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PHYSICS OF SEMICONDUCTOR DEVICES

Current Flow and Potential Efficiency of Solar Cells Based on GaAs and GaSb *p–n* Junctions

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Abstract—Dependence of the efficiency of single-junction and multijunction solar cells on the mechanisms of current flow in photoactive *p–n* junctions, specifically on the form of the dark current–voltage characteristic J–V, has been studied. The resistanceless J–V_j characteristic (with the series resistance disregarded) of a multijunction solar cell has the same shape as the characteristic of a single-junction cell: both feature a set of exponential portions. This made it possible to develop a unified analytical method for calculating the efficiency of single-junction and multijunction solar cells. The equation relating the efficiency to the photogenerated current at each portion of the J–V_j characteristic is derived. For *p–n* junctions in GaAs and GaSb, the following characteristics were measured: the dark J–V characteristic, the dependence of the open-circuit voltage on the illumination intensity P–V_{OC}, and the dependence of the luminescence intensity on the forward current L–J. Calculated dependences of potential efficiency (under idealized condition for equality to unity of external quantum yield) on the photogenerated current for single-junction GaAs and GaSb solar cells and a GaAs/GaSb tandem are plotted. The form of these dependences corresponds to the shape of J–V_j characteristics: there are the diffusion- and recombination-related portions; in some cases, the tunneling-trapping portion is also observed. At low degrees of concentration of solar radiation ($C < 10$), an appreciable contribution to photogenerated current is made by recombination component. It is an increase in this component in the case of irradiation with 6.78-MeV protons or 1-MeV electrons that brings about a decrease in the efficiency of conversion of unconcentrated solar radiation.

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1. INTRODUCTION

Dependence of the efficiency on the density of the photogenerated current (photocurrent) and, consequently, on the extent of concentration of solar radiation (C) is one of the main characteristics of single-junction and multijunction solar cells (SCs). This dependence is governed by the shape and structure of the dark resistanceless (with the series resistance R_S disregarded) current–voltage (J–V_j) characteristic of both a single *p–n* junction and several series-connected photoactive *p–n* junctions in multijunction solar cells (MSC).

At present, the main attention is directed to the diffusion component of the current; numerical methods are used to determine the expected efficiency. The aim of this study was to show the necessity to take into account the recombination-related component of the current, especially at low extents of the solar-radiation concentration ($C < 10$) and, correspondingly, to determine the shape and structure of the current-voltage characteristics for MSCs and establish an analytical relation between this characteristic and the efficiency of a SC.

In this study, we, first, analyzed two methods for obtaining the resistanceless J–V_j characteristics for photoactive *p–n* junctions. The methods are based on making the experimental dark current-voltage (J–V) characteristics coinciding with characteristics independent of the series resistance of the *p–n* structures under study. To this end, we used the photovoltaic characteristic of the *p–n* junction, dependences of the open-circuit voltage on illumination intensity (P–V_{OC}), and electroluminescent characteristics representing the dependence of electroluminescence intensity on the forward current (the L–J characteristic). It should be noted that plotting of the dependences of the generated photocurrent on the open-circuit voltage (J_g–V_{OC}) and also the use of proportionality between the electroluminescence intensity and diffusion-related component of the current under the open-circuit conditions was used by Guchmazov et al. [1]. In that paper, they describe a contactless method for measuring the electrical and photoelectric parameters of SCs with the *p*-AlGaAs/(*p–n*)-GaAs.

Second, we analyzed the resulting dark resistanceless MSC J–V_j characteristic formed as a result of a series connection of photoactive *p–n* junctions. This characteristic features exactly the same shape as in the case of a single-junction structure: there is a set of exponential portions. This makes it possible to introduce the concept of the resulting *p–n* junction that imitates the series-connected photoactive *p–n* junctions.

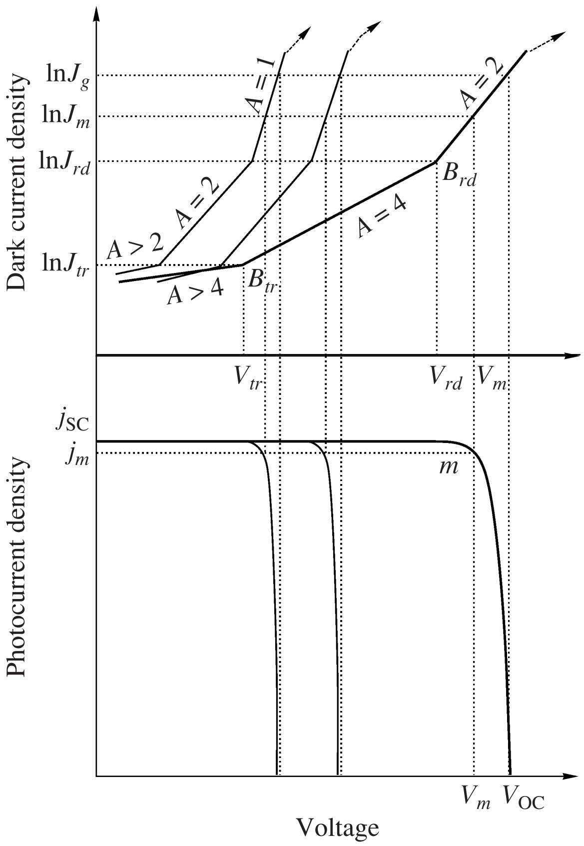

Fig. 1. The structure of "dark" J–V_j characteristics and the characteristics j–V_j obtained under illumination for two separate photoactive p–n junctions and a tandem formed of them.

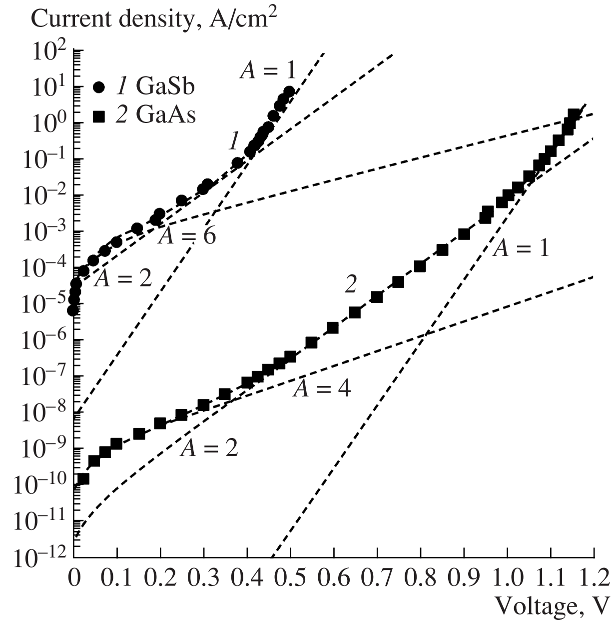

Fig. 2. Resistanceless dark J–V_j characteristics of p–n junctions based on (*1*) GaSb and (*2*) GaAs.

Third, we used the resistanceless dark J–V_j characteristic (including the resulting characteristic) to obtain the dependence of the efficiency (η) of a SC on a photogenerated current at various intensities of illumination (AM0, AM1.5, and so on). To this end, we derived an equation [2] that expresses the photogenerated current (J_g) in terms of an auxiliary quantity, the effective voltage (V_η); i.e., we obtained the V_η–J_g dependence. This voltage is proportional to the efficiency with the proportionality coefficient depending only on specific conditions of the SC illumination. Thus, all specific required variants for the p–n junction under consideration (including the resulting junction) are involved in a unified V_η–J_g characteristic, where $V_\eta \propto \eta$ and $J_g \propto C$.

The results obtained in this study and reported in this paper are applicable to photoactive p–n junctions correlated in the photocurrent in a MSC. In the case under consideration, these results were applied to a correlated pair of p–n junctions from GaAs and GaSb. The studied GaAs and GaSb p–n structures were grown by the methods of MOCVD and low-temperature liquid-phase epitaxy [3].

2. THE DARK RESISTANCELESS (FORWARD CURRENT)–VOLTAGE CHARACTERISTIC: METHODS FOR OBTAINING AND RELATION TO THE EFFICIENCY

2.1. Consistency Between the Current–Voltage Characteristics Measured in the Dark and Under Illumination

In the most general form, the density of the forward "dark" current of photoactive p–n junctions based on III–V materials is composed of at least three components of exponential form,

$$J = J_{0t}\left(\exp\frac{qV_j}{AkT} - 1\right) + J_{0r}\left(\exp\frac{qV_j}{2kT} - 1\right) + J_{0d}\left(\exp\frac{qV_j}{kT} - 1\right), \quad (1)$$

i.e., the tunneling-trapping component ($A > 2$), the recombination-related component, and the diffusion-related component (Figs. 1, 2). Here, $qV_j = (F_n - F_p)$ is the difference between the electron and hole quasi-Fermi levels at the boundaries of the space-charge region (SCR) of the p–n junction. Correspondingly, V_j is the so-called resistanceless voltage that does not depend on the series resistance of the structure R_S: $V_j = V - JR_S$, where V is the voltage over the entire p–n structure.

As a rule, the photocurrent density $J_g \geq 10^{-2}$ A/cm^2 in solar cells is used as the density of optical radiation ($C \geq 1$). Therefore, first, the working currents are governed mainly by the recombination- and diffusion-related mechanisms of the current flow; as a result, we do not consider the tunneling-trapping mechanism in this study. Second, since $J_g \gg J_0$, we can disregard unity (compared with the exponential function) in expression (1). As a result, the dark resistanceless (with R_S disregarded) J–V_j characteristic of a SC takes the two-exponential form:

$$J = J_{0r}\exp qV_j/2kT + J_{0d}\exp qV_j/kT. \tag{2}$$

Correspondingly, the load (obtained under illumination) j–V characteristic and also the dependence of the photogenerated current on the open-circuit voltage (the J_g–V_{OC} characteristic) [4, 5] take the form

$$j = J_g - (J_{0r}\exp q(V + jR_S)/2kT + J_{0d}\exp q(V + jR_S)/kT), \tag{3}$$

where j is the density of the current through the load

$$J_g = J_{0r}\exp\frac{qV_{OC}}{2kT} + J_{0d}\exp\frac{qV_{OC}}{kT}. \tag{4}$$

The shape of the J_g–V_{OC} (4) is exactly the same as of the sought for dark resistanceless J–V_j characteristic (2), which makes it possible in what follows to formally introduce the replacements $J_g \longrightarrow J$ and $V_{OC} \longrightarrow V_j$ in the case of transformation of the photovoltaic characteristic P–V_{OC} (the dependence of illumination intensity on the open-circuit voltage) into the desired J–V_j characteristic.

2.2. Obtainment of the Dark Resistanceless Current-Voltage (J–V_j) Characteristic

2.2.1. The characteristic representing the dependence of the illumination intensity on the open-circuit voltage (P–V_{OC}). This P–V_{OC} characteristic is transformed from the J–V_j characteristic (2) that is equivalent to the J_g–V_{OC} characteristic (4). The photogenerated current J_g is proportional to the illumination intensity $P = \chi J_g$, so that we use Eq. (4) to obtain the following expression for the P–V_{OC} characteristic:

$$P = P_{0r}\exp\frac{qV_{OC}}{2kT} + P_{0d}\exp\frac{qV_{OC}}{kT}. \tag{5}$$

Here, $P_{0r} = \chi J_{0r}$ and $P_{0d} = \chi J_{0d}$.

2.2.2. The characteristic representing the dependence of the electroluminescence intensity on the forward current (L–J). This L–J characteristic is transformed, the same as for the P–V_{OC} characteristic (4), from the dark resistanceless characteristic J–V_j (2). As is well known [6], the intensity of interband and quasi-interband electroluminescence L is expressed in terms of resistanceless V_j with the same dependence as in the case of the diffusion dark current:

$$V_j = \frac{kT}{q}\ln L/L_0. \tag{6}$$

We introduce (6) into (2) and obtain the following expression for the J–L characteristic:

$$J = k_r\sqrt{L} + k_d L, \tag{7a}$$

Here,

$$k_r = J_{0r}/\sqrt{L_0}, \quad \text{and} \quad k_d = J_{0d}/L_0. \tag{7b}$$

2.2.3. Conversion of the P–V_{OC} and J–L characteristics to the sought-for dark resistanceless J–V_j characteristic. Both characteristics under consideration (the P–V_{OC} and J–L characteristics) do not depend on the series resistance of the p–n junction, and these characteristics were transformed (see Subsections 2.2.1 and 2.2.2) from the dark resistanceless J–V_j characteristic. Therefore, the experimentally obtained P–V_{OC} and J–L dependences can be transformed back into the sought-for resistanceless J–V_j characteristic if the transformation parameters χ for the P–V_{OC} characteristic (Subsection 2.2.1) and L_0 for the J–L characteristic (Subsection 2.2.2) are determined by the method used in this study (see Section 3). This method is adequate only for single-junction solar cells and is based on fitting the results to the directly measured dark J–V_j characteristic at the recombination-related portion where the effect of R_S is not yet appreciable. By determining J_{0r} in this portion, we determine the transformation parameters, χ for the P–V_{OC} characteristic and L_0 for the J–L characteristic, i.e., $\chi = \dfrac{P_{0r}}{J_{0r}}$ and $L_0 = (J_{0r}/k_r)^2$. Moreover, even without the mentioned transformations, we can restrict ourselves to calculation of J_{0d}, the diffusion pre-exponential factor necessary to calculate the potential efficiency (see Subsection 2.4) in the diffusion-related portion:

$$J_{0d} = \frac{P_{0d}}{\chi} = J_{0r}\frac{P_{0d}}{P_{0r}} \quad \text{from} \quad (P\text{–}V_{OC}), \tag{8a}$$

$$J_{0d} = k_d L_0 = k_d\left(\frac{J_{0r}}{k_r}\right)^2 \quad \text{from} \quad (J\text{–}L). \tag{8b}$$

2.3. Resistanceless Current-Voltage Characteristics (Measured in the Dark and Under Illumination) of Multijunction Solar Cell

If all p–n junctions in a multijunction solar cell are connected in series, voltages at each of p–n junctions are summed. Each portion of the dark resistanceless J–V_j characteristic (2) is described by the following expression:

$$V_j = A\frac{kT}{q}\ln\frac{J}{J_0} = \frac{kT}{q}\ln\left(\frac{J}{J_0}\right)^A, \tag{9}$$

where $A = 1$ or 2.

The sum of resistanceless voltages across the p–n junctions represents the resistanceless voltage across the MSC:

$$\begin{aligned} V_{jMJ} &= \frac{kT}{q}\sum_{k=1}^{n}\ln\left(\frac{J}{J_{0k}}\right)^{A_k} = \frac{kT}{q}\ln\prod_{k=1}^{n}\left(\frac{J}{J_{0k}}\right)^{A_k} \\ &= \frac{kT}{q}\ln\left(\frac{J}{J_{0MJ}}\right)^{A_{MJ}} = A_{MJ}\frac{kT}{q}\ln\left(\frac{J}{J_{0MJ}}\right). \end{aligned} \tag{10a}$$

Here,

$$\begin{aligned} A_{MJ} &= A_1 + A_2 + \ldots + A_n, \\ J_{0MJ} &= (J_{01}^{A1} J_{02}^{A2} \ldots J_{0n}^{An})^{1/A_{MJ}}. \end{aligned} \tag{10b}$$

Thus, the dark resistanceless J–V_j characteristic for an MSC consists of a set of exponential portions (10a) as in the case of a single p–n junction (9) (Fig. 1). Therefore, it is expedient to use the concept of the resulting p–n junction that imitates the series-connected p–n junctions of the exponential portions of the dark resultant resistanceless J–V_{jMJ} characteristic.

In particular, if all built-in photoactive p–n junctions feature the same diode coefficient ($A = 1$ or 2) for the portion of the resultant characteristic under consideration, the resulting diode coefficient increases by n times, $A_{MJ} = nA$, while the resulting pre-exponential factor is the geometric mean of corresponding pre-exponential factors, $J_{0MJ} = \sqrt[n]{J_{01}J_{02}\ldots J_{0n}}$. If an MSC is illuminated with, for example, solar radiation and the conditions for consistency in the current (i.e., the equality of photogenerated currents flowing through each series-connected p–n junction $J_{g1} = J_{g2} = \ldots = J_{gn} = J_{gMJ}$) are satisfied, we can also use the concept of the resultant p–n junction in order to describe the load j–V characteristic of an MSC under illumination. For an MSC, the load resistanceless ($R_S = 0$) current-voltage characteristic (measured under illumination) at each of considered portions has the same form as in the case of a single-junction SC (3):

$$j = J_g - J_{0MJ}\exp\left(\frac{qV_j}{A_{MJ}kT}\right). \tag{11}$$

Consequently, the efficiency of multijunction and single-junction SCs in the case of correlation between the photogenerated currents can be calculated using the same method (Subsection 2.4) as in the case of monoexponential portions (Fig. 1) of the dark J–V_j characteristic.

2.4. The Characteristic Efficiency-(Photogenerated Current) (η–J_g)

We now derive the equation relating the photogenerated current $J_g(\propto C)$ to the efficiency η. In the case of the standard approach ($R_S = 0$) [4], each exponential portion in expression (11) is analyzed separately. At the operation point (the point of optimal load), the released specific power $P = jV_j$ is at a maximum. Equating the derivative to zero $\frac{d}{dV_j}(jV_j) = 0$, where j is defined by expression (11), we obtain, as is well known [4, 7], a transcendental equation relating the open-circuit voltage V_{OC} to the resistanceless voltage at the operation point V_m:

$$u_{OC} = \ln(1 + u_m) + u_m \tag{12a}$$

or

$$\exp u_{OC} = (1 + u_m)\exp u_m. \tag{12b}$$

Here, we use the dimensionless quantities $u_m = \frac{qV_m}{AkT}$ and $u_{OC} = \frac{qV_{OC}}{AkT}$. According to (4), we have

$$J_g = J_0 \exp u_{OC}; \tag{13}$$

at the same time, we use (11) to find that, at the operation point (j_m, u_m), we obtain

$$j_m = J_g - J_0 \exp u_m. \tag{14}$$

Substituting $\exp(u_{OC})$ from (12b) into (13) and then substituting J_0 from (13) into (14), we obtain the following expression for the current density j_m:

$$j_m = J_g\left[1 - \frac{\exp u_m}{(1 + u_m)\exp u_m}\right] = J_g\frac{u_m}{1 + u_m}. \tag{15}$$

Following [4, 8] and using (15), we express the released specific power in terms of the photogenerated current and effective voltage V_η, i.e., $P_m = j_m V_m = J_g V_\eta$, where

$$V_\eta = \frac{AkT}{q}\frac{u_m^2}{1 + u_m}. \tag{16}$$

Consequently, the efficiency $\eta = \frac{P_m}{P_{inc}}$ is expressed in terms of the ratio between the effective voltage and the conversion voltage V_{conv},

$$\eta = \frac{V_\eta}{V_{conv}}. \tag{17}$$

Here, $V_{conv} = \frac{P_{inc}}{J_g} = \left(\frac{P_{inc}}{J_g}\right)_{C=1}$, where P_{inc} is the density of power of optical radiation incident on the SC. The conversion voltage V_{conv} is independent of the illumination intensity and, consequently, of the extent of concentration of the solar radiation since $J_g \propto P_{inc} \propto C$; however, this voltage depends on the spectral composition of the incident and absorbed optical radiation (AM0, AM1.5, laser radiation, and so on). The photo-

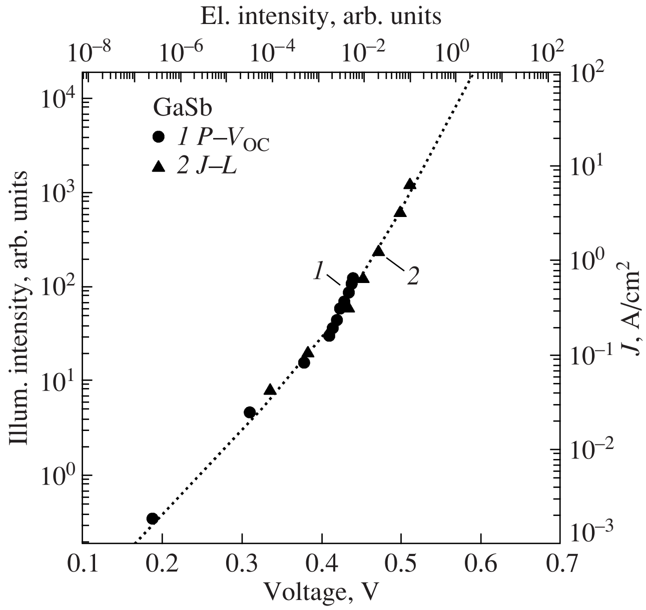

Fig. 3. (*1*) Photovoltaic P–V_{OC} and (*2*) electroluminescent J–L characteristics of a GaSb p–n junction; these characteristics were transformed into a resistanceless dark J–V_j characteristic.

generated current J_g is expressed in terms of the efficiency η. It follows from (16) that

$$u_m = \frac{1}{2}(u_\eta + \sqrt{u_\eta(u_\eta + 4)}), \quad (18a)$$

where

$$u_\eta = \frac{qV_\eta}{AkT}. \quad (18b)$$

Equalities (13), (12b), and (18a) for $J_g \propto C$ and (17) and (18b) for $V_\eta \propto \eta$ yield, as a result, the sought-for equation

$$J_g = J_0\left(1 + \frac{u_\eta + \sqrt{u_\eta(u_\eta + 4)}}{2}\right) \times \exp\frac{u_\eta + \sqrt{u_\eta(u_\eta + 4)}}{2}, \quad (19a)$$

where

$$u_\eta = \frac{qV_{\rm conv}}{AkT}\eta. \quad (19b)$$

We will use the obtained Eq. (19a) in what follows (Section 4) to plot the dependence $V_\eta(\propto\eta)$ on $J_g(\propto C)$ at various portions of the dark resistanceless J–V_j characteristics under consideration. The effect of the series resistance R_S on the efficiency is taken into account by correcting Eq. (19b): the introduced correction J_gR_S is valid at $J_g < \frac{V_{OC}}{2R_S}$ and is insignificant in the case of $R_S \longrightarrow 0$,

$$u_\eta = \frac{q(\eta V_{\rm conv} + J_gR_S)}{AkT}. \quad (19c)$$

3. DETERMINATION OF THE RECOMBINATION- AND DIFFUSION-RELATED COMPONENTS IN PHOTOACTIVE p–n JUNCTIONS BASED ON GaAs and GaSb

For the forward-current densities $J < \frac{AkT}{qR_S}$, in which case the resistanceless approximation is valid, direct measurement of the dark current and voltage makes it possible to reveal only two components (Fig. 2): the tunneling-trapping component (excess, $A > 2$) and the recombination-related component ($A = 2$). In the case of the latter component, the pre-exponential factors are typically equal to $J_{0r} = (1–5) \times 10^{-11}$ A/cm^2 (for GaAs) and $J_{0r} = (1–5) \times 10^{-5}$ A/cm^2 (for GaSb) [9]. At high current densities, we used the results reported in Subsections 2.2.1 and 2.2.2 and additionally measured two characteristics: the photovoltaic characteristic V_{OC}–P (Subsection 3.1) and the electroluminescence characteristic L–J (see Subsection 3.2), and these characteristics made it possible to derive the total resistanceless J–V_j characteristic (Fig. 2).

3.1. Dependence of the Open-Circuit Voltage on Illumination Intensity (V_{OC}–P) for GaSb p–n Junctions

The GaSb p–n structures were illuminated using a semiconductor laser (λ = 1.3 μm and $h\nu$ = 0.95 eV) with the irradiation intensity as high as 3 W/cm^2. Experimentally obtained dependences of the open-circuit voltage V_{OC} on the illumination intensity P (Fig. 3) are consistent with expression (5) and, consequently, yield the parameters P_{0r} and P_{0d}. These parameters are combined with the data on J_{0r} obtained from the experimental dark J–V characteristic.

As a result, we use expression (8a) to determine the sought-for diffusion-related pre-exponential factors J_{0d} = (5–10) × 10^{-9} A/cm^2 (GaSb). We also determined the conversion parameter χ (Subsection 2.2.3) and, as a result, we fit the V_{OC}–P characteristic to the dark J–V characteristic (Fig. 2).

3.2. The characteristic (Electroluminescence Intensity)-(Forward Current) (L–J) for p–n Junctions Based on GaAs and GaSb

Integrated intensity of luminescence was measured at room temperature with the GaAs and GaSb structures subjected to a forward pulsed current (τ = 1 μs, f =

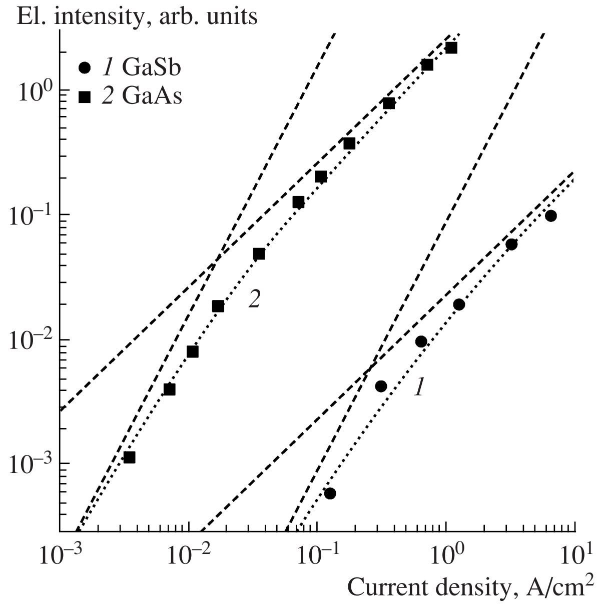

Fig. 4. Electroluminescent *J–L* characteristics of the (*1*) GaSb and (*2*) GaAs *p–n* junctions.

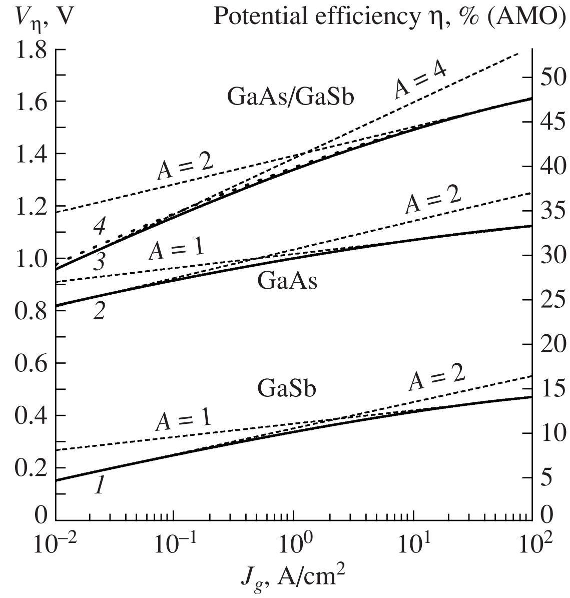

Fig. 5. Dependences of effective voltage V_η and potential efficiency η on photogenerated current for *p–n* junctions based on (*1*) GaSb, (*2*) GaAs, and (*3*) for the GaAs/GaSb tandem; curve (*4*) represents the sum of efficiencies of separate *p–n* junctions based on (*1*) GaSb and (*2*) GaAs. We used the following values of pre-exponential factors: $J_{0r} = 3.7 \times 10^{-5}$ A/cm^2 and $J_{0d} = 5.5 \times 10^{-9}$ A/cm^2 for GaSb; $J_{0r} = 1.4 \times 10^{-11}$ A/cm^2 and $J_{0d} = 1.2 \times 10^{-20}$ A/cm^2 for GaAs; and $J_{0r} = 4.5 \times 10^{-7}$ A/cm^2 and $J_{0d} = 4.1 \times 10^{-16}$ A/cm^2 for the GaAs/GaSb tandem.

1 kHz); under these conditions, the samples were not heated. In the case of the used pump densities (10^{-2}–10^2 A/cm^2), the bands of interband luminescence (and, close to these, bands of the edge luminescence) were dominant in the emission spectra, which makes it possible to use the method described above in Subsection 2.2.2. The experimentally obtained dependence of the electroluminescence intensity on the current for the GaAs and GaSb *p–n* junctions (Fig. 4) corresponded to expression (7a), i.e., the *L–J* characteristic featured two power-law portions with exponents that are equal to two and unity, and coincide with diode coefficients in the corresponding dark resistanceless J–V_j characteristic (2). The parameters k_r and k_d (7a), as was shown above (Subsection 2.2.3), are combined with pre-exponential factors J_{0r} determined from the dark *J–V* characteristic. As a result, we used expression (8b) to determine the sought-for diffusion-related pre-exponential factors: $J_{0d} = (1–10) \times 10^{-20}$ A/cm^2 (GaAs) and $J_{0d} = (5–10) \times 10^{-9}$ A/cm^2 (GaSb). We also determined the conversion factor L_0 (see Subsection 2.2.3); as a result, we managed to fit the $\log J - \log L$ characteristic to the dark $\log J - V$ characteristic (Fig. 2).

4. POTENTIAL EFFICIENCY OF SOLAR CELLS BASED ON GaAs AND GaSb *p–n* JUNCTIONS

4.1. Dependence of the Potential Efficiency of SC on the Photogenerated Current (the η–J_g Characteristic)

By potential efficiency, we mean the efficiency of either a single-junction SC or an MSC composed of *p–n* junctions with real and varying values of pre-exponential factors and diode coefficients under idealized conditions: (I) the external quantum yield in the case of the generation of a photocurrent is equal to unity ($\gamma = 1$) and (II) the SC features the zero series resistance ($R_S = 0$). The potential efficiency of an SC increases as the photogenerated current is increased [4] and, consequently, as the extent of the concentration of the incident optical radiation is increased. Using Eq. (19a), we obtained (and show in Fig. 5) the dependences of the effective voltage V_η on the photocurrent density J_g for the GaAs and GaSb *p–n* junctions and also for a GaAs/GaSb tandem composed of these series-connected *p–n* junctions. In this case (Fig. 5), the current boundaries B_{rd} (Fig. 1) between the recombination- and diffusion-related portions for GaAs and GaSb *p–n* junctions practically coincide with each other (Fig. 2). In general, these boundaries can differ. In Fig. 5, two portions of the J_g–η curve correspond to the recombination- (the lower portion) and diffusion-related (the upper portion) mechanisms of the current flow. Since the number of junctions $n = 2$, in accordance with (10b), we have the diode coefficient $A_{MJ} = 4$ and the pre-exponential factor $J_{0r(MJ)} = \sqrt{J_{0r(\mathrm{GaAs})}J_{0r(\mathrm{GaSb})}}$ within the lower portion of the characteristic while we have $A_{MJ} = 2$ and $J_{0d(MJ)} =$

Table 1

Proton fluence F_p, cm^{-2}	Potential efficiency, η (C = 1, AM0)		
	GaAs	GaSb	GaAs/GaSb
0	26.1	6.2	32
3×10^{10}	24.6	5	28.9
3×10^{11}	23.9	3.5	26.5
3×10^{12}	22.2	2.5	23.5

Note: Proton energy E_p = 6.78 MeV.

Table 2

Electron fluence F_e, cm^{-2}	Recombination preexponential factor J_{0r}, A/cm^2	Potential efficiency, η (C = 1, AM0) %
0	1.3×10^{-11}	26.2
3×10^{14}	2.6×10^{-11}	25.3
3×10^{15}	6.9×10^{-11}	23.9
3×10^{16}	1.9×10^{-10}	22.5

Note: Electron energy E_e = 1 MeV; GaAs p–n junction.

$\sqrt{J_{0d(\mathrm{GaAs})}J_{0d(\mathrm{GaSb})}}$ within the upper portion. Dependences of potential efficiencies on the photocurrent $J_g(\propto C)$ were obtained by multiplication of V_η by the proportionality coefficient $1/V_{\mathrm{conv}}$ (17) that corresponds to the actual conditions of illumination (AM0). Under the condition that the series-connected GaAs and GaSb p–n junctions are well fitted to each other with respect to the current, the conversion coefficient $1/V_{\mathrm{conv}}$ is the same for all three cases under consideration: $V_{\mathrm{conv}} = \frac{P_{\mathrm{inc}}}{J_g} = 3.4$ V, $P_{\mathrm{inc}}|_{C=1} = 136.5$ mW/cm^2, and $J_g|_{C=1} = 40$ mA/cm^2 (the result of calculation at $\gamma = 1$).

The curves shown in Fig. 5 were obtained in analogy with the dark resistanceless J–V_j characteristic, i.e., by summing the photogenerated currents calculated separately with the use of recombination- or diffusion-related parameters. It is worth noting that the sum of potential efficiencies for independently operating (connected to separate loads) SCs based on the GaAs and GaSb p–n junctions is somewhat larger than the efficiency of the GaAs/GaSb tandem (Fig. 5, Table 1). This statement is valid under the condition that autonomously operating GaSb p–n junction is found in the same state of illumination as in the case of the GaAs/GaSb tandem; i.e., the spectrum of incident radiation is limited from the short-wavelength side by the condition of passage through the GaAs filter.

4.2. Reduction of the Potential Efficiency of a SC in the Case of the Radiation-Induced Degradation of the J–V_j Characteristic

An increase in the pre-exponential factor J_0 (including an increase in the resulting J_{0MJ} (10b) brings about a decrease in the efficiency η as can be seen from Eq. (19). In practice, an increase in J_0 in photoactive p–n junctions can be caused by conditions of growth of the SC structures, postgrowth technological factors, and also the effect of damaging irradiations.

Irradiation of photoactive GaAs and GaSb p–n junctions with high-energy protons and electrons increases the recombination-related pre-exponential factor J_{0r} [9]. As can be seen from Fig. 5, it is the J_{0r} that governs the efficiency of the GaAs and GaSb photoactive junctions in the case of nonconcentrated ($C \le 1$) solar radiation. Therefore, C = 1, a decrease in the calculated potential efficiency is mainly caused by an increase in the J_{0r}. In Table 1, we list the results of the potential efficiency for p–n junctions based on GaAs and GaSb and for a tandem on the basis of these p–n junctions in the case of irradiation with 6.78-MeV protons. In Table 2, we list the corresponding results for GaAs p–n junctions irradiated with 1-MeV electrons. The photogenerated current J_g = 40 mA/cm^2 used in calculations of efficiencies (Tables 1, 2) corresponds to the idealized photocurrent at C = 1, AM0. The values of J_{0r} were taken from [9]. In contrast to previous calculation (see Subsection 4.1), Eqs. 19a, 19b was not used in the present calculation; rather, we calculated in sequence the following quantities: u_{OC} (using equality (13)), u_m (from solution of transcendental Eq. (12)), V_η (from (16)), and η (from (17)).

5. CONCLUSIONS

As we showed, the multijunction solar cells exhibit the dark resistanceless J–V_j characteristic with the features the same as that of single-junction solar cells: the dark current is the sum of exponential components each of which includes a specific pre-exponential factor $J_{0(MJ)}$ and a specific diode coefficient A_{MJ}. This similarity of characteristics made it possible to use and develop the same analytical method for calculating the efficiency of both the single-junction and multijunction solar cells.

We derived an equation that relates the photogenerated current to the efficiency of an SC at specified values of the pre-exponential factors J_0 and diode coefficients A determined from the dark resistanceless J–V_j characteristic of the SC. As a consequence, the fitted photogenerated current includes the same number of components as the dark current and, presumably, is represented by the sum of corresponding components, similarly to the case of the dark current.

For the GaAs and GaSb p–n junctions, we obtained resistanceless (with the series resistance of the structure disregarded) J–V_j characteristics, which were used to form the J–V_j characteristic of the GaAs/GaSb tandem. The obtained characteristics were used in calculations of the potential efficiency (i.e., in the case of idealization, the external quantum yield equals unity and the series resistance equals zero).

It is established that, as the illumination intensity is decreased, the contribution of the recombination component to the photogenerated current increases. Consequently, in the case of unconcentrated solar radiation ($C = 1$), the SC efficiency is mainly controlled by the recombination mechanism of the current flow.

Irradiation with 1-MeV electrons and 6.78-MeV protons increases the pre-exponential factor, which brings about a decrease in the efficiency in the case of unconcentrated solar radiation.

As it follows, in particular, from the derived Eq. (19), the efficiency for both the single-junction and multijunction SC decreases with the increasing pre-exponential factor J_0, including the resultant factor $J_{0(MJ)}$. Correspondingly, one observes a decrease in the efficiency η for the GaAs and GaSb p–n junctions and for the GaAs/GaSb tandem formed of them.

For the single-junction and multijunction solar cells irradiated with unconcentrated solar light ($C = 1$), the efficiency of an MSC is mainly governed by the recombination mechanism of the current flow; however, in some cases, one should also take into account the tunneling-trapping mechanism (the latter predominantly manifests itself in a wide-gap photoactive p–n junction of an MSC.

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