text{-}8)$$

A similar procedure may be used for the u side with the result:

$$J_p\ (t) = q \frac{D_p}{L_p} Po\ (\exp \frac{qV}{k_B T}\ ) - \frac{q^{\alpha} N_o 1_p}{\alpha L_p + 1} e^{-\alpha t} \qquad (6\text{-}9)$$

where the following conditions have been used

$$p(t) = Po\ (\exp \frac{qV}{k_B T} - 1\ ) \qquad (6\text{-}10)$$

for x = i, and p(d) = o for x = d

The total current is then given as a function of by

$$J\ (\tau) = J_n\ (\tau) + J_p\ (\tau) \qquad (6\text{-}11)$$

$$= (A+B) \left(\exp \frac{qV}{k_B T} - 1\right) + C \qquad (6\text{-}12)$$

where the constants A,B,C can easily be computed from Eq. (6-7) and (6-9)

Note that Eq. (6-12) is very similar in form to the equation for the ideal solar cell. Integrating over all the solar spectrum:

$$J = -J_0 \left(\exp \frac{qV}{k_B T} - 1\right) + J_{sc}^{1} \qquad (6\text{-}13)$$

An important role is played by the absorption coefficient $\alpha$ in Eq. (6-13). If this parameter were a constant for $\tau < \tau_g$, then each useful photon would be absorbed within the same depth from the surface and it would be easy to locate the junction at a proper depth so that all generated electron hole pairs would be separated from the junction field.

Actually, $\alpha$ varies quite strongly with $\tau$ so that the junction depth has to be chosen to maximize the collection of generated electronhole pairs.

A high value of $\alpha$ indicates that the photons are absorbed near the surface, while a low $\alpha$ allow deeper photon penetration and the absorption will be predominantly in the bulk of the material. If this last type of absorption predominates, then large values of diffusion lengths would be required, since most of the electronhole pairs will be generated far from the junction region.

Absorption can also occur without generation of electronhole pairs.

Also, photons of energy E < Eg can generate electronhole pairs by multistage excitation provided there are metastable trapping levels within the bandgap.

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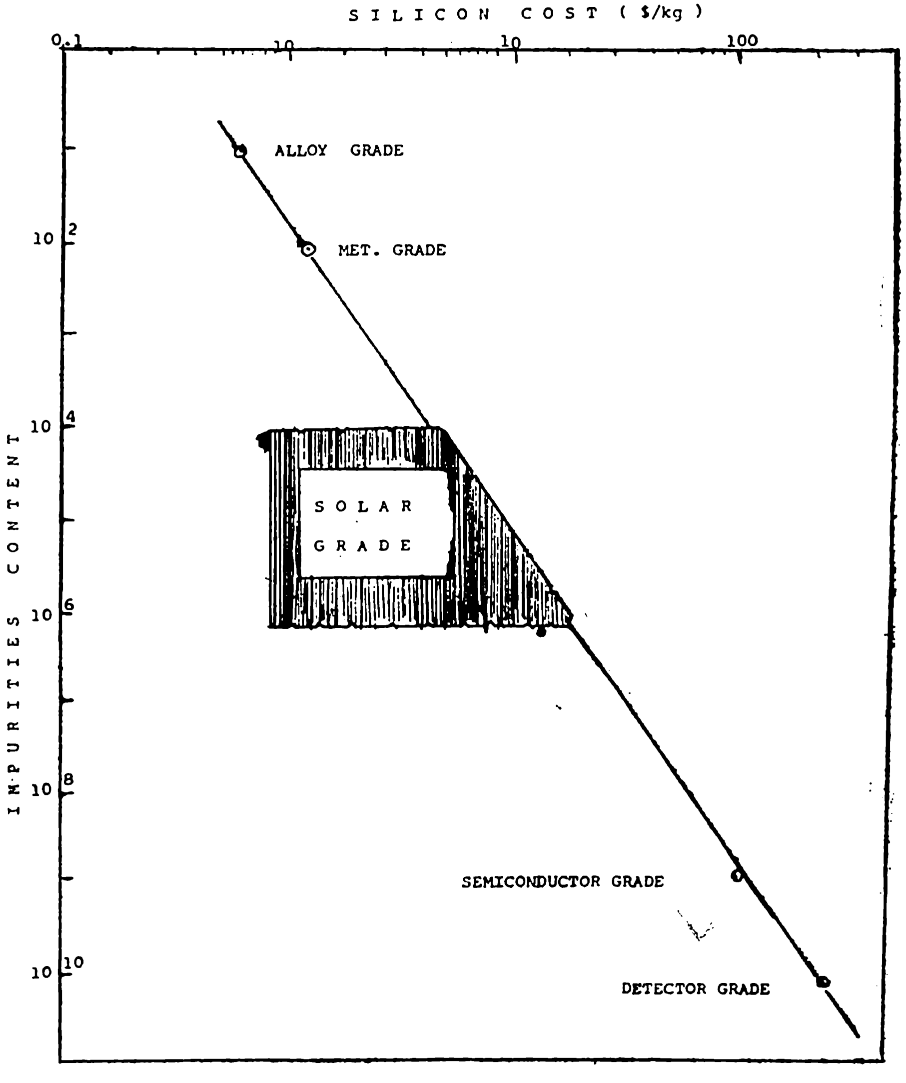
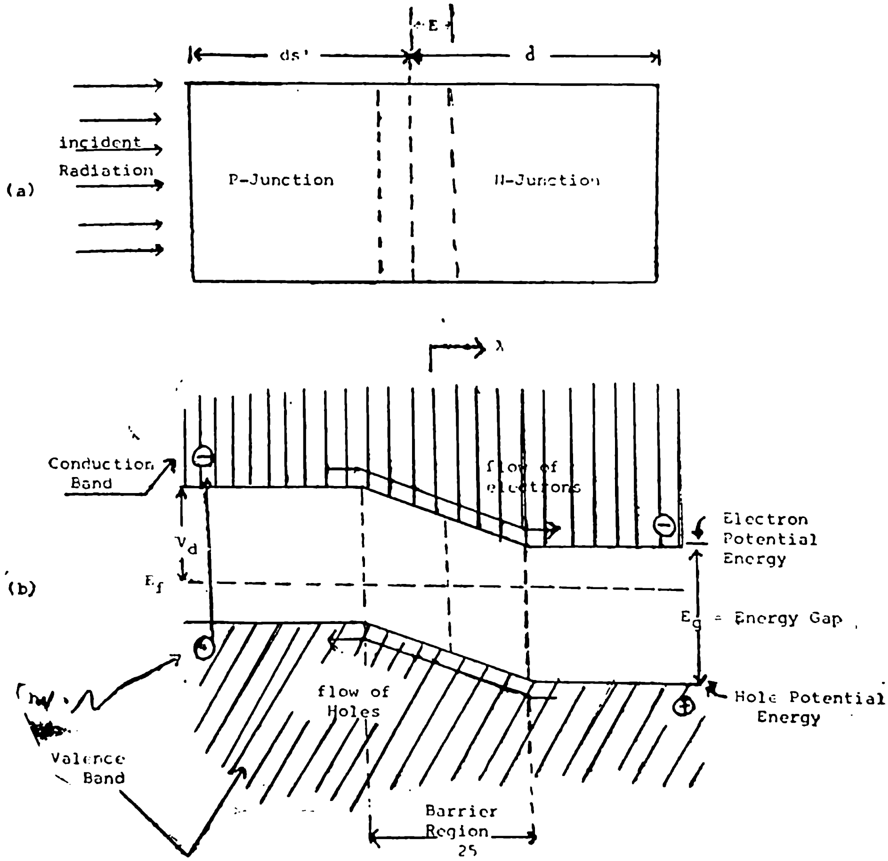

SILICON COST ( $/kg )
0.1
10
10
100
IMPURITIES CONTENT
10^2
10^4
10^6
10^8
10^10
ALLOY GRADE
MET. GRADE
SOLAR GRADE
SEMICONDUCTOR GRADE
DETECTOR GRADE


E
ds'
d
incident Radiation
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P-Junction
N-Junction
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Conduction Band
flow of electrons
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V_d
E_f
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E_g = Energy Gap
Hole Potential Energy
hν
Valence Band
flow of Holes
Barrier Region
25