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Method For Direct Measurements Of Luminescent Coupling Efficiency In Concentrator MJ SCs

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Abstract: A theoretical model describing the coupling effect for p-n junctions being in a direct optoelectronic contact in the multi-junction solar cell structures is elaborated. The experimental method for determination of the transfer function (coupling yield) is proposed. The method is realized at investigation of triple-junction GaInP/GaAs/Ge solar cells.

Keywords: multi-junction solar cells, optical coupling, electroluminescence
PACS: 42.79.Fm, 42.79.Dj, 88.40.jp.

INTRODUCTION

Substantial progress achieved in the last decade in developing the concentrator multi-junction (MJ) solar cells (SCs) has allowed on the one hand demonstrating record values of their efficiency (greater than 40%) [1-3], and on the other – has emphasized a number of problems associated with peculiarities of the processes proceeding in SCs, with difficulties arising in testing them and in determining the sunlight conversion efficiency. In MJ SCs the radiative recombination of charge carriers in wide-bandgap (*WB*) p-n junctions creates photons, which result in appearance of additional electron-hole pairs in the layers of narrow-bandgap (*NB*) p-n junctions. In this case, the processes derived from the so-called "optical coupling effects" in MJ SCs will result, at creation of additional photo-generated charge carriers, in redistribution of the photocurrents between photoactive p-n junctions and change the conditions for the current matching. This makes the methodology for theoretical description and experimental investigation of such systems rather complicated and may affect noticeably both the SC efficiency and the accuracy of its determination by traditional methods.

Recently a significant number of papers that discuss the impact of the coupling effects on the accuracy of photoresponse measurements and on SC efficiency determination were published [4-15].

The aim of the present work was to elaborate a theoretical model for describing the coupling effect processes in the MJ SC structure and determining experimentally the transfer (coupling) function, which characterizes the conversion of the current creating the luminescent radiation in a *WB* subcell into the *NB* subcell photocurrent.

THEORETICAL BACKGROUND

To analyze the effect of luminescence in a *WB* p-n junction on the value of the current induced by this radiation in a *NB* junction and the current flow mechanisms with allowing for the radiation charge carrier recombination in *NB* subcells of MJ SC, we consider an equivalent circuit of two p-n junctions being in a direct optoelectronic contact (Figure 1). The pointed out processes are realized in MJ SCs and known as "luminescent coupling" [4-15].

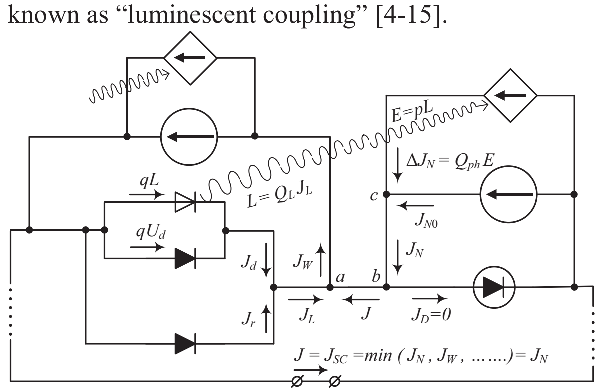

FIGURE 1. A principal equivalent circuit for two subcells being in direct optoelectronic contact. The indices "*W*" and "*N*" are used for the wide- and narrow-bandgap p-n junctions, correspondingly.

The dark resistanceless I-V characteristic $J_L(V_j)$ of the *WB* (emitting) p-n junction is described by a sum of two exponential current components: diffusion one J_d (ideality factor m=1, [16]) and recombination one J_r (m=2, [17]). Along with nonradiative charge carrier

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recombination U_d the contribution into the diffusion component of current is given by band-to-band radiation recombination (luminescence) L (Figure 1).

The following set of equations gives in a parametric form the dependence of the L on the "internal" current density J_L :

$$\begin{cases} J_L = J_d + J_r = J_{0d} exp\left(\dfrac{V_j}{kT/q}\right) + J_{0r} exp\left(\dfrac{V_j}{2kT/q}\right) \\ L = L_{0d} exp\left(\dfrac{V_j}{kT/q}\right) \\ J_d = qL + qU_d \\ J_{0d} = qL_{0d} + qU_{0d} \end{cases} \quad (1)$$

where V_j is voltage on the p-n junction (difference between the quasi-Fermi levels inside the p-n junction space charge region; J_L is the "internal" current density, i.e. the current flowing through the emitting p-n junction and causing electroluminescence; L is the quantum luminosity (luminescence) characterizing the number of photons irradiated per unit time from unit area in the half-space; q is the electron charge; kT is the thermal energy; $J_{0d}, J_{0r}, L_{0d}, U_{0d}$ are the preexponents.

The "transfer" function in the proposed method is defined as:

$$\gamma(J_L) = Q_L(J_L) \cdot p \cdot Q_{ph} \quad (2)$$

where γ is transfer (coupling) yield, $Q_L = qL/J_L$ is the *WB* p-n junction quantum yield of EL (in half space); p is the transmittance coefficient of layers between p-n junction; Q_{ph} is the narrow bandgap p-n-junction quantum yield of the photoresponse.

Motivation for introducing the γ and two proportionality coefficients p and Q_{ph} will be considered in the next paragraph.

So, if in the system (1) instead of luminosity L entering γ and eliminating $exp\left(\dfrac{V_j}{2kT/q}\right)$, the function $\gamma(J_L)$ (exact inverse function) takes the form:

$$J_L = J_{rd} \frac{\gamma/\gamma_s}{(1-\gamma/\gamma_s)^2}, \quad (3)$$

where $J_{rd} = J_{0r}^{\ 2}/J_{0d}$ is a conditional current boundary between the recombination and diffusion sections of the dark I-V characteristic for the radiating p-n junction; $\gamma_s = Q_{ph} \cdot p \cdot Q_s$ is the limiting (saturated) value for function $\gamma(J_L)$, in which $Q_s = qL_{0d}/J_{0d}$ is the limiting quantum yield of the electroluminescence into the half-space on the diffusion portion of the dark I-V characteristic.

LUMINESCENCE INDUCED CURRENT IN *NB* P-N JUNCTION

Quantum irradiance E of the *NB* p-n junction is proportional to luminosity: $E = p \cdot L$, and the additional current induced in this subcell at absorption of luminescent radiation is also proportional to E :

$$\Delta J_N = Q_{ph} \cdot qE, \quad (4)$$

Since the luminosity L is related to the "internal" current J_L through the EL quantum yield $Q_L(J_L)$, the current increment ΔJ_N and "internal" current J_L are coupled by the function:

$$\gamma(J_L) = \Delta J_N / J_L . \quad (5)$$

From the equivalent circuit (see Figure 1) for each of nodes "a", "b", "c" of electrical circuit the following current balances are:

$$J_W = J_L + J \ , \quad J_N = J + J_D , \quad J_N = J_{N0} + \Delta J_N$$

Then it follows from equation (5):

$$\gamma(J_L) = \frac{J_N - J_{N0}}{J_W - J} = \frac{J_N - J_{N0}}{J_W - J_N + J_D} \quad (6)$$

In the short circuit regime the following equalities are: $J = J_N$, $J_D = 0$, then (6) could be rewritten as:

$$\gamma(J_L) = \frac{J_N - J_{N0}}{J_W - J_N} \quad (7)$$

Physical meaning embodied in the $\gamma(J_L)$ is fully consistent with the definition of "quantum efficiency of the luminescent coupling", proposed in [15], and parameter γ_s is equivalent to the «coupling efficiency» in [8]. The variable quantity γ is associated with X_{LC} («luminescent coupling factor») from [10] via the relationship $\gamma = X_{LC}/(1 - X_{LC})$.

EXPERIMENTAL DETERMINATION OF FUNCTION $\gamma(J_L)$

In this section the two-stage experiment for obtaining $\gamma(J_L)$ for any pair of subcells being in a direct optoelectronic contact is presented.

In the first experiment, the J_{SC} is always equal to the current of *WB* subcell $J_{SC} = J_W$ (at the condition of

$R_S < V_{oc} / J_W$). The relationships between the irradiances for subcells are preset in such a way that J_W is much lower than J_N, and also lower than currents generated in any subcells, which have not been chosen as a pair for the analysis. Further, in increasing the irradiance E_W in the spectral sensitivity range of the *WB* subcell, the rise of J_W is recorded.

In the second experiment, the initial ratios of the irradiances are adjusted so that the currents generated in any other (not included into the pair of interest) subcells would be greater then J_W and J_N, while the $J_W \geq J_N$. Then, to ensure the rise of J_W the irradiance have been increased in the same way as in the previous case, and the current $J_{SC} = J_N = \Delta J_N$ is registered ($J_{N0} = 0$ since external illumination within spectral range of the *NB* subcell is absent in presented below practical case and only current induced by EL irradiation is accounted).

So for each irradiations E_W the two values J_W and J_N are obtained and the sought-for dependence of the transfer (coupling) function $\gamma(J_L)$ is calculated.

TECHNIQUE AND PROCEDURE FOR MEASUREMENT

In carrying out experiments, a dual-lamp sunlight simulator has been used with a system for positioning interference filters and two movable light shields (Figure 2). The radiation flux from two pulsed lamps located close to each other and operating synchronously passes through blue, red and IR interference filters and creating conditions for selective action on GaInP, GaAs and Ge subcells of a 3J SC. The simulator design allows setting the filters in different combinations. For the light action on the GaInP and GaAs subcells, blue (λ=300-650 nm) and red (λ=690-900 nm) filters were used, and at operation with the GaInP and Ge subcells – blue and IR (λ>900 nm) ones. Introducing IR glass narrow strips between the blue and red filters ensured simultaneous action on a 3J SC in three spectral ranges. In increasing number of IR glass strips, a step-like enrichment of the IR irradiation was performed, i.e. irradiation level rise for Ge subcell is realized.

A set of the light-filters can be moved with respect to the light window. At that, the introducing one filter into the light flux at simultaneous taking-off of another one. So, the radiation spectrum is enriched in the blue or red wavelength ranges (Figure 2, in shifting filters to the right or left to obtain conditions for excess current in the top or middle subcells, correspondingly). A smooth regulation of the irradiance levels in the range of subcells sensitivity was fulfilled at overlapping a part of the light-filters´ apertures by movable shields. Irradiance levels as high as 500X were possible to be achieved for each of subcells of 3J SC in decreasing illuminator-SC distance with keeping good uniformity of irradiance on SC. It is obvious that, in accordance with the sequence in introducing the radiation of corresponding spectral range into the general light flux and with the color balance "blue/red/IR" established at each shield position, a 3J SC can be "configured" by values of the generated current in the subcells in any of the following versions: $I_{top}>I_{mid}>I_{bot}$, $I_{bot}>I_{top}>I_{mid}$, $I_{bot}>I_{mid}>I_{top}$ and so on.

Recording of the SC I-V characteristic was being carried out during the flat part of the 1msec light pulse. Taking into account a probable current flow through the Ge subcell at a reverse voltage bias in recording the I-V characteristic, in scanning in the voltage range of -4 ÷ +3.5V, it was allowed registering the photocurrent values at once for two subcells being in the conditions of strong current mismatch. The light flux density increase/decrease is ensured by a smooth shift of opaque shields with respect to the installed filters, and the irradiance level (E) in each spectral range obtained for selected shield position appears to be strictly proportional to the corresponding filter aperture width. Thus, in carrying out experiments, a direct monitoring of the irradiance level in each spectral range is not obligatory. It is just enough to control the corresponding light filter aperture width.

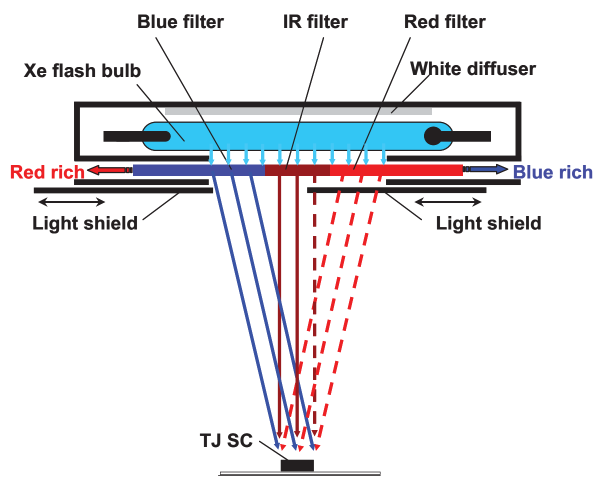

FIGURE 2. Optical scheme of pulsed solar simulator. By colored arrows the possible directions of filter movement are indicated. Right shield is shown in a position then IR light flux intended for Ge subcell is slightly reduced, but red light for GaAs subcell is fully blocked.

RESULTS AND DISCUSSION

Construction of the transfer (coupling) function for the pairs of GaInP-GaAs and GaAs-Ge subcells being analyzed was carried out on the basis of experimental data (Figure 3) recorded at the two-stage measurement procedure described above. Since $J_L = J_W - J_N$, substituting for J_W, J_N and $J_{N0} = 0$ into the (7) the dependence $\gamma(J_L)$ was obtained and later on approximated by (3), where the sought-for values J_{rd} and γ_s were used as fit parameters (Figure 4).

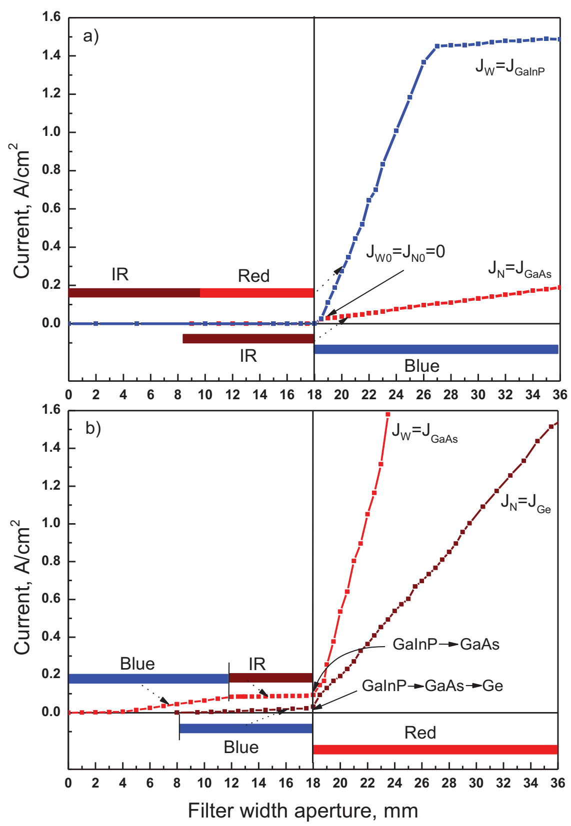

FIGURE 3. Dependencies of the subcells photocurrents of on the light pumping level for cell pairs: a) GaInP-GaAs, b) GaAs-Ge. The colored rectangles show the ranges of openings of the filters transmitting light within the sensitivity ranges of subcells: blue – GaInP, red – GaAs, brown – Ge.

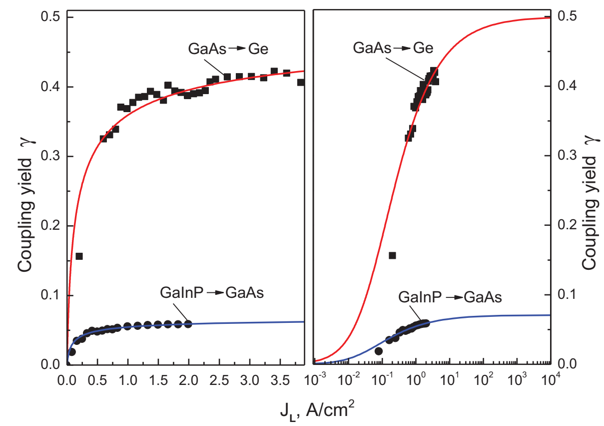

FIGURE 4. Transfer function $\gamma(J_L)$ for the GaInP–GaAs and GaAs-Ge subcells pairs in linear (on the left) and semi-logarithmic (on the right) scales: dots are the experimental data, solid lines are the calculated by formula (3) data.

It is clear that, for the pair GaInP-GaAs the luminescent induced current in GaAs can, at high irradiances, achieve 7% (coupling yield) of the GaInP "internal" current. The obtained value of J_{rd} = 7·10^{-2} A/cm^2 corresponds to those from [18].

For the GaAs-Ge pair, the fit parameters are γ_s =0.5 и J_{rd} =1.1·10^{-1} A/cm^2, which also correspond to those from [18]. It should be noted that coupling yield rise for the GaAs-Ge pair almost stops (within an accuracy of up to 5%) at the current densities of higher than 100 A/cm^2. However, so high photocurrents are practically not achievable for SCs operating in practical systems with sunlight concentrators. At the same time the obtained $\gamma(J_L)$ dependencies allow determining the luminescent contribution into the generated current at low levels of the photocurrent mismatch between subcells.

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