Degradation of solar cell parameters due to irradiation.

4.1 Introduction.

----------- When solar cells are used in an environment where the nuclear radiations constantly strike the cell surface, the cell performance is likely to degrade with the passage of time. The solar cell parameters which are affected most are the short circuit current ($I_{SC}$), open circuit voltage ($V_{OC}$), Fill factor ($FF$) and the efficiency ($\eta$). These parameters change due to the degradation in the electronic/photoelectronic properties of the cell material. The changes in the minority carrier lifetime/diffusion and the carrier concentration have been discussed and also computed in the third chapter. In the present chapter we determine the changes in the MIS solar cell parameters due to the changes in $\gamma$, $L$, $n$. As the irradiation effects on the P-N homojunction solar cells have been investigated both experimentally and theoretically (Masafumi et al., 1982; Carlson et al., 1981). We discuss only the effects of radiation induced defects on the GaAs MIS solar cells. These cells may not be useful at present for the space application but the results give an important and useful information on the physical mechanism of the cell degradation in the nuclear radiation environment.

4.2 Various solar cell parameters.

---------------------------- Figure (4.2) shows the equivalent circuit of a diode under illumination. When the photons are incident with an energy greater than the bandgap of the semiconductor, absorption of the photons takes place and electrons are raised in energy from the valence bond to the conduction band, thereby creating
electron-hole pairs. If the excess minority carrier are able to
diffuse to the edges of the space charge region before they
recombine, they are swept across the junction giving rise to the
photocurrent, photovoltage and power into the load.

By connecting a load across the
terminals of a solar cell a current $I_L$ can flow through the load and
develop a voltage $V_L$ across it. The values of $V_L$ and $I_L$ besides
depending upon the nature of the load will be related to the
photogenerated current $I_{ph}$ and the properties of the diode. The
different relations can be obtained from the equivalent circuit
diagram itself, were the imperfection in the diode leading to current
leakage are represented by a shunt resistance $R_s$ and parasitic series
resistance effects by $R_s$.

Also due to the fact that the diode is operating in a photoconducting
mode the current components forming the normal diode dark current
and the light generated $I_{ph}$ can not be assumed to operate
independently, however for many practical purpose the principal of
superposition implied in fig. (4.1) holds and it follows that

$$I_L \left(1 + \frac{R_s}{R_{sh}}\right) = I_{ph} - I_D \left(\frac{V_f}{V_{oc}}\right) - \frac{V_L}{R_{sh}}$$  \hspace{1cm} (4.1)

Where $V_f$ is the voltage drop across the junction region of the diode
due to either optical or electrical biasing. The actual operating
point in a solar cell $I$-$V$ characteristics is determined by $R_L$. The
value of $(R_L)$ should be such that the maximum biasing occurs at the
maximum power points $(I_m, V_m)$. The conversion efficiency is given by

$$\eta = \frac{I_m \cdot V_m}{P_i \cdot a} = \frac{F \cdot F \cdot I_{sc} \cdot V_{oc}}{P_i \cdot a}$$  \hspace{1cm} (4.1')

where $(P_i)$ is the incident solar intensity and "a" is the active
area of the solar cell. The fill factor $(F \cdot F)$ is given by $F \cdot F = \frac{I_m \cdot V_m}{I_{sc} \cdot V_{oc}}$
where $(I_{sc})$ is the highest value of the photocurrent and $(V_{oc})$ is the
FIG. 4.1 SIMPLE EQUIVALENT CIRCUIT
OF A SOLAR CELL (PULFERY 1978)
highest value of the photovoltage. The active area of the cell is in practice less than the full front surface because of the need to position opaque metal grade on the top of the cell to collect the light generated carriers (Sze, 1969).

4.2.1 Current -Voltage characteristics:

A solar cell is mainly characterised by using its I-V characteristic plots. Under the dark conditions the majority carrier current flowing in the device is the dark current itself, because under these conditions a solar cell behaves typically as a diode in the sense that the illumination necessary for generating the electron hole pairs in the semiconductor is absent, while as under the lighted conditions, it behaves perfectly as a solar cell capable of converting the solar radiation into useful electrical energy. It is possible to obtain the current-voltage characteristics under dark as well as in the lighted conditions. While calculating the dark I-V characteristics, the diode is kept in an environment which prevents the light from reaching the device directly. The solar cell or the diode under the dark conditions is usually operated in the voltage range of $0.1-1.0$ V. Under the illuminated conditions the solar cell is characterised by its lighted (I-V) characteristics. I/V characteristics is the most essential part to be carried, while the device characterisation is being made, as it yields the information regarding the diode parameters.

4.3 MS and MIS solar cells.

Schottky barrier (MS) solar cell is
formed, when a metal is brought into contact with a clean surface of the semiconductor material and a readjustment of the charge takes place in order to establish the thermal equilibrium. If the metal is thin enough to be potentially transparent to light (while still maintaining an acceptable sheet resistivity), then some of the incident light can penetrate the semiconductor and a photocurrent will result.

For the fabrication of the MIS solar cells, a thin film insulator can be made by the oxidation of the semiconducting crystal (native oxide) or by the physical deposition (non-native oxide). In the case of Gallium Arsenide the oxide layer for the MIS cells first reported were grown by heating GaAs (100-200 °C in an air atmosphere (Stirn et al., 1975). In this way the open circuit voltage ($V_{oc}$) of (0.6-0.65V) were obtained and by using the other oxidation methods the ($V_{oc}$) values of 0.82V were reached (Stirn et al., 1977). It has been agreed upon (Stirn et al., 1977) that the instability and also the reproducibility of the native oxide MIS solar cells are intimately related to the insulator—semiconductor interfaces. The non-native oxide MIS solar cells may minimise the interface effect through the better control of the layer thickness and the environment during the deposition process.

Figures (4.1) a and (4.2) b show the schematic representation of the MS and MIS structures.

Metal-semiconductor (MS) and metal-insulators-semiconductor (MIS) solar cells are simple photovoltaic structures. Schottky barrier solar cells are majority carrier devices and hence have large saturation current densities leading to low open circuit voltage (about 0.5 V for GaAs under illumination. Therefore the conversion efficiency of a SB solar cell is limited compared to P-n junction solar cells. Recent developments of the metal-oxide-semiconductor solar cells have shown that
conversion efficiencies up to 16% are achievable (Stirn et al., 1977), if a proper oxide layer is chosen. More recently several improvements in MOS solar cell fabrication have been made, which not only give slightly higher cell conversion efficiency, but also have a high degree of reproducibility. These improvements consist mainly of new chemical surface preparations, oxide layer and antireflection coating depositions.

In a Schottky barrier solar cell just as in a P-n junction, the photocurrent passing through a load causes the device to be forward biased and a dark current flows in the opposite direction to the photocurrent. I/V characteristics obtained under the illumination appears qualitatively same as for P-n junction cell, but the dark current in a SB cell is very different in nature from the dark current in a P-n junction.

However in case of MIS structures the thermionic emission dark current can be reduced either by increasing the metal-semiconductor barrier height or by decreasing the probability of majority carrier tunneling. In this MIS structure the purposefully inserted ultrathin layer can modify the Schottky barrier height by blocking the chemical reactions between the reactive metal/semiconductor pairs (Tongson et al., 1979, Fonash, 1980) by blocking the cross diffusion, modifying the intrinsic surface states (Child et al., 1978) by protecting the semiconductor surface from damage and by containing the charges which perturbs the electrostatic field in the semiconductor (Child et al., 1978). These effects of the insulating layers have been advantageously used in case of MIS solar cells, where the majority carrier thermionic emission current must be reduced to enhance the efficiency (Ruth et al., 1981)
In brief it can be said that MIS solar cells have advantages over conventional P-n junction solar cells mainly because of three factors (1) devices processing at lower temperature results in longer minority carrier lifetimes (2) the collecting junction is located right at the surface of the base and (3) elimination of heavy doping effects (Singh et al., 1980). In fact the highest efficiency demonstrated to date for photovoltaic energy conversion device employing various solar cell materials has been achieved with a PN configuration.

4.4 MIS Solar cell theory.

In this section we discuss MIS solar cell theory. We first consider the Schottky barrier solar cell. Schottky barrier solar cell is simple and also economical to fabricate, but the expected efficiency (η) may be somewhat lower than the conventional cell because of lower (VOC). Schottky barrier solar cell can be potentially efficient under optimum conditions and could be important for terrestrial applications because of potentially low cost and because they do not necessarily entail diffusion processes, which can be detrimental to polycrystalline devices.

The energy band diagram of a Schottky barrier solar cell under illumination is shown in the figure (4.2a). The metal must be thin enough to allow a substantial amount of light to reach the semiconductor. There are three photocurrent components (1) light with an energy \( E = h \nu > E_g \) can be absorbed in the metal and excite holes over the barrier into the semiconductor (2) short wavelength light entering the barrier into the semiconductor is mainly absorbed in the depletion region i.e. with the barrier (3) long wavelength light is absorbed in the neutral region creating electron hole pairs just as in a \( P-n \)
junction, the electrons must diffuse to the depletion edge to be collected. For solar cell applications the excitations of the carriers from the metal into the semiconductor contributes less than 1% of the total photocurrent and therefore can be neglected. To determine the light I-V characteristics of this device, we have evaluated the current density \( J \) at some advantageous plane in the cell. In this case we choose \( x = 0 \) (Fonash, 1980).

Thus

\[ J = J_p(0) + J_n(0) \quad \cdots \quad (4.3) \]

Since the semiconductors shown is n-type, \( J_p \) is a diffusion current given by (Fonash, 1981).

\[ J_p(0) = -eDP \frac{dP}{dx} \bigg|_{x=0} \quad \cdots \quad (4.4) \]

Where \( p = P(x) \) satisfies the equation

\[ \frac{d^2p}{dx^2} - \frac{P - P_m}{L^2} + \frac{\phi_0 k e^{-x/k}}{DP} = 0 \quad \cdots \quad (4.5) \]

For a base of width \( L \) and back surface recombination speed \( S_p \), we obtain

\[ J_p(0) = -e\phi_0 \left\{ \begin{array}{c}
\frac{L^2 e^{-x/k} e^{-Lk}}{L^2 - L^2/2} \\
\frac{L^2 e^{-x/k} e^{-L^2/2}}{L^2 - L^2/2} \\
\frac{L^2 e^{-x/k} e^{-L^2/2}}{L^2 - L^2/2}
\end{array} \right\} \left[ \begin{array}{c}
\frac{S_p}{DP} - 1 \\
\frac{L^2 S_p \sinh L/L_p + 1k e L/L_p}{DP} \\
\frac{L^2 S_p \sinh L/L_p + 1k e L/L_p}{DP}
\end{array} \right] \]

\[ J_p(0) = -e\phi_0 \left\{ \begin{array}{c}
\frac{L^2 e^{-x/k} e^{-Lk}}{L^2 - L^2/2} \\
\frac{L^2 e^{-x/k} e^{-L^2/2}}{L^2 - L^2/2} \\
\frac{L^2 e^{-x/k} e^{-L^2/2}}{L^2 - L^2/2}
\end{array} \right\} \left[ \begin{array}{c}
\frac{S_p}{DP} - 1 \\
\frac{L^2 S_p \sinh L/L_p + 1k e L/L_p}{DP} \\
\frac{L^2 S_p \sinh L/L_p + 1k e L/L_p}{DP}
\end{array} \right] \]

Where \( \phi_0 \) is the photon flux.

This equation can be written as

\[ J_p(0) = -J_p^\text{BASE} + J_p^\text{DIFF} \left( e^{V_{KT-1}} \right) \quad (4.7) \]

where

\[ J_p^\text{BASE} = -e\phi_0 \left\{ \begin{array}{c}
\frac{L^2 e^{-x/k} e^{-Lk}}{L^2 - L^2/2} \\
\frac{L^2 e^{-x/k} e^{-L^2/2}}{L^2 - L^2/2} \\
\frac{L^2 e^{-x/k} e^{-L^2/2}}{L^2 - L^2/2}
\end{array} \right\} \left[ \begin{array}{c}
\frac{S_p}{DP} - 1 \\
\frac{L^2 S_p \sinh L/L_p + 1k e L/L_p}{DP} \\
\frac{L^2 S_p \sinh L/L_p + 1k e L/L_p}{DP}
\end{array} \right] \]

\[ J_p^\text{DIFF} = \frac{eDP P_m}{L_p} \left[ \begin{array}{c}
\frac{L^2 S_p \sinh L/L_p + 1k e L/L_p}{DP} \\
\frac{L^2 S_p \sinh L/L_p + 1k e L/L_p}{DP}
\end{array} \right] \]

and

\[ J^\text{DIFF} = \frac{eDP P_m}{L_p} \left[ \begin{array}{c}
\frac{L^2 S_p \sinh L/L_p + 1k e L/L_p}{DP} \\
\frac{L^2 S_p \sinh L/L_p + 1k e L/L_p}{DP}
\end{array} \right] \]
The majority carrier current density is given by

\[ J_n(0) = -e \phi_0 (1 - e^{-\frac{V}{kT}}) + A^* T^2 e^{-\frac{\Phi_s}{kT}} (e^{\frac{V}{kT}} - 1) \]

\[ + \frac{V}{q} R \left( e^{\frac{V}{kT}} - 1 \right) + f_1(V) \]  \( \ldots <4.10> \)

Where the last two terms represent the bulk recombination in the depletion region and a current flowing through the interface channels respectively.

The first bucking current component is a thermonionic emission current. Of course, the light dependent term is the photocurrent generated in the barrier region. The equation (4.10) can be written as

\[ J_n(0) = -J_{PA} + J_{BAR} (e^{\frac{V}{kT}} - 1) + \frac{V}{q} R \left( e^{\frac{V}{kT}} - 1 \right) \]  \( \ldots <4.11> \)

with

\[ J_{PA} = -e \phi_0 (1 - e^{-\frac{V}{kT}}) \]  \( \ldots <4.12> \)

and

\[ J_{BAR} = A^* T^2 e^{-\frac{\Phi_s}{kT}} \]  \( \ldots <4.13> \)

From equations (4.10) and (4.11), the light I-V characteristics of a MS solar cell is seen to be

\[ J = -\left( J_{BASE} + J_{DEP} \right) + J_{BAR} (e^{\frac{V}{kT}} - 1) + J_{DIF} \left( e^{\frac{V}{kT}} - 1 \right) \]

\[ + \frac{V}{q} R \left( e^{\frac{V}{kT}} - 1 \right) + f_1(V) \]  \( \ldots <4.14> \)

It is seen that MS solar cells are majority carrier devices whose open circuit voltage is dictated by the bucking thermoionic emission current. Since \( J_{BAR} \gg J_{DIF} \), this MS open circuit voltage will be much less than that of P-n homojunction device made with the same semiconductor. Since \( (V_{OC}) \) is limited by a strong thermionic emission component of the bucking current, the efficiency of MS solar cell can never be as good as that of P-n homojunction (Fonash, 1981).

While examining figure (4.2) a and its light I-V characteristics, it is seen that the photocurrent in that structure is carried across the plane \( x = -W \) by holes. Clearly any
useful modification undertaken to reduce the bucking current must be done without interfering with this flow of holes. Since \( \bar{J}_{\text{BAR}} (e^{V_{J}T} - 1) \) is the largest component of the bucking current of a MIS solar cell structure, it is clear this term must be reduced to allow the bucking current to approach its lower bound \( J_{\text{DIF}} (e^{V_{J}T} - 1) \). The guide to improving the MIS device performance is seen to be simple to reduce \( \bar{J}_{\text{BAR}} (e^{V_{J}T} - 1) \) without interfering with minority carrier transport at the interface. This is the role of the insulating layer in the MIS configuration. The majority carrier bucking current is

\[
\bar{J}_{\text{MAJ}} = \bar{J}_{\text{BAR}} (e^{V_{J}T} - 1) < 4.15
\]

If an insulator is inserted between a metal and a semiconductor of figure (4.2)a to produce figure (4.2)b and the equation (4.15) modifies to

\[
\bar{J}_{\text{MAJ}} = \gamma \left[ \bar{J}_{\text{BAR}} (e^{V_{J}T} - 1) \right] < 4.16
\]

where \( \gamma < 1 \) and it characterises the transport across the I layer.

The quantity in the square brackets of the equation (4.16) is the supply of the majority carriers approaching \( x = -W \) in figure (4.2)b, where as \( \gamma \) gives the probability that they actually cross the I layer. Further \( V_{S} \) is the voltage developed in the semiconductor and is not the total device voltage. The supply of the majority carriers in the figure (4.2)b increases with \( V_{S} \) and not with \( V \). They are related by

\[
V = V_{S} + VI < 4.17
\]

\[
\gamma = \frac{V}{V_{S}} < 4.17
\]

With \( n > 1 \). Here \( V \) is any voltage developed across the I layer and \( n \) is the diode ideality factor. From the equation (4.16), it is seen that there are three approaches to reduce \( \bar{J}_{\text{MAJ}} \): (1) Increase the barrier height (2) reduce the factor \( \gamma \) and (3) develop some of the voltage across the I layer. The conditions (1) and (3) reduce the supply of
FIGURE 4 Band diagrams for (A) MS and (B) MIS solar cells under illumination.
the majority carriers available at a given voltage. The (2) reduces their chances of crossing the I-layer. All these reduce $J_{maj}$ which increase the performance. From the above discussion it follows that for an ideally designed MIS solar cell using the n-type material (Fonash, 1980),

$$J = - (J_{DEP} + J_{BASE}) + \gamma J_{BAR} \left( e^{\frac{V}{n_{AT}} - 1} \right) + J_{DIF} \left( e^{\frac{V}{n_{AT}} - 1} \right)$$  \hspace{1cm} (4.16)

Moreover one or more of the above three approaches is used (Fonash, 1975, Fonash et al, 1979) to reduce $\gamma J_{BAR} \left( e^{\frac{V}{n_{AT}} - 1} \right)$. Generally it is seen that $J_{BAR} \gg J_{DIF}$ if bulk recombination and the interface state paths for $J_{DEP}$ are neglected.

4.5 Spectral Response.

Spectral response is defined as the relative short circuit current ($I_{SC}$) as a function of the wavelength of the incident light for equal energy incident upon the cell at all wavelengths. In other words we may state that the spectral response (amps/watt) is the measure of the short circuit current density generated by the cell under various monochromatic illuminations of a known power density. The spectral response measurements are very useful for evaluating the changes in the cell parameters due to the radiation effects. Spectral response is often reported in terms of relative units, when the absolute values of the light intensities are not determined. The spectral response measurements can be done both in the unirradiated and irradiated conditions. The significance of finding the spectral response of the solar cell lies in the fact that we can get some insight into the power output of the cell as a function of the wavelength of the incident light. The determination of
FIG. 4.3. ABSOLUTE SPECTRAL RESPONSE OF GaAS SOLAR CELL UNDER UNIRRADIATED AND IRRADIATED CONDITIONS
the power output of the cell gives a clue to the responsivity of the solar spectrum. From the determination of the power output of the cell, we are led to the values of the efficiency (\( \eta \)). Thus we see that spectral response is sometimes known as the quantum efficiency or the collection efficiency. Spectral response is experimentally measured using a monochromatic source of light, a detector and a recording instrument. The light source can be a well-calibrated grating or a prism spectrometer or a set of narrow bandpass filters.

However, for computing the spectral response theoretically we have made use of the equation (4.7) incorporating our computed values of the absorption coefficient (\( \alpha \)) in it. For knowing the value of (\( \alpha \)) as a function of the wavelength (\( \lambda \)), we make use of the equation (Heinbockel et al., 1978)

\[
\alpha = 1.2824 \times 10^4 (E - 0.5)^{2.50} \quad \text{where} \quad 1.50 \leq E \leq 4.19
\]

\( E \) is the photon energy in eV and is related to the wavelength (\( \lambda \)) by the relation

\[
E = \frac{1.2405}{\lambda}
\]

\( \lambda \) has been selected in the visible spectrum range accommodating wavelengths from (4000-7000) Å. By incorporating the values of (\( \alpha \)) as computed using above set of equations, we get the computed spectral response as a function of wavelength from the equation (4.6) described in the section (4.3).

### 4.6 Computation of \( V_{oc} \) and \( I_{sc} \) before and after irradiation.

In this section we will briefly outline the analytical expressions used by us for computing the two most important solar cell parameters i.e \( I_{sc} \) and \( V_{oc} \) in both the conditions i.e unirradiated and irradiated ones. One can compute the effect of irradiation on these solar cell parameters by taking into account the already used equation
for \( J_t(J_o) \). However, the general practice of the solar cell radiation
degradation analysis is to reduce the experimental data in terms of
the changes in the short circuit current, open circuit voltage and also
the changes in the minority carrier diffusion length. As can be seen
from the equation (4.6) that the two parameters namely recombination
speed \( S_f \) and minority carrier diffusion length \( L_{p_0} \) are affected by
the electron radiation in our case maintaining all other parameters
constant. No consensus regarding the value of \( S_f \) is seen from the
findings reported in the literature and therefore we have chosen
three different values as \( 10^4, 10^5, 10^6 \), cm sec\(^{-1}\). Also that \( S_f \) value of
\( 10^6 \) cm sec\(^{-1}\) is considered to be an optimum value for the solar cell
performance under best conditions and the value of \( 10^6 \) cm sec\(^{-1}\) is
regarded as the least desirable value, so far the question of
satisfactory working of the cell is concerned. Therefore we have
selected the middle value of i.e \( 10^5 \) cm sec\(^{-1}\) also for use in our various
calculations. Different values of minority carrier diffusion length
after irradiation computed by us in chapter (3) have been inserted in
place of a fixed value of \( L_{p_0} = 3.3 \mu \) used by us for computing the
short circuit current after irradiation.

Therefore for the computation of
\( \frac{I_{sc}}{I_{sc}} \), i.e the ratio of the short circuit current before and after
irradiation, we have deduced its values corresponding to the changes
made in the values of \( N_d \) as well as \( S_f \). As already stated in
chapter no.3, the electron fluence range chosen by us for the purpose
of computing different parameters is \( (10^8 - 10^{17}) \) e cm\(^{-2}\).

For the computation of open
circuit voltage \( (V_{oc}) \) before and after irradiation, we have made use of
the equation (NASA report, 1982).

\[
V_{oc} = \frac{kT}{q} \ln \left( \frac{I_{sc}}{V_{oc}} + 1 \right) \quad \text{<4.20>}
\]

\[
\alpha V_{oc} = \frac{kT}{q} \ln \left( \frac{S_f}{V_{oc}} + 1 \right) \quad \text{<4.217>}
\]
Where the current component \( I_0 \) is a thermoionic emission current determined by the expression

\[
I_0 = A \theta T^2 \exp \left( -\frac{\Phi_A}{kT} \right) \exp \left( \frac{V}{kT} - 1 \right) \tag{4.22}
\]

Where for the dark conditions under the reverse bias, the bulk recombination current \( I_0 \) is given by

\[
I_0 = \frac{\rho D_p n_o}{L_p} \tag{4.23}
\]

The main difference between these two equations is that the expression (4.23) for \( I_0 \) does not involve its dependence on the input bias voltage \( V \), whereas the expression (4.22) for \( I_0 \) involves the term \( V \) and secondly the second expression (4.23) yields the lower value of \( I_0 \) roughly of the order of \( I_0 \), which results in the reduced values of the open circuit voltage under such conditions. However the first expression (4.22) yields \( I_0 \) of the desired order thereby producing the better values of \( V_{oc} \).

Moreover in case of metal-insulator-semiconductor structures we have included the contribution to \( I_0 \) due to the tunneling term in the expression (4.24). The tunneling is caused by the presence of an interfacial layer and this factor is equivalent to a term given by \( \exp \left( -c \chi^{1/2} \alpha \right) \). Therefore the expression for \( I_0 \) involving the tunneling component becomes

\[
I_0 = A \theta T^2 \exp \left( -\frac{\Phi_A}{kT} \right) \exp \left( \frac{V}{kT} - 1 \right) \exp \left( -c \chi^{1/2} \alpha \right) \tag{4.24}
\]

Where we have used the values for \( c=0.26 \) (Ashok et al., 1979) and \( \chi = 0.05 \) ev (Srivastava et al., 1982). The oxide thickness in our case has been chosen to be around 50 A°.
4.7 Summary of our computed results.

The equation (4.6) has been used to compute the short circuit current in case of MIS solar cell under the illuminated conditions. From our various calculations we observed that only $J_{\text{base}}$ component contributes largely to the development of the evaluated current while as the magnitude of $J_{\text{diff}}$ component in the device has been found to be of a very small value compared with the value of the former component. It is thus obvious that only the base component has an appreciable effect on the photovoltaic I/V Characteristics of the MIS solar cell in our case. The values of some of the parameters introduced in our various calculations are as under:

$$\phi_0 (\text{Photon flux}) = 10^7$$

Which is the computed value of ($\phi_0$) choosen by us corresponding to a wavelength of 5000Å.

$$L (\text{Base layer width}) = 10^2 \text{ cm}$$

$$W (\text{Depletion layer width}) = 10^5 \text{ cm}$$

$$D (\text{Diffusion coefficient}) = 3.885 \text{ cm}.$$  

($Sze, 1969$)

$$S (\text{Recombination velocity}) = 10^4, 10^5, 10^6 \text{ cm sec}^{-1}.$$ 

From the plot of $\frac{I_{\text{sc}}}{I_{\text{sc0}}}$, as a function of the electron fluence choosen in the range of ($10^3 - 10^7$) cm$^2$, we observe that these values reduced drastically at a fluence of $10^7$ cm$^2$, which leads us to conclude that at higher electron fluences, the reduction in the values of short circuit...
(Nd) = 1.34 cm⁻³
Nd = 3.75 cm⁻³
For Sp = 1E⁶ cm s⁻¹
& & βP = 5E⁻¹⁵ cm²

Fig. 5: Variation of ISC/ISCO with Fluence
$\Delta (N_d) = 1.34 \text{ cm}^{-1}$
$\nabla (N_d) = 3.75 \text{ cm}^{-1}$
For $SP = 1 \times 10^15 \text{ cm}^2$
$SP = 1 \times 10^4 \text{ cm sec}^{-1}$

**FIG. 4.6**: Variation of $ISC/ISC_0$ with fluence.
\[ \frac{\text{ISC/ISCO}}{\text{FLUENCE}} \]

\[ 10^{13} \quad 10^{14} \quad 10^{15} \quad 10^{16} \quad 10^{17} \]

**FIG. 4**

\[ \text{FLUENCE IN cm}^{-2} \]

\[ \text{ISC/ISCO WITH FLUENCE} \]

\[ \theta (\text{Nd}) = 1.34 \text{ cm}^{-1} \]

For SP = 1.6E cm sec

\[ \theta (\text{Nd}) = 3.75 \text{ cm}^{-1} \]

For SP = 1E-16 cm sec
\[ \Delta (N_d) = 0.61 \text{ cm}^{-1} \]
\[ (\sigma_F) = 1 \times 10^{-16} \text{ cm}^{-1} \]
\[ (s_p) = 1 \times 10^4 \text{ cm sec}^{-1} \]

FIG. 8: VARIATION OF ISC/ISC0 WITH FLUENCE
(Nd) = 0.61 cm⁻¹
(6P) = 5E-15 cm⁻¹
(sP) = 1E6 cm sec⁻¹

FIG. 4: VARIATION OF ISC/ISC0 WITH FLUENCE
$\frac{V_{oC}}{V_{oCo}}$ vs Fluence in $\text{cm}^{-2}$

- $\text{Nd} = 1.34 \text{cm}^{-1}$
- $\text{Nd} = 3.75 \text{cm}^{-1}$

For $s_{P} = 1E4 \text{ cm sec}^{-1}$ and $\theta_{P} = 1E-15$

**Figure 4.10 Variation on $V_{oC}/V_{oCo}$ with Fluence**
\[ \frac{\alpha_{\text{Nd}}}{\alpha_{\text{Co}}} = 1.34 \text{ cm}^{-1} \]

\[ \frac{\alpha_{\text{Nd}}}{\alpha_{\text{Co}}} = 3.75 \text{ cm}^{-1} \]

For \( \text{SP} = 1\times10^5 \) and \( \sigma_{\text{D}} = 1\times10^{-16} \)

**FIGURE 4.11** Variation of \( \frac{\alpha_{\text{C}}}{\alpha_{\text{Co}}} \) with fluence
FIG. 4.12  VARIATION OF $\frac{V_oC}{V_oCo}$ WITH FLUENCE

- $Nd = 3.75 \, cm^{-1}$
- $Nd = 1.34 \, cm^{-1}$

FOR $SP = 1E6$
& $\sigma_p = 5E-15$
FIG. 4.13 VARIATION OF $\frac{V_o}{V_o'}$ WITH FLUENCE

$\phi$ = 1E -15

$\phi$ = 1E -16

$\phi$ = 1E 4

$\phi$ = 1E 5

$N_d = 0.61 \text{ cm}^{-1}$

$N_d = 0.61 \text{ cm}^{-1}$
\[ V_C / V_{Co} \] vs. fluence in cm^{-2}

- Nd = 0.61 cm^{-1}
- FOR \( sP = 1E6 \)
- \( P = 5E-15 \)

FIG. 4-14 VARIATION OF \( V_C / V_{Co} \) WITH FLUENCE
current before and after irradiation brings about the subsequent decrease in the power output of the cell. Our results are in close conformity with the theoretical arguments put forward by various workers (Carlson et al., 1980) regarding the degradation caused in the values of the short circuit current due to the irradiation. The plot of the open circuit voltage as a function of the electron fluence in the same range as described above brings out the fact that these values are not so seriously effected by irradiation as observed in case of the values of the short circuit current.

4.8 Conclusions.

--------- In this chapter we have attempted to study the degradation caused in the various solar cell output parameters as a result of electron irradiation. As previously believed the output parameters, i.e., $V_{oc}$ and $I_{sc}$, in particular are radiation sensitive parameters, as a result of which the power output of the solar cell under irradiated conditions is expected to register a marked decrease. Of the two parameters as stated above, the short circuit current seems to be more effected by radiation than $V_{oc}$. 
REFERENCES