

ON THE SPECTRAL AND LIGHT INTENSITY DEPENDENCE OF PHOTON RECYCLING IN GAAS SOLAR CELLS

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ABSTRACT: Photon Recycling can be briefly described as a process involving the reabsorption of photons emitted in radiative recombination process. It affects the operation and design of direct-gap solar cells, as it has been theoretically and experimentally proved in different ways. Many of its effects can be described in terms of an effective radiative coefficient B which becomes reduced, non-constant along the device and dependent on the working conditions and the structure of the cell. In this paper, we deepen knowledge in the non-linear dependence of photon recycling on the wavelength and the intensity of the light exciting the device. To verify such dependences, dark I-V and illumination Isc-Voc curves of some GaAs solar cells, measured under high intensity monochromatic light, are compared. Experimental results show that photon recycling introduces noticeable deviations between dark and illuminated curves at different wavelengths. These deviations vary at different voltage values, and illumination curves can overpass or underpass dark I-V curve at different points.

Keywords: Photon Recycling, Recombination, Gallium Arsenide Based cells.

1. INTRODUCTION

Photon recycling (PR) is the phenomenon by which photons radiatively emitted by a semiconductor material are re-absorbed within the device and new carriers are generated. The process can be consecutively produced until photons are emitted outside the cell, or carriers are annihilated by non-radiative processes. Its effects can be roughly characterised by a reduction of the radiative recombination rate or, equivalently, as an increase of the radiative lifetime. When PR is significant, the radiative lifetime becomes larger and the solar cell efficiency increases. In general, the open-circuit voltage of the cell is the parameter primarily affected (enhanced) by PR .

In some of our previous works, we have carried out an in depth theoretical study and numerical simulation of PR effects on the performance, efficiency losses, design and quantum efficiency of GaAs solar cells [1,2,3,4]. Some of our results showed how the wavelength and the intensity of the light exciting a sample could have a different influence in the extra carrier generation introduced by PR , mainly because every layer of the cell (emitter, base) contributes differently to photon re-absorption, depending on the cell structure considered. An additional difficulty arises from the fact that, although PR can be treated as a non-linear term in the standard equations driving the semiconductor [5], its effects are practically indistinguishable from the rest of physical phenomena when the external excitation over the cell (for example, the light) is small in magnitude.

The objective of this work is to make clear the effects of PR by means of the experimental test of different GaAs samples, demonstrating how it is a non-linear, wavelength and light intensity dependent effect. As many of these effects can be described by means of a reduced radiative recombination coefficient, a relevant theoretical approach on this matter is first provided. Then, we present the results obtained with a novel experiment based on the measurement of dark I-V and illumination Isc-Voc curves of GaAs solar cells with monochromatic light of different wavelengths and at high intensity levels.

2. THEORETICAL BACKGROUND

The net radiative recombination rate per unit volume in a semiconductor is usually expressed as [6]:

$$R_R = B_R (pn - p_0 n_0) \quad (1)$$

where B_R is the radiative recombination coefficient, p and n are the hole and electron concentrations, and p_0 and n_0 are their corresponding values in equilibrium conditions. Hence, $B_R n_0 p_0$ represents the radiative recombination rate in equilibrium (equal to the equilibrium generation rate). If band tail effects are neglected and the absorption coefficient $\alpha(E)$ is assumed to be zero below band the gap energy E_G , the radiative coefficient in a non-degenerate material is given by [7, 8]:

$$B_R = \frac{1}{p_0 n_0} \frac{8\pi}{h^3 c^2} \int_{E_G}^{\infty} \frac{\nu^2 \alpha E^2}{\exp\left(\frac{E}{kT}\right) - 1} dE \quad (2)$$

ν being the index of refraction of the material. Note that the coefficient B_R is tightly linked to the absorption coefficient α and therefore, can not be arbitrarily fixed. Additionally, B_R as defined in Eq. (2) depends on the temperature T (besides its explicit dependence, due also to the dependence of n_0 , p_0 , E_G , α and ν on T) following, when all effects are globally considered, a law of the form [9,10]: $B_R = B_0 T^{-3/2}$, B_0 being a reference value. On the other hand, B_R is also dependent on the doping (through $n_0 p_0$, E_G and α), and decreases at high doping densities, when the material becomes degenerated [10,11]. Both dependences have also been experimentally proved (see the given references).

However, notice that Eq.(1) is implicitly neglecting the possibility of photons emitted by radiative recombination processes being re-absorbed [6]. When PR is taken into account, Eq.(1) can be written as:

$$R_R = B_R (pn - p_0 n_0) - G_{PR} \quad (3)$$

G_{PR} being the electron-hole pair generation rate due to this photon self-absorption (or PR). Then, in order to keep the conventional form of Eq. (1), an *effective radiative coefficient* B_{PR} can be defined, e.g. as:

$$B_{PR}(pn - n_0 p_0) = \left(B_R - \frac{G_{PR}}{pn - n_0 p_0} \right) (pn - n_0 p_0). \quad (4)$$

Two important consequences are derived from such a modification. First, the equivalent radiative coefficient B_{PR} , consistent with the existence of PR , is *reduced* [4] with respect to the theoretical value of B_R in Eq. (2). Actually, this result is equivalent to the traditional approach of including PR effects by means of a *photon recycling factor* ϕ ($\phi > 1$) which increases the radiative lifetime [12,13] given, in low injection conditions, by:

$$\tau_R = \frac{\phi}{B_R N} = \frac{1}{(B_R/\phi)N} \quad (5)$$

where N is the doping density.

Nevertheless, the theoretical value of B_R for GaAs, obtained from Eq.(2), ranges $4.5-5.5 \times 10^{-10} \text{ cm}^{-3}\text{s}^{-1}$ (depending on the model for α used and even using experimental data), which is a value higher than the one commonly accepted of $2 \times 10^{-10} \text{ cm}^{-3}\text{s}^{-1}$ [14,15]. From our point of view, the higher values calculated for B_R must be considered as the right ones for GaAs when PR is disregarded. We postulated [1] that, in practice, the value of $2 \times 10^{-10} \text{ cm}^{-3}\text{s}^{-1}$ was already including PR effects to a certain extent (equivalent to a factor of $\phi \sim 2.5$) and, therefore, PR had implicitly been taken into account in numerical simulations of solar cells in the past.

The second consequence of (4) is that, in addition to the dependences of B_R on T and on doping level, the effective radiative coefficient becomes also dependent on the design and structure of the cell and on their operating conditions. These dependences can be grasped from the fact that, in a one-dimensional model, the G_{PR} term is given by [1,4]:

$$G_{PR}(x) = 2\pi \int_0^\infty dE \int_{-1}^1 \alpha \cdot b(E, x, \mu) d\mu \quad (6)$$

where b is the photon flux spectral density [7] and $\mu = \cos\theta$ defines its direction of propagation. Values of b are obtained from:

$$b(E, x, \mu) = \frac{\alpha}{\mu} e^{-\alpha x/\mu} \left[\frac{R_F}{\Phi} \Psi_{0F} + \int_0^x b_n e^{\alpha x'/\mu} dx' \right] \quad (7)$$

for angles with $1 \leq \mu < 0$, and from:

$$b(E, x, \mu) = \frac{-\alpha}{\mu} e^{-\alpha x/\mu} \left[\frac{R_p}{\Phi} \Psi_p + \int_x^w b_n e^{\alpha x'/\mu} dx' \right] \quad (8)$$

for angles with $0 < \mu \leq -1$, w being the cell thickness. The parameters Φ and Ψ stands for the optical properties of the surfaces bounding the cell, R_p , R_F being the rear and frontal reflectance values (dependent on μ and on the light polarization), and b_n for the spectral distribution of the photons spontaneously emitted by the cell:

$$b_n \equiv b_n(E, x) = \frac{2}{h^3 c^2} \frac{v^2 \alpha E^2}{\exp\left(\frac{E - e\varphi(x)}{kT}\right) - 1}, \quad (9)$$

where $\varphi(x)$ is the difference between the local pseudo-Fermi levels at each point of the structure.

The working conditions are now incorporated to B_{PR} by means of the explicit dependence of G_{PR} on $\varphi(x)$. Factors as temperature, light intensity or polarization voltage, as well as the device structure, determine the final value of $\varphi(x)$. As an example of how working conditions and device structure can strongly influence the

PR generation rate, the explicit shape of $\varphi(x)$ for a thin GaAs solar cell with a back reflector has been calculated by using the PC-1D program [16]. In Figure 1 it can be observed how $\varphi(x)$ values obtained under illumination change for different polarization voltages and different depths within the cell. Figure 2 is obtained by averaging the values of $\varphi(x)$ along the cell at each polarization:

$$\langle \varphi \rangle = \frac{1}{w} \int_0^w \varphi(x) dx \quad (10)$$

and the same figure is computed for dark conditions. As result, it is evidenced how dark and light conditions bring $\varphi(x)$ to present very different values and only when polarization is near open-circuit conditions both curves reach a similar value. As a consequence, B_{PR} results also variable along the device cross-section, $B_{PR} = B_{PR}(x)$, in agreement with results obtained by other authors [17]. Notice also how pseudo-Fermi levels become near uniformly separated for V_{oc} .

On the other hand, the dependence of B_{PR} on the optics and geometry of the structure become apparent from the dependence of G_{PR} on parameters such as Φ and Ψ . At this respect, a varying radiative coefficient for GaAs, as function of the geometry of the sample (explicitly, of the index of refraction of the mediums surrounding the layer of GaAs) has also been experimentally observed [18], as illustrated in Fig. 3. These results support the validness of the approach here presented.

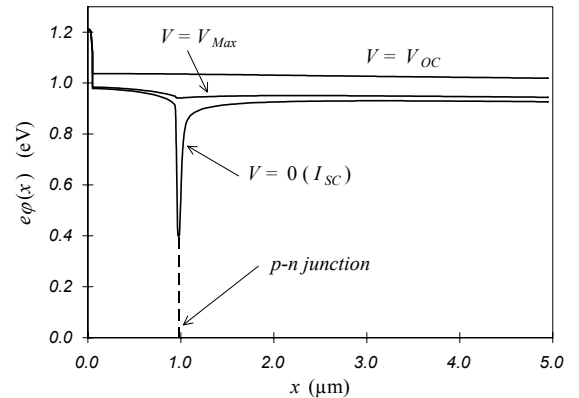


Figure 1. Separation between Fermi pseudo-levels calculated for a thin GaAs solar cell with back reflector under illumination conditions.

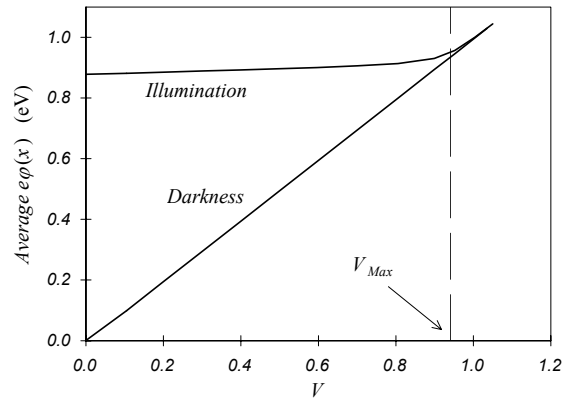


Figure 2. Average values of $\varphi(x)$ under illumination and dark conditions as function of the polarization voltage.

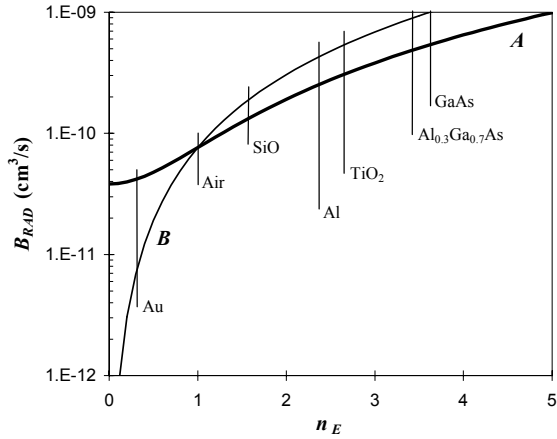


Figure 3. Dependence of B_R on the index of refraction n_E of the materials bounding a layer of GaAs, calculated from [18]. In A, the GaAs layer has air and a material of n_E on each face. In B, the material n_E is on both faces.

3. EXPERIMENTAL APPROACH

PR appears therefore as a process causing radiative coefficient being affected by the sample structure and its operation state. The most relevant aspect we want to detach here is that, mainly due to the complex dependence of the pseudo-Fermi levels split on the different factors mentioned, the PR carrier generation is a non-linear term which can be sometimes difficult to detect. For certain structures and working conditions, the phenomenon is greatly promoted and their effects are perceptible. At a first sight, high $\phi(x)$ values bring both b_n and G_{PR} to increase. As a consequence, when operation conditions or design are not appropriate, the PR process interferes weakly on the solar cell performance, and their effects can be masked by comparable dependences in other parameters (E_G , α , ...) or by the use of a reduced value for B_R ($2 \times 10^{-10} \text{ cm}^{-2} \text{ s}^{-1}$) in simulations.

An easy way to understand the possible influence of PR on solar cell operation is by means of the reverse saturation current density J_0 , a familiar parameter which appears in the ideal solar cell characteristic:

$$J = J_{SC} - J_0 \left(\exp \frac{eV}{mkT} \right) \quad (11)$$

The reverse saturation current, J_0 , has a straight relation with the radiative coefficient [19] since J_0 counts for the total recombination taken place in the device. Then, if B_R is reduced in a factor ϕ by effect of photon recycling, J_0 becomes also reduced. As result, the cell V_{oc} is improved. Observe also that, if non-radiative recombination processes are dominant for a particular device, or the effect of PR is small, the change on J_0 can be negligible [19].

With the objective of experimentally demonstrate our previous theoretical approach, we are going to take advantage of this effect in an indirect way. Note that illumination and dark profiles of $\phi(x)$ can significantly differ each other, but also they can vary at different wavelengths: photon collection and carrier generation are determined by the absorption coefficient α , which can vary in some orders of magnitude among $E_G - UV$ spectral range. Equivalently, a shifting J_0 value would be obtained at different wavelengths, different from those of

dark conditions too. Thus, we have designed an experiment based on the comparison between the dark $I-V$ and illumination $I_{sc}-V_{oc}$ curves measured at different wavelengths. This supposes simpler approach for detecting PR effects with respect to the common approach for evaluating PR effects by measuring luminescence decay curves or by changing the design of the structure, e.g., by incidentally producing a series of devices with different thickness or doping [10,12,13].

In order to reach a monochromatic intensity level to measure sufficient $I_{sc}-V_{oc}$ pairs, we have developed a novel illumination system which combines several light emitting diodes in an optical cavity [20]. When operated at pulsed current, this system can produce current density levels as high as 5 A/cm^2 in GaAs solar cells when only illuminated with a 20 nm spectral bandwidth.

Several concentrator GaAs solar cells have been tested with such a system, which has allowed to measure both dark $I-V$ and $I_{sc}-V_{oc}$ curves at two different wavelengths ($\lambda=620 \text{ nm}$ and 845 nm). The cells have small areas (between $0.16-0.25 \text{ cm}^2$, total area) and are grown over thick substrates. The samples were fixed to a copper plate providing adequate thermal and electrical contacts. Additionally, the cells are not disconnected from the system during the acquisition of the different current-voltage curves in order to avoid errors derived from the resistance of the contacts. The plate is then coupled to an electrically cooled stage. The use of this plate, combined with the application of very short light pulses (up to $15-20 \mu\text{s}$), allowed to keep the temperature of the samples constant.

Figure 4 shows the measured curves for three of the GaAs cells, selected to illustrate the obtained results. The basic selection criteria has been their different dark $I-V$ curve shape, which can be primarily attributed to different resistive and recombination losses present in their structure.

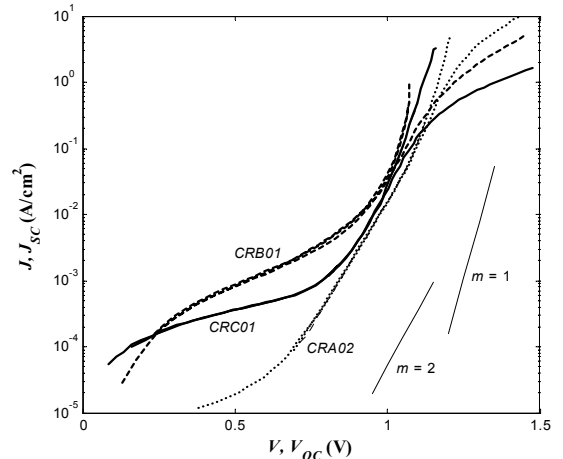


Figure 4. Dark $I-V$ and monochromatic $I_{sc}-V_{oc}$ curves for some of the samples tested. Lines showing slopes of $m=1$ and $m=2$ are included for comparison purposes.

Following our previous discussion, the most important aspect to be evaluated is the separation between the curves measured under monochromatic light. In Figure 5, we analyze the separation between current densities measured at red and infrared wavelengths. In order to better illustrate the results, they have been plotted in terms of the logarithm of the illumination current

density minus the logarithm of the dark current density. When the curves reach negative values, it means that dark curve is above the illuminated ones. The curves obtained for the *CRC01* sample have been not depicted because the differences found were very small as to be easily grasped. As it can be observed in this graph, the current density obtained with IR light is higher than that obtained with red light for a given V_{oc} value. This difference is kept approximately constant until voltage increases above ~ 1 V (when dark curves start to experience series resistance effects) and then IR and red curves tend to approach.

A similar result has been observed for V_{oc} values, as presented in Figure 6. Notice that higher values of current density for IR curves are consistent with higher values of V_{oc} for Red curves. In all the cases, V_{oc} differences also diminish for high values of voltage, after reaching a maximum difference of a few millivolts. Thus, as V_{oc} increases, the separation between both current density and open-circuit voltage curves decreases. From our point of view, photon recycling is causing these deviations.

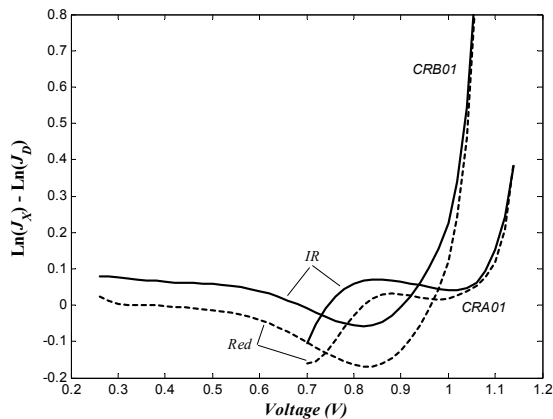


Figure 5. Differences between the current densities measured with monochromatic light (J_x) and the dark J_D for samples *CRA01* and *CRB01*.

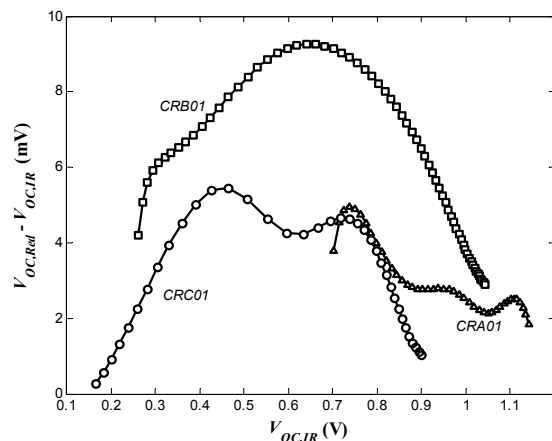


Figure 6. Calculated difference in V_{oc} values between red and infrared curves.

Finally, the reader must take into account that the GaAs samples tested rely on a thick rear substrate. This is a very common solar cell configuration but is a structure with a very poor 'PR efficiency' [19]: the passive substrate absorbs much of the photons reemitted

by the cell and they can not longer contribute to PR. In structures with higher degrees of light confinement (e.g., thinner cells with a rear reflector), internally emitted photons would be better trapped and have lower possibilities of escaping from the active regions, making PR effects more evident. Further measurements with such structures could be carried out in order to highlight additional aspects on the approach here presented.

5. CONCLUSIONS

The theoretical approach explaining how photon recycling is a non-linear process affecting the operation of solar cells has been described. Some of its effects have been modelled by introducing a reduced radiative coefficient, which becomes dependent on the specific structure and working conditions of the device. On the other hand, PR has shown to be dependent on the intensity and wavelength of the light exciting the sample, and can present a varying influence at different polarization voltages. Finally, the measuring system developed for testing purposes has proved to be a valuable tool for characterizing the solar cells.

6. ACKNOWLEDGEMENT

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