AUGER RECOMBINATION LIMIT ON THE EFFICIENCY OF A SOLAR CELL AT HIGH LEVEL OF ILLUMINATION

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Non-linear diffusion equation in the presence of Auger recombination is solved for a typical solar cell and the limiting value of light intensity above which the collection efficiency starts reducing rapidly is calculated.

1. *Introduction*

Terrestrial application of photovoltaic conversion require a large reduction in its existing cost. Properties of solar cells at light intensities as high as hundred SUNS or more have been studied for this purpose [1]. It is expected that if the thermal degradation and resistive drops can be eliminated at higher intensities these cells will give conversion efficiencies comparable with those obtained at low intensities. This is basically due to the assumption that at large intensities, the open circuit voltage saturates at the diffusion potential and the short circuit current increases linearly with photon flux if internal resistance of the cell is very low [2]. In this paper it is shown that other processes like Auger recombination may become effective at such intensities and may limit the application of these cells.

2. *Theory*

At ordinary levels of illumination, recombination of electron hole pairs generated by light is mostly through recombination with energy levels near the centre of the band gap of semiconductor. Recombination rate due to this process is proportional to the number of injected carriers both at low and high levels of illumination, except for a small non-linearity when a number of injected carriers becomes equal to the thermal concentration of majority carriers in the semiconductor. At large intensities of illumination,

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rate of radiative recombination is proportional to square of the injected carrier concentration whereas Auger recombination rate is proportional to its cube.

Taking account of these non-linear terms, the diffusion equation becomes

$$D_n \frac{\partial^2 n}{\partial x^2} - \alpha n - \beta n^2 - \gamma n^3 = 0, \tag{1}$$

where α, β and γ are coefficients for recombination through traps, and by radiative and Auger processes respectively. $\alpha = 1/\tau_n$, where τ_n is the life time of carriers at low levels of illumination. Due to its non-linearity a general analytical solution of equation (1) cannot be obtained. However, it is possible to get an expression for short circuit current under the assumption that the light is absorbed only at the surface of the cell which is free of recombination centres. The expression thus obtained enables us to predict trend and effectiveness of these processes. Equation (1) can be rewritten as

$$\frac{1}{2D_n} \frac{\partial}{\partial n} \left(D_n \frac{\partial n}{\partial x} \right)^2 = \alpha n + \beta n^2 + \gamma n^3.$$

Integrating this on n, one obtains

$$\frac{1}{2D_n} \left(D_n \frac{\partial n}{\partial x} \right)^2 = \tfrac{1}{2} \alpha n^2 + \tfrac{1}{3} \beta n^3 + \tfrac{1}{4} \gamma n^4 + C. \tag{2}$$

Constant C is evaluated by noting that

$$D_n \frac{\partial n}{\partial x} \bigg|_{\text{surface}} = -N, \tag{3}$$

where N is the number of photons absorbed per unit area per unit time of the cell, at its surface. This gives

$$C = \frac{N^2}{2D_n} - \tfrac{1}{2} \alpha n_s^2 - \tfrac{1}{3} \beta n_s^3 - \tfrac{1}{4} \gamma n_s^4 \tag{4}$$

where n_s is the density of excess carriers at the surface of the cell. Short circuit current density at the junction is obtained by noting that

$$n|_{x=0} = 0,$$

and

$$J_{sc} = -qD_n \frac{\partial n}{\partial x} \bigg|_{x=0},$$

where $x = 0$ gives the position of the junction. Substituting these in equation (2)

$$J_{sc} = q\sqrt{2D_n C}\,. \tag{5}$$

Substituting the value of C from equation (4) in equation (5) we have

$$J_{sc} = q\sqrt{N^2 - D_n\alpha n_s^2 - \tfrac{2}{3}D_n\beta n_s^3 - \tfrac{1}{2}D_n\gamma n_s^4}\,. \tag{6}$$

Value of n_s at low levels of illumination is given by

$$n_s = \frac{NL_n}{D_n}\tanh a/L_n, \tag{7}$$

where $L_n = \sqrt{D_n/\alpha}$ is the diffusion length of the minority carriers at the levels at which radiative and Auger recombinations are negligible.

For a cell with $a \ll L_n$, which is the case of practical interest, we get

$$n_s = \frac{Na}{D_n}\,. \tag{8}$$

Also, for such a cell, J_{sc} at low levels of illumination can be written as,

$$J_{sc} = qN\sqrt{1 - a^2/L_n^2}\,. \tag{9}$$

Equation (6) can be reduced in a form similar to equation (9) by writing

$$J_{sc} = qN\sqrt{1 - a^2/L_n^{*2}}\,, \tag{10}$$

with

$$L_n^* = L_n\left(1 + \tfrac{2}{3}\frac{\beta}{\alpha}n_s + \tfrac{1}{2}\frac{\gamma}{\alpha}n_s^2\right)^{-1/2} \tag{11}$$

L_n^* gives the effective diffusion length of the carriers at high levels of illumination. Here we are interested in finding out values of N for the onset of radiative and Auger recombination processes. For this we substitute value of n_s from equation (8) in equation (11), and get

$$L_n^* = L_n\left(1 + \tfrac{2}{3}\frac{\beta a}{\alpha D_n}N + \tfrac{1}{2}\frac{\gamma a^2}{\alpha D_n^2}N^2\right)^{-1/2}. \tag{12}$$

3. Results and discussions

Figure 1 shows L_n^*/L_n as a function of N for a cell with $a = 0.1\,L_n$, $D_n = 1\ \text{cm}^2\,\text{s}^{-1}$, $\alpha = 10^4\ \text{s}^{-1}$, $\beta = 10^{-15}\ \text{cm}^3\,\text{s}^{-1}$, for three values of $\gamma = 10^{-29}$, 10^{-30}, and $10^{-31}\ \text{cm}^6\,\text{s}^{-1}$ (curves 1, 2 and 3 respectively). It is found that contribution of the term with β (radiative recombination) remains negligible throughout the calculation. The Auger recombination becomes operative at values of N lying between 10^{19} to $10^{21}\ \text{cm}^2\,\text{s}^{-1}$, which correspond to light of 30 to 3,000 SUNS and is of great practical interest.

We conclude from this analysis that large reduction occurs in the short circuit current of a solar cell for $N > \sqrt{\frac{2\alpha D_n^2}{\gamma a^2}}$. This limits its application at higher intensities.

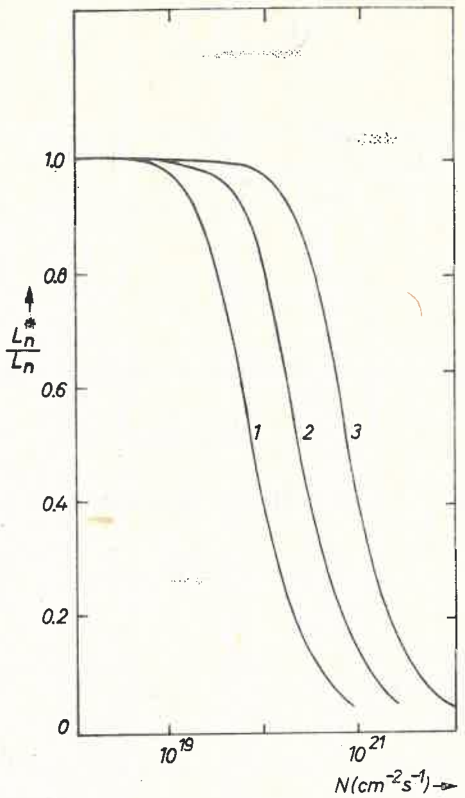

Fig. 1. Ratio of effective diffusion length L_n^* and diffusion length L_n is plotted as a function of the density of photons. Curves *1*, *2* and *3* correspond to $\gamma = 10^{-29}$, 10^{-30} and 10^{-31} cm^6 S^{-1} respectively

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