STUDY OF ELECTRICAL PROPERTIES OF A TRIPLE JUNCTION SOLAR CELL TYPE GAAS/GAINP/GE

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Abstract

The aim of this search is to study electrical properties of GaAs/GaInP/Ge solar cell in conditions, witch like outer space one. The investigated in our search solar cell consist on three junctions: gallium arsenide, gallium-indium-phosphor and germanium. They have exposed to different doses of electronic beams by Van de Graff accelerator. We obtained curves, witch represent changes of the short circuit current and open circuit voltage of the multi-junction cell device versus the logarithm of the electronic flux and calculated quantities, witch characterize the recombination centers based on extracted in this search experimental data for GaAs/GaInP/Ge solar cell. We found that open circuit voltage of GaAs/GaInP/Ge solar cell varies when we vary the electron flux dose φ, which varied in the range $2\times10^{12}\,e.cm^{-2} \le \varphi \le 5\times10^{15}\,e.m^{-2}$. Besides, we found that changes of curves, witch represent this property are linear, it means they lines and its slopes in the recombination regime are four times that in diffusion one. In addition, the density of the short circuit current has been measured and we found that it varies linearly too with the electron flux dose according to their qualitative relationships. The obtained results have been compared with those for each individual solar cell, which composes the triple junction solar cell considered in this work. Finally, we estimated quality of the investigated GaAs/GaInP/Ge solar cell and found that values of the maximum power, the fill factor and efficiency oscillated in following ranges $(140-68)\,mW$, $(81-67)\,\%$ and $(26-12.62)\,\%$ respectively.

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دراسة الخواص الكهربائية للخلية الشمسية ثلاثية الوصلة من النوع GaAs/GaInP/Ge

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ملخص

يهدف هذا البحث إلى دراسة الخواص الكهربائية للخلية الشمسية GaAs/GaInP/Ge في ظروف مشابهة تماماً لتلك المتوافرة في الفضاء الخارجي. تتألف الخلية الشمسية المدروسة في هذا البحث من ثلاث وصلات: غاليوم – زرنيخ، وغاليوم – إنديوم – فوسفور، وجرمانيوم تم تعريضها لجرعات مختلفة من الحزم الإلكترونية بوساطة مُسَّرع فان – ديغراف. لقد حصلنا على المنحنيات البيانية التي تُمثّل تغيرات تيار الدارة المقصورة وجهد الدارة المفتوحة للخلية الشمسية ثلاثية الوصلة بتغير لوغاريتم التدفق الإلكتروني، ومن ثم قمنا بحساب المقادير المميزة لمراكز إعادة الاتحاد استناداً إلى المعطيات التجريبية الناتجة في هذه الدراسة من أجل الخلية الشمسية GaAs/GaInP/Ge. وجدنا أن جهد الدارة المفتوحة للخلية الشمسية GaAs/GaInP/Ge يتغير بتغير لغاريتم تدفق الحزمة الإلكترونية ضمن المجال $2\times10^{12}\,e.cm^{-2} \le \varphi \le 5\times10^{15}\,e.m^{-2}$. إضافة إلى ذلك، وجدنا أن تغيرات المنحنيات التي تدرس هذه الخاصية خطية؛ أي أنها خطوط مستقيمة، وأن ميلها في حالة إعادة الاتحاد غير المشع تفوق أربع مرات ميلها في حالة الانتشار. علاوةً على ذلك، وانسجاماً مع العلاقات النوعية التي حصلنا عليها عند قياس كثافة تيار الدارة المقصورة من أجل قيم مختلفة للجرعة الإلكترونية وجدنا أن هذه الكثافة تتغير بشكل خطي أيضاً. تمت في هذا البحث مقارنة النتائج التي حصلنا عليها من أجل الخلية الشمسية الثلاثية المدروسة هنا مع نتائج دراسة كل خلية شمسية منفردة من الخلايا الشمسية المكونة لها. وأخيراً، تم تقييم جودة الخلية الشمسية المدروسة، والحصول على قيم الاستطاعة العظمى التي تُقدمها حيث تأرجحت بين القيمتين $(68-140)\,mW$، وعامل ملئها الذي تأرجحت قيمته بين $(67-81)\,\%$، وفعاليتها التي تأرجحت بين النسبتين $(12.62-26)\,\%$ من أجل جرع التشعيع الإلكتروني التي تغيرت ضمن المجال المشار إليه أعلاه.

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1. Introduction

The evaluation of solar cell degradation in space induced by energetic particles, such as protons and electrons, has become of great importance so that multijunctoin (MJ) cells used to fill the increasing need for power in satellites. The aim of this work is to the study the solar cells in nearly like space conditions. These cells are triple junctions (TJ) of a GaAs/GaInP/Ge. Therefore, to consider the TJ cell we have to study the behavior of each individual cell, which constitute the whole cell when it is exposed to the electron irradiation.

The behavior of GaAs [1], pure Ge, GaInP sub-cell [2] and GaAs/GaInP (dual junction -DJ-) [3] has been studied in detail. Now we consider GaAs/GaInP/Ge solar cells, which have been delivered by France Emcore Company with 4cm^2 area. Their description can be found in [4]. They prepared by metal organic chemical vapor deposition method (MOCVDM) [5].

The irradiations of TJ cells performed at room temperature with $1\,MeV$ accelerated electrons by using Van de Graff accelerator. The beam (intensity is approximately $1\,\mu A.cm^{-2}$), is scanned to insure a uniform distribution of the fluency over the whole area $4\,cm^2$ of the cell. We are interested in the as-induced defects, which play as majority non-radiative recombination centers, i.e. transport between levels in gap by means of other level placed in later two levels.

It is now established that the degradation can be quantified by describing the variations of the short circuit current density (J_{SC}), the open circuit voltage (V_{OC}) and fill factor (*FF*), from which the maximum power $(P_{\max})$ can be deduced versus irradiation fluency φ. This degradation is due to the generation of non-radiative recombination centers (RCs) [4]. The degradation of the MJ cell has been deduced from the characteristics of the introduced-irradiation defects. We shall demonstrate here how these characteristics can be directly obtained on the GaAs/GaInP/Ge cell.

2. Analytical Study of the Degradation

Once the $\kappa\sigma$ (κ is introduction rate of RCs and σ is their capture cross section for minority carriers) are known for each of the materials composing the MJ cell, it is possible to deduce for each one the variations of V_{OC} and J_{SC} versus the fluency of irradiation. These centers are created with a rate κ [6] so that their concentration N is $(N = \kappa\varphi)$ [7, 8].

In this paragraph, we will consider the variations of V_{OC} and J_{SC}, which induced by a fluency of irradiation. The open circuit voltage is the voltage for which the current $I(V)$ provided by the solar cell for a voltage V [9, 10], is difference between the photo-generated current (I_{Ph}) and the dark current $I_{dc}(V)$. The difference

$$I(V) = I_{dc} - I_{ph}(V) \qquad (1)$$

is zero in the open circuit. That means

$$I_{dc}(V_{OC}) = I_{Ph}. \qquad (2)$$

As if I_{Ph} is the short circuit current I_{SC}:

$$I_{SC} = I_{Ph}. \qquad (3)$$

So,

$$I_{dc}(V_{OC}) = I_{SC.} \qquad (4)$$

Short circuit current

The short circuit current density J_{SC} is the sum of a generation current density induced by electron-hole pair creation and a diffusion current density of electrons and holes on each side of the junction. The irradiation introduces non-radiative recombination centers, which decrease the minority carrier lifetime affecting only the diffusion current. In fact, in the short circuit regime, the potentials are equal on both sides of the space charge region and the carriers distributions are near the equilibrium ones. The resulting rate of Shockley-Read recombination is very weak [11] and the generation current can be considered as constant until the width of the space charge region varies as a result of the compensation of the free carriers.

Therefore, the degradation of J_{SC}, is that of the diffusion current density (J_d). In Ref. [4], it is confirmed that, for low enough fluencies such as the ones encountered in space conditions, V_{OC} and J_{SC} vary with φ as

$$V_{OC} = \varepsilon - \eta \log \varphi ; \qquad (5)$$

$$J_{SC} = \xi - \rho \log \varphi . \qquad (6)$$

In these expressions only the parameters ε and ξ are dependent on the recombination centers induced by the irradiation. The slope η is only a function of intrinsic quantities:

$$\eta = 2.3 \times i \frac{kT}{q} , \qquad (7)$$

when $i = 2, 1/2$ for recombination (η_r) and diffusion (η_d) regimes, respectively. In the expression (7), q is the electric charge, k is the Boltzman's constant and T is the absolute temperature.

The value of V_{OC} at origin $(\log \varphi = 0)$ is

$$\varepsilon = \frac{kT}{q} \ln\left(\frac{J_{SC}}{J_1^*}\right) \quad \textit{for a diffusion regime} \qquad (8)$$

or

$$\varepsilon = \frac{2kT}{q} \ln\left(\frac{J_{SC}}{J_2^*}\right) \quad \textit{for a recombination regime} \qquad (9)$$

thus, both regimes provide current densities J_1^* and J_2^*, from which information on the recombination center can be extracted using expressions (23) and (24) (see later).

The slope ρ of the plot J_d versus $\log \varphi$ is dependent on the recombination centers introduced by the irradiation. Moreover, it depends on the material itself, through the constant r characterizing the absorption coefficient and on the illumination conditions, through the A:

$$\rho = 2.3 \frac{qA}{2r} \qquad (10)$$

On other hand, the value ξ, which contains the characteristics of the recombination center, is J_d at the origin $(\log \varphi = 0)$:

$$\xi = \frac{qA}{r}\left[\ln \alpha(\lambda_1) - \frac{1}{2}\ln\left(\frac{\kappa \sigma \upsilon}{D}\right)\right] \qquad (11)$$

where $\alpha(\lambda_1)$ is the absorption coefficient at wavelength λ_1, υ is the thermal velocity of the minority carriers and D is their diffusion coefficient. This result demonstrates that photovoltaic solar cells made of the same material exhibit identical slopes for the degradation, even if the recombination centers introduced by the irradiation are different. This is well be demonstrated in later figures, showing that the slopes of the degradation are identical for different materials. The nature and concentration of these centers are given by the value ξ of J_d extrapolated at the origin.

In the expression, (10) A is:

$$A = \phi(\lambda) e^{-\alpha(\lambda)(d+d_S)}, \qquad (12)$$

where $\phi(\lambda)$ is the intensity of illumination at the wavelength λ, d is the base thickness, d_s is the width of the space charge region and $\alpha(\lambda)$ is the absorption coefficient, which, for λ values lower than the limit of absorption (the limit of the gap of the material), for GaAs and GaInP, can be sensibly well approximated by the relation [12, 13]:

$$\alpha(\lambda) = \alpha_0 \, e^{-r\lambda} . \qquad (13)$$

where r is the inverse of the diffusion deep. Hence, the values of $\phi(\lambda)$ and T set the rates of degradation of V_{OC} and J_{SC} for a given material.

The degradation of J_{SC} occurs for a fluency larger than a minimum fluency φ_m for which is:

$$\xi - \rho \log \varphi_m = J_{SC}(0). \qquad (14)$$

where $J_{SC}(0)$ is the value obtained from non-irradiated samples. This minimum fluency is given by

$$\log \varphi_m = \frac{\xi - J_{SC}(0)}{\rho}. \qquad (15)$$

where φ_m relates to the recombination centers induced by irradiation, through parameter ξ, and their native, through $J_{SC}(0)$.

Open circuit voltage

The dark forward current density of a junction is the sum of diffusion and recombination current densities [9, 14]:

$$J(V) = J_1 \exp\left[\left(\frac{qV}{kT}\right) - 1\right] + J_2 \exp\left[\left(\frac{qV}{2kT}\right) - 1\right] \qquad (16)$$

where J_1 and J_2 are the corresponding saturation current densities and given by following expressions:

$$J_1 = \frac{q n_i}{N_A}\sqrt{\frac{D_n}{\tau_n}} + \frac{q n_i}{N_D}\sqrt{\frac{D_h}{\tau_h}} , \qquad (17)$$

and

$$J_2 = \frac{\pi}{2} \frac{n_i kT}{\sqrt{\tau_n \tau_h}} \frac{d_{s0}}{\sqrt{V_b}} . \qquad (18)$$

In these expressions n_i is the intrinsic carrier concentration, $D_{n,h}$ the electron-hole diffusion coefficients, $\tau_{n,h}$ the minority carrier lifetime in the p- and n- regions, $N_{A,D}$ the acceptor and donor impurity concentration on each side of the junction, V_b the built-in voltage and d_{s0} the width of the space charge region with no applied bias.

The diffusion length (L) being defined as

$$L = \sqrt{D\tau} \tag{19}$$

and the lifetime τ as

$$\tau = \frac{1}{N\sigma\upsilon} \tag{20}$$

Therefore, using expressions (19) and (20), and replacing the rate κ by $(N = \kappa\varphi)$, we can rewrite the two expressions (17) and (18) in following way:

$$J_1 = J_1^* \sqrt{\varphi} \tag{21}$$

$$J_2 = J_2^* \varphi \tag{22}$$

where

$$J_1^* = q n_i^2 \left(\sqrt{\frac{\kappa\sigma_n\upsilon_n D_n}{N_A}} + \sqrt{\frac{\kappa\sigma_h\upsilon_h D_h}{N_D}} \right) \tag{23}$$

and

$$J_2^* = \frac{\pi}{2} n_i k T d_{s0} \sqrt{\frac{\kappa^2 \sigma_n\sigma_h\upsilon_n\upsilon_h}{V_b}} \tag{24}$$

Therefore, according to expression (4), and for $qV_{OC} >> kT$ we get

$$J_{SC} = J_1^* \sqrt{\varphi} \exp\left(\frac{qV_{OC}}{kT}\right) \tag{25}$$

when the dark current is fundamentally induced by the diffusion regime. However, for the dark current, which induced in recombination regime we have:

$$J_{SC} = J_2^* \varphi \exp\left(\frac{qV_{OC}}{2kT}\right) \tag{26}$$

Thus, in both cases, we can write V_{OC} in form of the expression (5).

For the multijunctoin solar cell, we can express open circuit voltage by relation [3]:

$$V_{OC} = \sum_j \left[\varepsilon_j - \eta_j \log\varphi \right] , \tag{27}$$

Therefore, for the GaAs /GaInP/Ge cell, using expressions (5) and (7), V_{OC} being the sum of the open circuit voltages of the junctions, which compose it, we can write it in case of diffusion and recombination regimes in the following formula, respectively:

$$(V_{OC})_d = \sum_{j=1}^{3} \left[\varepsilon_j \right] - 3 \times \frac{1}{2} \times 2.3 \frac{kT}{q} \log\varphi ; \tag{28}$$

$$(V_{OC})_r = \sum_{j=1}^{3} \left[\varepsilon_j \right] - 3 \times 2 \times 2.3 \frac{kT}{q} \log\varphi . \tag{29}$$

where j stands for each individual cell and the η_j is the same for all cells.

Experimental and theoretical results and discussion

Current-voltage measurements were performed under one air mass zero (1AMO) solar illuminations provided by a Xe and quartz-tungsten-halogen (QTH) arc lamps. The variations of the current-voltage characteristics of the GaAs/GaInP/Ge solar cell for different values of fluency φ are shown in figure 1.

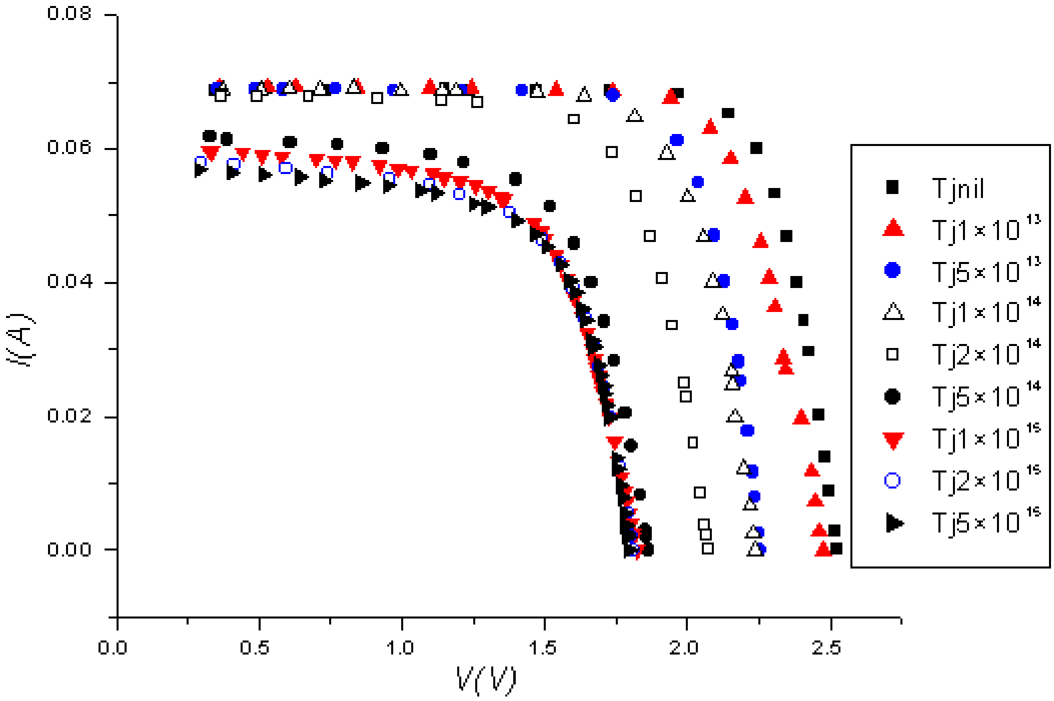


Fig.1. Voltage-current characteristics of TJ cell for different electron irradiation doses.

We have drawn the provided cell photoelectric current $I = f(V)$ prior to and after their exposure to electron irradiation. Note that photoelectric current and in the same time voltage of the cell decrease starting from $\varphi \geq 10^{13}\ e.cm^{-2}$ dose. The first curve represents the photoelectric current of the non-irradiation cell (nil).

Measurement of the open circuit voltage V_{OC}

To obtain the open circuit voltage V_{OC} the intersection of the recent curves $I = f(V)$ (figure 1) with the horizontal axis was taken for each irradiation dose. The first value of V_{OC} was determined at non-irradiation.

The variations of the open circuit voltage versus fluency of GaAs/GaInP/Ge cell are shown in figure 2. Note that in all figures the first values of V_{OC} and J_{SC} (see later) are those indicated for the non-fluency. This figure indicates that the decrease V_{OC} occurs for $\varphi \geq 10^{13}\ e.cm^{-2}$ dose.

The recent studies did not take into account the diffusion range [4, 15] and assumed that linear decreases of the open circuit voltage V_{OC} appear only in the recombination one. Indeed, we can determine both the diffusion and recombination ranges on figure 2. Therefore, from the experimental measurements and applying fitting by relation $\eta_r = 4\eta_d$,

$$V_{OC} = 7.20 - 0.36 \log \varphi \quad (V) \qquad \textit{for the recombination regime};$$

$$V_{OC} = 3.19 - 0.09 \log \varphi \quad (V) \qquad \textit{for the diffusion regime}.$$

i.e. the slope of $V_{OC} = f(\log\varphi)$ curve in the recombination regime is four times that in diffusion regime. Thus, the real experimental values of factors ε_d and ε_r determined from figure 2. Therefore, for a given GaAs/GaInP/Ge solar cell we can write the two following expressions:

$$V_{OC,\,r} = 7.20 - 0.36\log\varphi \quad (V);$$
$$V_{OC,\,d} = 3.19 - 0.09\log\varphi \quad (V),$$

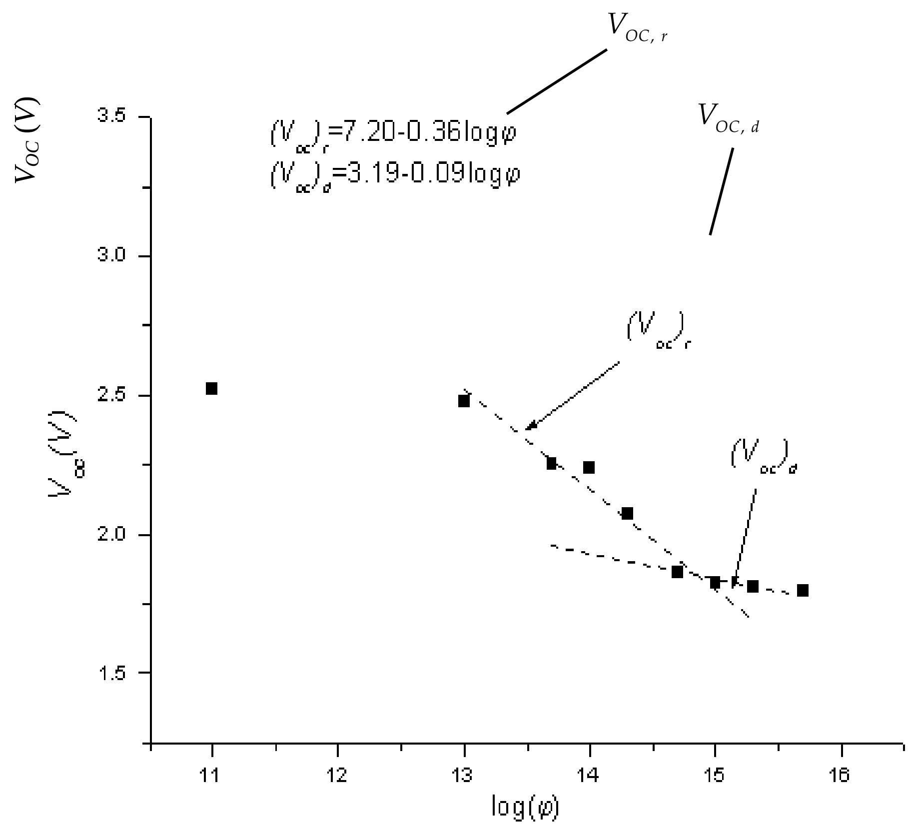


Fig. 2: Variations of V_{OC} versus fluency in both the diffusion, and recombination ranges for TJ cells. The dashed line is the fits with calculated values (η_r and η_d).

TABLE 1. Theoretical and experimental values of the various parameters used to calculate the degradation parameters for GaAs, GaInP, and Ge junctions of a 3J cell

Parameters	GaAs	GaInP	Ge
$\lambda_1\ (nm)$	670	310	870
$\alpha(\lambda_1)\times10^4\ (cm^{-1})$	1	60	3
$D\ (cm^2/s)$	200	60	100
$\upsilon_{th}\times10^7\ (cm/s)$	4.7	3.5	3.1
$N_d\times10^{17}\ (cm^{-3})$	4	5	1
$n_i\ (cm^{-3})$	1×10^6	2.3×10^2	2×10^{13}
$V_d\ (V)$	1.2	1.5	0.55
$d_{s0}\times10^{-2}\ (\mu m)$	1.8	1.8	2.5
$B\times10^{-10}\ (cm^3/s)$	1.5	2	6.4×10^{-4}
$\tau_0\times10^{-5}, s$	2.1	0.00677	9800
$\kappa\sigma\times10^{-13}\ (cm)$	5.1	0.12	4.96×10^{-4}
$\beta\times10^{-10}\ (cm^2)$	5	2.8×10^{-4}	1.5
$J_{SC}(0)\ (mA/cm^2)$	21	17	150

In order to find theoretical factors ε and η in two regimes of open circuit voltage of GaAs/GaInP/Ge cell, first we find their theoretical and experimental factors for each individual cell using (7), (8), (9), (23), and (24) expressions (see table 1). Then apply the relation (27), from which can be written $\varepsilon=\sum_{j=1}^{3}\varepsilon_j$ and $\eta=\sum_{j=1}^{3}\eta_j$. These results listed in tables 1 and 2. We see here a good agreement between the theoretical and experimental parameters of the given solar cells.

TABLE 2: Calculated and experimental values of ε_d and ε_r for diffusion and recombination regimes of GaAs, GaInP, and Ge , GaAs/GaInP and GaAs/GaInP/Ge solar cells

	Experimental				**Calculated**			
cell	$\varepsilon_r\ (V)$	$\varepsilon_d\ (V)$	$\eta_r\ (V)$	$\eta_d\ (V)$	$\varepsilon_r\ (V)$	$\varepsilon_d\ (V)$	$\eta_r\ (V)$	$\eta_d\ (V)$
GaInP	2.80	1.46	0.14	0.04	3.40	1.93	0.12	0.03
GaAs	2.36	1.02	0.12	0.06	2.74	1.43	0.12	0.03
Ge	-	-	-	-	2.36	0.67	0.12	0.03
2J	5.10	2.52	0.24	0.08	6.14	3.36	0.24	0.06
3J	7.20	3.19	0.34	0.08	8.50	4.03	0.36	0.09

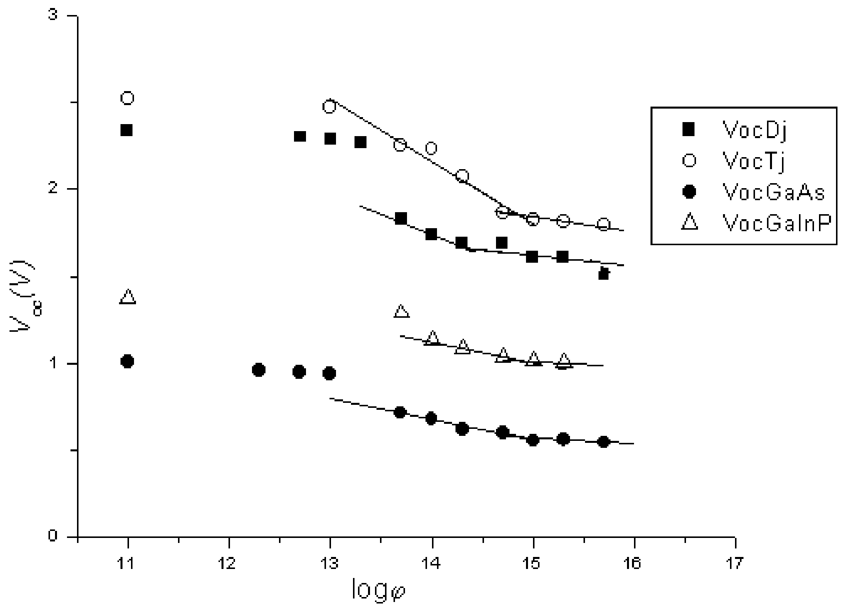


Fig. 3. Variations of the open circuit voltage for GaAs (●) and GaInP (△) subcells and for DJ (■) and TJ (○) cells versus fluency. The full lines are the fits with calculated values (η_r and η_d). The slopes of the 2J and 3J cells are respectively 2 and 3 times that of a single cell.

The $V_{OC} = f(\log\varphi)$ variations of all solar cells illustrated in figure 3. Note that the decrease of open circuit voltage due to electron irradiation for any cell of them is the same and starts at dose $\varphi > 1\times10^{13}, e.cm^{-2}$. As appearing from figure 3, the open circuit voltage of dual- and triple junctions is the sum of open circuit voltages of the primitive two- and three junctions, respectively.

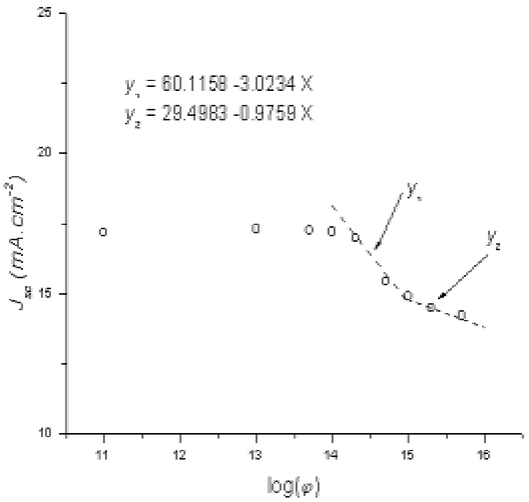
Measurement of the short circuit current density J_{SC}

When the solar cell works in short current regime, the current density is approximately the diffusion one $J_{SC} \cong J_d$ [6]. To calculate the short circuit current density J_{SC} the intersection of the curves $I = f(V)$ (figure 1) with the vertical axis was taken for each irradiation dose, and then resulting values divided by the area of cell surface $4\,cm^2$. The results of the calculations of ξ and ρ are given in table 3, and compared with experimental data shown in figures 4 and 5. Note the induced-irradiation result degradation in photocurrent of TJ cell, as well as GaAs, GaInP, and GaAs/GaInP one. It is apparent, that decrease of J_{SC} is linear, and it starts at $\varphi > 1\times10^{13}, em^{-2}$. Therefore, we can write from figure 4 for the TJ the two following relations:

$$J_{SC} = 60.00 - 3.42\log\varphi\,(mA.cm^{-2});$$
$$J_{SC} = 29.47 - 0.98\log\varphi\,(mA.cm^{-2}).$$

Fig.4. Variations of the short circuit current versus fluency in both the diffusion and recombination ranges for TJ cell. The dashed line is the calculated values of the rates of degradation given in Table 3.

Fig. 5. Variations of the short circuit currents versus fluency for GaAs (▲) and GaInP (■) subcells and for Dj (△) and Tj (○) cells. The full lines are the calculated values of the rates of degradation given in Table 3.



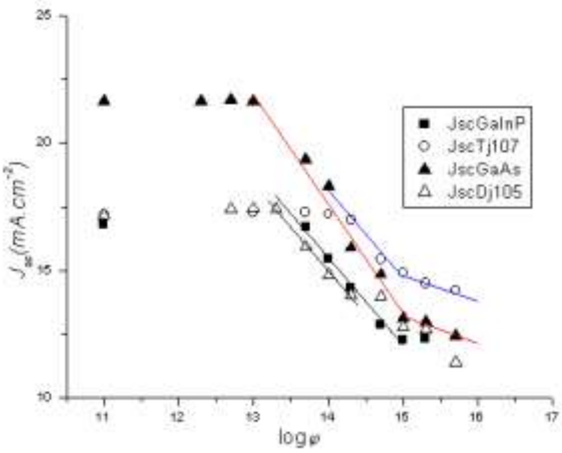


TABLE 3. Comparison between the experimentally determined and calculated parameters describing the degradation of V_{OC} and J_{SC}

	Experimental		Calculated	
cell	$\rho\left(mA.cm^{-2}\right)$	$\xi\left(mA.cm^{-2}\right)$	$\rho\left(mA.cm^{-2}\right)$	$\xi\left(mA.cm^{-2}\right)$
GaInP	3.4	63	2.6	54
GaAs	4.3(1)	78(29)	3.7	59
Ge	-	-	4.3	85
2J	3.4	62	2.6/3.7	54/59
3J	3(1)	60(29)	2.6/3.7	54/59

It is interesting to note, that the calculated results of TJ, DJ, and GaInP cells at $\varphi < 10^{15}\ e.cm^{-2}$ are the same (figure 5) because the photocurrent, provided by two cells in series connection, is the smallest one. On other hand, the experimental results of TJ and GaAs cells at $\varphi > 10^{15}\ e.cm^{-2}$ are the same (figure 5) i.e. that J_{SC} limited by the GaInP (low fluency) and GaAs (high fluency) cells, respectively, as expected.

<u>Calculation of The maximum power, efficiency and full factor of GaAs/GaInP/Ge cell</u>

The main purpose of using multijunctoin solar cell is to get the available maximum power $\left(P_{\max}\right)$ of it. The maximum power of GaAs/GaInP/Ge solar cell was determined in terms of drawing straight line, which passing through the origin (0, 0) and intersecting each of the $I = f(V)$ curves (figure 1) in point $\left(I_{\max}, V_{\max}\right)$. The present points were choosing, where the area $(I_{max} \times V_{max})$ was maximum. Therefore, the maximum power, fill factor and efficiency (Eff) of GaAs/GaInP/Ge cell were being determined by following relations:

$$P_{max} = I_{max} . V_{max} \; ;$$
$$FF = \frac{P_{max}}{I_{SC} . V_{OC}} \; ;$$
$$Eff = \frac{P_{max}}{P_i} \; ,$$

where P_i is the power of incident light on surface unit, and has the value $135.3\, mW.cm^{-2}$ [16].

Variations of P_{max} and Eff versus $\log \varphi$ are shown in figure 6. The maximum power P_{max} decreases linearly with increasing irradiation dose due to induced irradiation defects creation in GaAs/GaInP/Ge cell. The fill factor of given cell is 81% prior to irradiation and became 67% after irradiation, up to $\varphi = 5 \times 10^{15}\; e.cm^{-2}$ value. Therefore, we found that the maximum power, the fill factor and efficiency of GaAs/GaInP/Ge solar cell when we vary the electron irradiation dose φ, in the range $2 \times 10^{12}\; e.cm^{-2} \le \varphi \le 5 \times 10^{15}\; e.cm^{-2}$, varied in the following intervals, respectively:

$$P_{max} = (140 - 68)\, mW \; ;$$
$$FF = (81 - 67)\,\% \; ;$$
$$Eff = (26 - 12.62)\,\% \, .$$

These results, which listed in table 4 for comparison, confirm the importance and the activity of using multijunctoin solar cells.

TABLE 4: Contains the calculated values of P_{max}, *FF* and Eff prior to and after irradiation at $\varphi = 5 \times 10^{15}\; e.cm^{-2}$, of cell

cell	**GaAs**		**GaInP**		**DJ**		**TJ**	
	prior	after	prior	after	prior	after	prior	after
$P_{max}\ (mW)$	54	14	54	13	106	34	140	68
FF (%)	77	55	77	50	82.7	61.75	81	67
Fff (%)	14.5	3.7	14.8	7.1	19.63	6.27	25.97	12.62

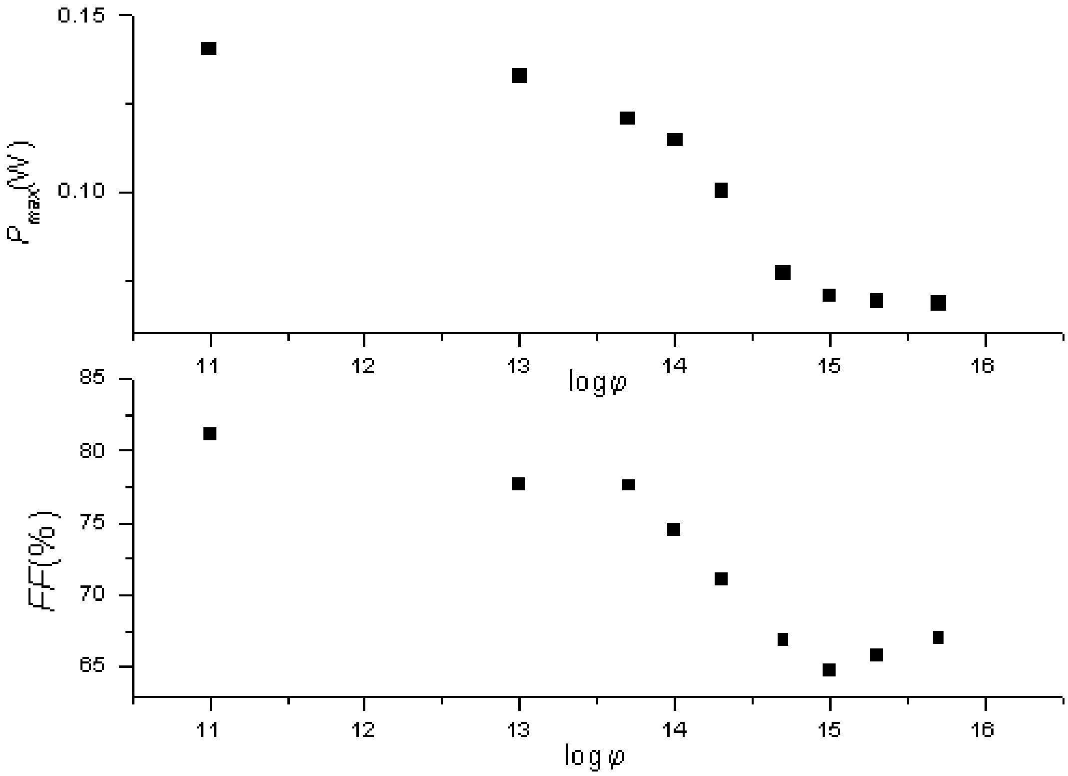


Figure 6. Variations of the maximum power and the fill factor versus log φ

Conclusion

The current study contributes to the explanation of degradation mechanisms of solar cells, when they are exposed to electron irradiation. We recalled how the variations of the open circuit voltage and the short circuit current density of a given solar cell versus the fluency of electron irradiation could be calculated. We have confirmed that the dependence of the V_{OC} and J_{SC} versus the logarithm of the irradiation fluency φ is linear in diffusion and recombination regimes, as well as the degradation induced of non-radiative centers. We illustrated that results obtained are consistent with experimental data obtained on DJ cell irradiated with 1 *MeV*. Finally, we can state that the use of multijunctoin devices in a scope technology of solar cells is recommended because of the increasing provided power.

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