N O T I C E

THIS DOCUMENT HAS BEEN REPRODUCED FROM
MICROFICHE. ALTHOUGH IT IS RECOGNIZED THAT
CERTAIN PORTIONS ARE ILLEGIBLE, IT IS BEING RELEASED
IN THE INTEREST OF MAKING AVAILABLE AS MUCH
INFORMATION AS POSSIBLE

Diffusion Length Measurements of Thin GaAs Solar Cells by Means of Energetic Electrons

Oldwig von Roos

February 1, 1980

Diffusion Length Measurements of Thin GaAs Solar Cells by Means of Energetic Electrons

Oldwig von Roos

February 1, 1980

CONTENTS

ABSTRACT

A calculation of the short circuit current density j_{sc} of a thin (thickness of the active region ≈10 μm) GaAs solar cell induced by fast (≈1 MeV) electrons is presented. The active region of the cell, manufactured by Hughes, consists of a layer of P^+-Al_xGa_{1-x} As deposited on a P^+-N-N^+ GaAs junction. It is shown that in spite of the disparity in thickness between the N-type portion of the junction (≈10 μm) and the P-type portion of the junction (≈0.3 μm) the measurement of the bulk diffusion length L_p of the N-type part of the junction is <u>seriously</u> hampered due to the presence of a sizable contribution to the j_{sc} from the P-type region of the junction. Corrections of up to 50% have to be made in order to interpret the data correctly. Since these corrections are not amenable to direct measurements it is concluded that the electron beam method for the determination of the bulk minority carrier diffusion length, which works so well for Si solar cells, is a poor method when applied to thin GaAs cells.

I. INTRODUCTION

When a semiconductor junction is irradiated by energetic electrons (≈ 1 MeV) generation of electron-hole pairs takes place. The resulting short circuit current gives a direct measure of the minority carrier diffusion length if certain conditions are met.[1] The junction must be shallow and the generation rate must be uniform throughout the specimen. While the last condition can always be met by choosing the proper energy of the monoenergetic electron beam, the shallowness of the junction is necessary in order that the j_{sc} is dominated by the contribution from the bulk of the junction. Consider a Si solar cell. It is a N^+-P junction with the N^+ region ≈ 0.1 µm thick and the P region ≈ 200 µm thick. The total j_{sc} is the sum of j_p, the hole current originating in the N^+ layer, j_W, the current generated in the depletion layer and finally j_n, the current stemming from the bulk, the P-region. For uniform electron hole pair generation j_W is directly proportional to the depletion layer width W which is of the order of 1 µm. We see then, that because of the enormous disparity between the widths of the various regions of the cell $j_n \gg j_W \gg j_p$. Therefore an accurate and simple measurement of the bulk diffusion length L_n is possible with the fast electron beam method provided, of course, that the generation rate is known.

How does the situation look when we apply the electron beam method to a GaAs solar cell? Fig. 1 shows a cross section through such a cell and various dimensions of interest.[2] At first glance one might think the situation is similar to the previous one inasmuch as we again have a fairly large disparity between the various widths of the different regions. But unfortunately this is not the case as we are going to show in the next section. The reason is largely due to the difference in mobility between electrons and holes. The electrons, the minority carriers in the P^+ region of the junction, have a much larger

1

mobility than the holes of the N region. Therefore, the diffusion of electrons is facilitated over that of the holes and j_n is not negligible over j_p.

II. ANALYSIS

In order to calculate the j_{sc} of the GaAs cell depicted in fig. 1 a number of reasonable assumptions and approximations have to be made. The generation rate G cm^{-3} sec^{-1} of electron-hole pairs due to the incoming fast electrons is considered uniform throughout the three regions I, II and III of the cell and sufficiently small that the condition of low level injection applies. That G is considered the same in region I (the AlGaAs layer) as in region II is an approximation which is not felt to be seriously in error. All three regions are assumed to be uniformly doped and the junction proper is assumed to be abrupt. It is further assumed that both the diffusion constants and life times of electrons in region I and II may differ. Designating by τ_1 and τ_2, D_1 and D_2 their respective life times and diffusion constants we have $L_1 = (D_1 \tau_1)^{1/2}$ and $L_2 = (D_2 \tau_2)^{1/2}$ for the diffusion lengths in region I and II respectively. Finally we represent the N-N$^+$ junction by a vanishing surface recombination velocity (total reflection of holes at the boundary between N- and N$^+$-type material[3]). Shockley's depletion layer approximation is used to calculate the current components j_n, the diffusion current of electrons collected at the left boundary of the depletion layer, j_W, the current generated in the space charge region, and j_p, the diffusion current collected at the right boundary of the depletion layer. The total current density is then:

$$j = j_p + j_W + j_n \tag{1}$$

2

The derivation is given in the appendix. Here we quote the result:

$$j_p = - q G L_3 \tanh (\ell_3/L_3) \quad , \tag{2}$$

$$j_W = - q G W \quad . \tag{3}$$

The expression for j_n, the current originating in regions I and II (fig. 1) and collected at the left hand side of the space charge region, is more involved because of the more complicated structure of the cell on the left of the P-N junction (see fig. 1), viz:

$$j_n = - q G L_2 (A + \eta B) (C + \eta D)^{-1} \quad , \tag{4}$$

where:

$$A = L_2 \sinh (\ell_2/L_2) \cosh (\ell_1/L_1) + \kappa L_1 \cosh (\ell_2/L_2) \sinh (\ell_1/L_1)$$
$$- (\kappa-1) L_1 \sinh (\ell_1/L_1) \quad , \tag{5a}$$

$$B = L_2 \sinh (\ell_2/L_2) \sinh (\ell_1/L_1) + \kappa L_1 \cosh (\ell_2/L_2) \cosh (\ell_1/L_1) - L_1$$
$$- (\kappa-1) L_1 \cosh (\ell_1/L_1) \quad , \tag{5b}$$

$$C = L_2 \cosh (\ell_2/L_2) \cosh (\ell_1/L_1) + \kappa L_1 \sinh (\ell_2/L_2) \sinh (\ell_1/L_1) \quad , \tag{5c}$$

$$D = L_2 \cosh (\ell_2/L_2) \sinh (\ell_1/L_1) + \kappa L_1 \sinh (\ell_2/L_2) \cosh (\ell_1/L_1) \quad . \tag{5d}$$

Here η is defined as

$$\eta = L_1 S/D_1 \tag{5}$$

with S as the surface recombination velocity at the front surface ($x = 0$ in fig. 1). L_1, L_2 and L_3 are the diffusion lengths pertaining to regions I, II and

III respectively, ℓ_1, ℓ_2 and ℓ_3 are their respective widths, q is the charge of an electron (positive), W is the depletion layer width, $\kappa = \tau_2/\tau_1$ is the ratio of the lifetimes of electrons τ_2 in region II and τ_1 in region I, and finally G is the pair production rate in cm^{-3} sec^{-1}. The negative sign takes account of the fact that the current flows into the negative x-direction. In the next section the relative significance of the three current components, eqs. (2), (3) and (4), will be discussed using realistic numbers for the various parameters such as diffusion length, widths, etc.

III. RESULTS

Since we are interested in the relative magnitude of the various current contributions we define the quantity

$$j/(-qG) = \alpha \ [\mu m] \quad , \tag{6}$$

and express α in μm. From eq. (3) α_W for instance is simply given by:

$$\alpha_W = W \quad . \tag{7}$$

The depletion layer width depends strongly on the doping level and is given by[3]:

$$W = \left[\frac{2 \ \epsilon \ \epsilon_0 \ kT}{q^2 \ N_D} \ \ell n \left(N_A \ N_D/n_i^2 \right) \right]^{1/2} , \tag{8}$$

if N_D, the donor concentration, is much larger than N_A, the acceptor concentration. With the information provided for in ref. 2 it turns out that

4

$$\alpha_W = W = 0.117 \ \mu m \tag{9}$$

at 300 K in GaAs ($n_i \approx 2 \cdot 10^6 \ cm^{-3}$). In our case $N_A = 10 \ N_D$.

The computation of j_n and j_p will be performed with values provided for by ref. 2 and 5. We give here a short list.

$$L_n = L_2 = 6 \ \mu m, \ L_p = L_3 = 2.2 \ \mu m, \ \ell_1 = 1.1 \ \mu m, \ \ell_2 = 0.3 \ \mu m, \ \ell_3 = 10 \ \mu m$$

$$\tau_n = \tau_2 = 4 \cdot 10^{-9} \ sec.$$

There is no hard information available about L_1 and τ_1, the diffusion length and lifetime of electrons in region I (the AlGaAs layer). It is how-ever conjectured[2] that $L_1 \approx 1 \ \mu m$. Using the appropriate diffusion constant of GaAs since the Hall mobility has been measured for $Al_x Ga_{1-x} As$ and has been found to be almost the same as the mobility of P-GaAs[2], we compute τ_1 by means of the expression $L_1 = \sqrt{D_1 \tau_1}$. This gives $\tau_1 \approx 10^{-10}$ sec. Therefore the ratio $\kappa = \tau_2/\tau_1$ is $\kappa = 40$.

The computation of j_p and therefore α_p is quite easy. From eq. (2) and the appropriate values for ℓ_3 and L_3 we find:

$$\alpha_p = 2.2 \ tanh \ (10/2.2) = 2.1995 = 2.2 \tag{10}$$

We already know that α_W is much smaller than α_p . If it were to turn out that α_n is also much smaller than α_p, the electron beam method would be a useful tool for the measurement of hole diffusion lengths in GaAs cells. However such is not the case, for, with the values given above it turns out that according to eqs. (4) and (5):

$$\alpha_n = L_2 \ (A + B\eta) \ (C + D\eta)^{-1} = 6 \cdot (1.9 + 1.15 \ \eta) \ (13.0 + 11.36 \ \eta)^{-1} \qquad (11)$$

We remind the reader that η, given by eq. (5), is governed by S, the surface recombination velocity. For S = 0 eq. (11) yields $\alpha_n = 0.88$ and for S = ∞, $\alpha_n = 0.61$. Since $\alpha_p = 2.2$, it is readily established that the correction to be applied to the measurement of L_3 ranges between 40% and 28% depending on the value of η. For S = 10^4 cm/sec, $\eta = 0.013$ in our example, assuming $D_1 = 78$ cm^2/sec. In this case then, the correction is also about 40%.

6

REFERENCES

1) W. Rosenzweig, Bell System Tech. J., 1573, September 1962.

2) B. E. Anspaugh from JPL and R. Loo from Hughes Research which fabricates the cells. Private communication.

3) O. von Roos, J. Appl. Phys., 49, 3503 (1978).

4) H. J. Hovel, Solar Cells, Vol. II of Semiconductors and Semimetals, Academic Press, 1975.

5) H. J. Hovel, loc. cit. p. 14.

The derivation of eqs. (2) to (4) will be outlined below. Denote the electron number density in region I n_1 and in region II n_2. Their diffusion equations then read (a prime means differentiation with respect to x):

$$n_1'' - \frac{n_1}{L_1^2} = - \frac{G}{D_1} \quad , \quad \text{in region I} \tag{A1}$$

and

$$n_2'' - \frac{n_2}{D_2} = - \frac{G}{D_2} \quad . \quad \text{in region II} \tag{A2}$$

The boundary conditions are standard[4] and are given by

$$D_1 n_1' = S n_1 \quad , \quad \text{at } x = 0 , \tag{A3}$$

$$n_1 = n_2 \quad , \quad \text{at } x = \ell_1, \tag{A4}$$

$$D_1 n_1' = D_2 n_2' \quad , \quad \text{at } x = \ell_1, \tag{A5}$$

and finally:

$$n_2 = 0 \qquad \text{at } x = \ell_1 + \ell_2 \tag{A6}$$

Eqs. (A4) and (A5) express continuity of number densities and currents across the boundary between regions I and II.* The solutions to eqs. (A1) and (A2) are

$$n_1 = \frac{GL_1^2}{D_1} \left(1 + A_1 \cosh (x/L_1) + B_1 \sinh (x/L_1) \right) , \tag{A7a}$$

---

* Neglecting an unknown but probably small current drain from interface recombinations.

$$n_2 = \frac{GL_2^2}{D_2}\left(1 + A_2 \cosh(x/L_2) + B_2 \sinh(x/L_2)\right) \quad . \tag{A7b}$$

The unknown coefficients A_1 to B_2 may then be determined by satisfying the boundary conditions (A3) to (A5). The current density is computed from

$$j_n = q\, D_2\, n_2' \quad , \quad \text{at } x = \ell_1 + \ell_2 \quad , \tag{A8}$$

and the result is eq. (4) of the text.

The depletion layer contribution is given by[4]

$$j_W = -q \int_0^W G\,dx = -q\,G\,W \tag{A9}$$

since we assumed a uniform generation rate G.

To compute the diffusion current in region III, denote the hole number density by $p(x)$. The diffusion equation reads:

$$p'' - \frac{p}{L_3^2} = -\frac{G}{D_3} \quad , \quad \text{in region III.} \tag{A10}$$

the boundary conditions are

$$p = 0 \quad , \quad \text{at } x = \ell_1 + \ell_2 + W \quad , \tag{A11a}$$

$$p' = 0 \quad , \quad \text{at } x = \ell_1 + \ell_2 + W + \ell_3 \quad . \tag{A11b}$$

10

In analogy to eqs. (A7) we have

$$p = \frac{GL_3^2}{D_3}\left(1 + A \cosh (x/L_3) + B \sinh (x/L_3)\right) \quad . \tag{A12}$$

A and B are determined by the boundary conditions (A11). The current is given by

$$j_p = - q D_3 p' \quad \text{at } x = \ell_1 + \ell_2 + W \tag{A13}$$

The result is eq. (2) of the text.

As can be seen from the derivation just given we treated regions I and II as a homogeneously doped P-type semiconductor, the only difference being that of lifetimes and diffusion constants. Actually, regions I and II form a hetero-junction. Therefore a built-in voltage exists which is of the order of the difference in band gap energies between regions I and II. A narrow region exists therefore at $x = \ell_1$ (see fig. 1) where a strong electric field will boost the electron current since the band gap of region I is larger than the band gap of region II. But the extent of the electrically active layer is of the order of a few Debye lengths ($\approx 10^{-7}$ cm). This "spike" of electrical activity has been ignored in the calculations outlined above. If anything, it gives a slight increase in j_n and therefore makes the electron beam method for the determination of the bulk diffusion length $L_3 = L_p$ even less attractive.
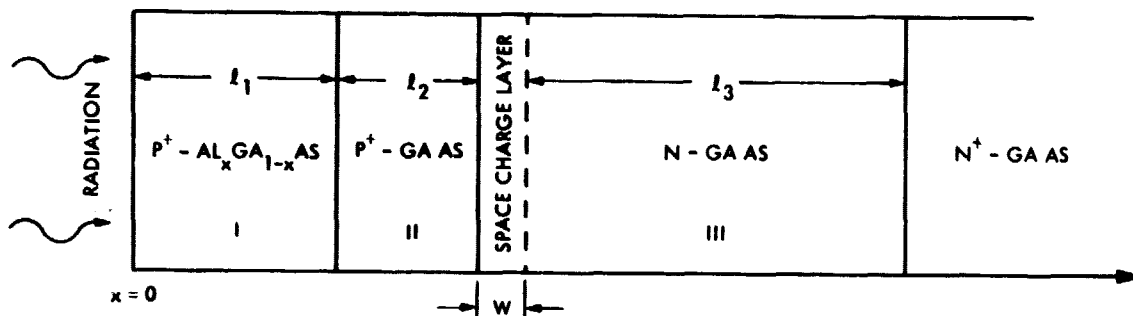
Fig. 1.   The GaAs Back Surface Field Cell. Dimensions not to Scale.

$$\ell_3 \approx 10 \ \mu m \quad \ell_1 \approx 1 \ \mu m \quad \ell_2 \approx 0.3 \ \mu m \quad W \approx 0.1 \ \mu m$$