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Illumination and temperature dependence of optical interactions in multijunction solar cells

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Abstract. Optical interactions in multijunction solar cells result from radiative charge carrier recombination in a wide-bandgap subcell, which generates additional photocurrent in a narrower-bandgap subcell via photovoltaic conversion of the emitted photons. This paper proposes a method for the experimental determination of the optical interactions efficiency, including the measurement of its limiting (saturation) value, γ_S. The method was tested on triple-junction GaInP/GaAs/Ge solar cells. The parameter γ_S was recorded at ultra-high current densities through the *p–n* junction, achieved using small-area samples and specialized equipment. The relationship between the obtained values and the properties of the semiconductor structure is discussed, including the temperature dependence of the radiative recombination efficiency (luminescence intensity).

Keywords: multijunction solar cells, optical interactions, electroluminescence intensity, saturation current

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Зависимость оптических взаимодействий в каскадных солнечных элементах от освещенности и температуры

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Аннотация. Оптические взаимодействия в многопереходных солнечных элементах являются следствием процесса излучательной рекомбинации носителей заряда в широкозонном субэлементе с соответствующей этому генерацией дополнительного фототока в более узкозонном субэлементе при фотоэлектрическом преобразовании излученных фотонов. В статье предложена методика экспериментального определения эффективности оптических взаимодействий, включающая регистрацию ее предельного значения γ_S. Методика апробирована на трехпереходных солнечных элементах GaInP/GaAs/Ge. Регистрация параметра γ_S осуществлялась при сверхвысоких плотностях тока через *p–n*-переход, что достигалось использованием малоразмерных образцов и специализированного оборудования. Обсуждается связь полученных значений со свойствами полупроводниковой структуры, в том числе зависимость эффективности излучательной рекомбинации (интенсивности люминесценции) от температуры.

Ключевые слова: многопереходные солнечные элементы, оптические взаимодействия, интенсивность электролюминесценции, ток насыщения

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Introduction

The record conversion efficiencies demonstrated by multijunction (MJ) solar cells (SCs) based on A_3B_5 semiconductor compounds make them particularly attractive for both space and specialized terrestrial applications [1, 2]. MJ SCs with record-breaking efficiency are based on high-quality direct-bandgap semiconductors (e.g., GaAs, GaInP), where radiative recombination of charge carriers dominates. Radiation generated in a wide-bandgap (WB) subcell can be absorbed in an adjacent narrower-bandgap (NB) subcell that is in an optical contact with it. This process of optical interaction results in the generation of an additional luminescence-induced photocurrent in the radiation-receiving subcell.

Radiative recombination in a WB subcell – and consequently, the optical interactions (OI) it initiates – occurs when a portion of the photogenerated carriers recombine within the *p–n* junction instead of being extracted into the external circuit. This situation is realized under a mismatch (difference) in the photocurrents of the subcells, which can arise either during device operation or be intentionally created to study the characteristics of an MJ SC. Correctly assessing the influence of OI is an important practical task, as this effect introduces systematic artifacts into the measured spectral quantum efficiency dependencies of MJ SCs [3, 4]. Moreover, a numerical description of OI can serve as a tool for determining the internal properties of the heterostructure. In this work, the model from Ref. [5] is chosen to describe OI. Its fundamental equation can be written as:

$$\gamma = \gamma_S \frac{J_{rd}}{4J_{pn}} \left(1 - \sqrt{1 + \frac{4J_{pn}}{J_{rd}}} \right)^2, \tag{1}$$

where γ_S and J_{rd} are two physically meaningful model parameters: the limiting OI efficiency and the current boundary between the recombination and diffusion sections of the current-voltage (*I–V*) characteristic of the emitting *p–n* junction, respectively.

According to the two-diode model, the current through the *p–n* junction J_{pn} is defined as the sum of the diffusion (diode ideality factor $A = 1$) and recombination ($A = 2$) components:

$$J_{pn} = J_1 + J_2 = J_{01}\left[\exp\left(\frac{qV}{kT}\right) - 1\right] + J_{02}\left[\exp\left(\frac{qV}{2kT}\right) - 1\right], \tag{2}$$

where V is the applied voltage, k is the Boltzmann constant, T is the temperature in kelvins, J_{01} and J_{02} are the diffusion and recombination reverse saturation currents, respectively.

The OI efficiency γ is defined for a pair of adjacent subcells. Consider a case where a WB subcell generates an excess photocurrent J_W under external broad-spectrum illumination, while a NB subcell generates a lower photocurrent J_{N0}. The luminescent radiation from the WB *p–n* junction propagates through the monolithic MJ SC structure and is absorbed by the NB subcell, increasing its current to a value J_N. Under the short-circuit condition of the NB subcell, the total output current of the MJ SC in a general case is given by J_N. Consequently, the current through the emitting *p–n* junction can be expressed as [5]:

$$J_{pn} = J_W - J_N. \tag{3}$$

From here on the OI efficiency will be defined as the ratio of the luminescence-induced current J_L to the excess current in the WB subcell's *p–n* junction:

$$\gamma = \frac{J_N - J_{N0}}{J_W - J_N} = \frac{J_L(J_{pn})}{J_{pn}}. \tag{4}$$

The key parameter for describing OI is its limiting efficiency γ_S, which is attained under the condition $J_1 >> J_2$. The second model parameter, J_{rd}, defines the point where $J_1 = J_2$, referred to above (see expression (1)) as the current boundary between the recombination and diffusion sections of the dark *I–V* characteristic of the emitting *p–n* junction [5]:

$$J_{rd} = \frac{J_{02}^2}{J_{01}}. \tag{5}$$

Previous experimental studies of OI in MJ SCs [5, 6] were conducted in the range of low current densities through the *p–n* junction, where direct observation of the OI efficiency reaching its saturation mode is not feasible. Consequently, the experimental data were approximated using expression (1) (or its analogues), which involves fitting both parameters (γ_S and J_{rd}) simultaneously, thereby reducing the accuracy of their estimation. This work presents a method for the direct experimental determination of the parameter γ_S.

Materials and Methods

The study of OI was performed using GaInP/GaAs/Ge triple-junction SC. To operate under ultra-high current density conditions, small-area ($\sim$0.4 mm^2) devices were fabricated (the SC configuration was comparable in size with laser power converter [7]).

The experiment was based on recording the *I–V* curves under different ratios of photocurrents generated by the subcells of the MJ SC. This was achieved using lasers with emission wavelengths corresponding to the spectral sensitivity ranges of the subcells (532 nm, 810 nm, and 1064 nm). The laser radiation was delivered to the MJ SC through an optical fiber with a beam combiner and attached terminal optical homogenizer. To prevent overheating of the SC, a pulsed laser operation mode was employed. The sample was fixed on a thermostabilized platform with a Peltier unit monitored by a temperature controller.

According to the principles governing the *I–V* curves formation of MJ SCs [8, 9], when the bottom (Ge) subcell exhibits a sharply rising characteristic under reverse bias, the resulting dependence features two horizontal sections (Fig. 1, *b*): the first "plateau" corresponds to the short-circuit current of the middle subcell, and the second to that of the bottom subcell. This allows the current of the bottom subcell to be determined directly from the MJ SC *I–V* curve, which simplifies the methodology for tracing the OI efficiency (such methods typically require the synchronous measurement of photogenerated currents from individual subcells).

As a result of selective (external) illumination of the top, middle, and bottom subcells, the photocurrents $I_{top}^{ext}, I_{mid}^{ext}$ and I_{bot}^{ext} are generated, respectively. Depending on the applied voltage, V_1 or V_2 (see Fig. 1), current flows through the *p–n* junctions of the subcells, initiating electroluminescence. Part of this emitted radiation induces a photocurrent in the adjacent subcell. Consequently, the photocurrent of the radiation-receiving subcell consists of two components: the current I^{ext} induced by the external radiation and the current $I^L = \gamma \cdot I^{pn}$ induced by OI.

To find the induced currents, two operating regimes are analyzed (see Fig. 1). When the middle subcell is biased in short-circuit point (Fig. 1, *a*), the resulting absorption of luminescence from the GaInP *p–n* junction augments the photocurrent in the GaAs subcell: $I'_{mid} = I_{mid}^{ext} + I_{mid}^{L}$. Similarly, a current $I'_{bot} = I_{bot}^{ext} + I_{bot}^{L}$ is recorded under the short-circuit condition of the Ge (bottom) subcell. Consequently, even when $I_{bot}^{ext} = 0$, the measured photocurrent is non-zero due to electroluminescence from the WB *p–n* junctions.

To determine the OI efficiency, it is necessary to compare the currents generated by each subcell at different points on the *I–V* characteristic [8]. The current through the emitting (GaInP) *p–n* junction could be written as:

$$I_1^{pn} = I_{top}^{ext} - I'_{mid}, \tag{6a}$$

$$I'_{mid} = I_{mid}^{ext} + \gamma^{tm} \cdot I_1^{pn}, \tag{6b}$$

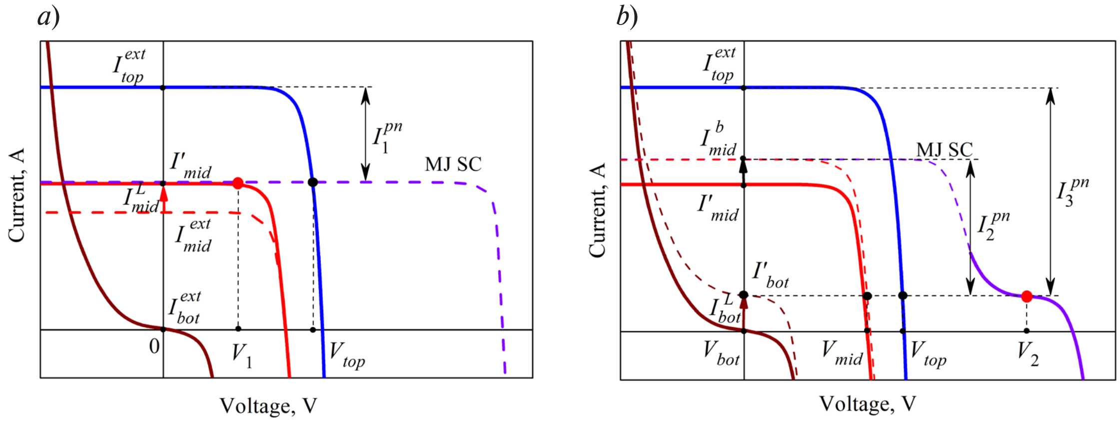

Fig. 1. I–V curves of the subcells with the middle (*a*) and bottom (*b*) subcell under the short-circuit condition.
The lines “MJ SC” correspond to the total I–V curve of the MJ SC

where γ^{tm} is the OI efficiency for the GaInP–GaAs subcell pair.

It should be noted that all currents appearing in equations (6) can be measured experimentally, enabling the calculation of the parameter γ^{tm}. To obtain I^{ext}_{top}, it is sufficient to record the total I–V curve of the MJ SC under conditions where $I^{ext}_{mid} > I^{ext}_{top}$ and $I^{ext}_{bot} > I^{ext}_{top}$. To identify I^{ext}_{mid} the current at the first plateau of the I–V curve is measured under a condition of photocurrent balance between the top and middle subcells: $I^{ext}_{mid} = I^{ext}_{top}$. In this balanced state, both subcells are effectively short-circuited, ensuring $I^L_{mid} = 0$.

When the second plateau on the I–V curve is recorded (see Fig. 1, *b*), the Ge subcell operates under the short-circuit condition, generating a current I'_{bot}. In this regime, the current of the middle subcell differs from its value I'_{mid}, extracted from the total I–V characteristic in the previously discussed case (Fig. 1, *a*). During the transition from middle-subcell to bottom-subcell current limitation, the middle subcell current increases to a new value, denoted here as I^b_{mid}. A cascade optical interaction is observed: the Ge subcell becomes coupled to both upper WB p–n junctions. The currents through these emitting junctions are given by:

$$I^{pn}_2 = I^b_{mid} - I'_{bot}, \tag{7a}$$

$$I^{pn}_3 = I^{ext}_{top} - I'_{bot}. \tag{7b}$$

The corresponding addition to the current of the middle subcell can be expressed as:

$$I^b_{mid} - I'_{mid} = \gamma^{tm} \cdot I^{pn}_3, \tag{7c}$$

while the total current of the bottom subcell is:

$$I'_{bot} = I^{ext}_{bot} + \gamma^{mb} \cdot I^{pn}_2, \tag{7d}$$

where γ^{mb} is the OI efficiency for the GaAs-Ge pair.

Thus, following the reasoning applied to the group of equations (6), all currents appearing in expressions (7) can be obtained experimentally, which enables the parameter γ^{mb} to be found.

Results and Discussion

Fig. 2, *a* presents the OI efficiency values for the GaInP-GaAs and GaAs-Ge pairs over a current density range of 20 to 60 A/cm^2. All experimental data points were obtained using the methodology described above. Achieving high current densities through the p–n junction enables observation of the saturation region of the function $\gamma(J_{pn})$, where the condition $J_1 >> J_2$ is met and the value of γ remains constant. The limiting OI efficiency values for the sample under study (i.e. for the certain multijunction heterostructure) can be estimated as $\gamma^{tm}_S \approx 0.1$ and $\gamma^{mb}_S \approx 0.6$.

The data presented in Fig. 2, *a* were acquired at room temperature. To identify the reasons for the lower OI efficiency in the GaInP-GaAs pair compared to the GaAs-Ge, the temperature dependences of the electroluminescence intensity from the respective emitting *p–n* junctions were investigated (Fig. 2, *b*). For GaAs, as expected, the electroluminescence intensity – and consequently the parameter γ_S – increases with decreasing temperature, which is attributed to a reduction in the non-radiative recombination rate. In contrast, and consistent with the study in [10], GaInP exhibits an inverse anomalous trend: at low temperatures, a region is observed where the electroluminescence intensity increases with rising temperature, followed by a gradual decline. This behavior is presumably due to the thermal activation energy of the dominant non-radiative recombination center being lower than that of the radiative recombination channel.

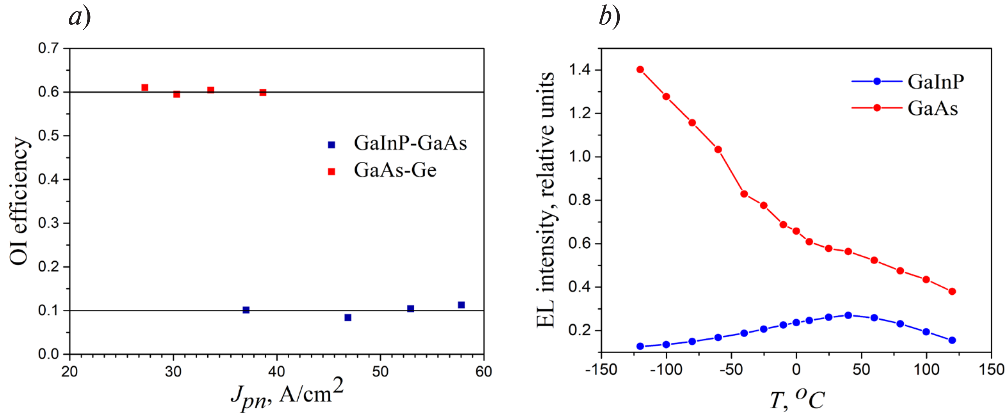

Fig. 2. Dependence of the OI efficiency on the current through the emitting *p–n* junction (*a*) and temperature dependences of the electroluminescence (EL) intensity from the emitting *p–n* junctions (*b*)

Based on the experimental data, the values of the parameter J_{rd} were determined for the GaInP and GaAs *p–n* junctions (Table 1). For comparison, this parameter was also calculated for a reference sample with an identical internal structure but a larger junction area (S_{pn}). The discrepancy observed for the top (GaInP) subcell may be attributed to an increased density of surface defects in the sample of larger size.

Table 1

J_{rd} values for the emitting *p–n* junctions

Subcell	J_{rd} value	
	S_{pn} = 0.4 mm^2	S_{pn} = 4 mm^2
GaInP	0.4	0.92
GaAs	0.51	0.51

Conclusion

An experimental methodology for determining the efficiency of optical interaction between subcells over a wide range of currents through the emitting *p–n* junctions has been developed and implemented. Applied to triple-junction GaInP/GaAs/Ge solar cells, this method yielded the values of the limiting optical interaction efficiency γ_S and the characteristic current J_{rd}.

Temperature dependences of the electroluminescence intensity from the emitting junctions were investigated. The GaInP subcell exhibits an anomalous temperature dependence, which may be attributed to the thermalization of non-radiative recombination centers in the material and the presence of surface states.

The parameters obtained for multijunction solar cells using this methodology, particularly the limiting optical interaction efficiency, can be employed to improve the accuracy of theoretical modeling and to mitigate the adverse influence of measurement artifacts that arise during the recording of spectral responsivity dependencies.

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