*Semiconductor Physics, Quantum Electronics & Optoelectronics, 2005. V. 8, N 1. P. 72-78.*

PACS: 73.40.-c, 84.60.It

# Experimental study and theoretical analysis of photoelectric characteristics of $Al_xGa_{1-x}As$–*p*-GaAs–*n*-GaAs-based photoconverters with relief interfaces

**N.L. Dmitruk, O.Yu. Borkovskaya, V.P. Kostylyov, A.V. Sachenko, I.O. Sokolovskiy**

*V. Lashkaryov Institute of Semiconductor Physics, NAS of Ukraine, 45, prospect Nauky, 03028 Kiyv, Ukraine*

**Abstract.** We studied experimentally the photoelectric characteristics of the $Al_xGa_{1-x}As$–*p*-GaAs–*n*-GaAs structures with relief interfaces. A theoretical analysis of spectral dependences of internal quantum efficiency of short-circuit current in the above solar cells (SC) was performed. In particular, the low-energy spectral region (where absorption is weak) was considered. A comparison was made between the experimental and theoretical photocurrent spectral curves. From it, we determined a number of parameters of the $Al_xGa_{1-x}As$ and GaAs *p*-layers, as well as of the *n*-GaAs layers. Some recommendations concerning the ways to increase photocurrent and extend photosensitivity spectral region were developed for technologists. A theoretical analysis of a "spotty" model for open-circuit voltage formation in relief $Al_xGa_{1-x}As$–*p*-GaAs–*n*-GaAs-based SC was made. This model enables one to give a qualitative explanation for decrease of open-circuit voltage in relief SC as compared to the case of flat interface.

**Keywords:** $Al_xGa_{1-x}As$–GaAs heterojunctions, solar cells, interface relief, photoelectric characteristics, short-circuit current, open-circuit voltage, internal quantum efficiency.

Manuscript received 30.11.04; accepted for publication 18.05.05.

## 1. Introduction

The relief $Al_xGa_{1-x}As$–*p*-GaAs–*n*-GaAs-based solar cells (SC) are of interest because they (i) enable one to minimize photocurrent losses related to light reflection from front surface, and (ii) demonstrate the wide-gap window effect that makes it possible to reduce the effect of surface recombination on photocurrent and photovoltage. When developing manufacturing technology for such photoconverters, one should optimize doping levels and thicknesses of the $Al_xGa_{1-x}As$ and GaAs *p*-layers, as well as doping level in the buffer *n*-GaAs layer.

The state-of-the-art in the current knowledge of operation principles, design and perfomance of gallium arsenide SC with relief surface and $Al_xGa_{1-x}As$–*p*-GaAs–*n*-GaAs-based SC is discussed in the reviews [1] and [2], respectively. There exist a number of studies dealing with photoconversion in gallium arsenide Schottky contacts with relief surface (see, e.g., [1, 3-5]). Much less papers deal with investigation of relief $Al_xGa_{1-x}As$–*p*-GaAs–*n*-GaAs-based SC [6].

Here we present the results of our studies of the photoelectric characteristics inherent to $Al_xGa_{1-x}As$–*p*-GaAs–*n*-GaAs structures with relief interfaces. Based on the approach developed in [6], we made a theoretical analysis of spectral dependencies of the internal quantum efficiency of short-circuit current (IQE) in the above SC. In particular, the low-energy spectral region (where absorption is weak) is considered. A comparison is made between the experimental and theoretical photocurrent spectral curves. From it, we determined a number of parameters of the $Al_xGa_{1-x}As$ and GaAs *p*-layers, as well as of the *n*-GaAs layers. Some recommendations concerning the ways to increase photocurrent and extend photosensitivity spectral region were developed for technologists.

We analyze theoretically a possible model for reduction of open-circuit voltage $V_{OC}$ in relief SC with $Al_xGa_{1-x}As$–GaAs heterojunction as compared to the case of flat SC. This is the so-called "spotty" model for $V_{OC}$ formation in relief SC. According to this model, the hole concentrations in flat and relief areas of the *p*-GaAs layer are different.

## 2. Spectral characteristics of photocurrent in the low-energy range of fundamental absorption

Bearing in mind determination of recombination parameters for SC made on the basis of $Al_xGa_{1-x}As$–*p*-GaAs–*n*-GaAs heterojunction, we studied experimentally the spectra of short-circuit current $J_{SC}$ in a number of SC samples made with LPE technique. After this, we performed a theoretical analysis of the obtained $J_{SC}(\lambda)$ curves to determine the characteristic diffusion lengths of nonequilibrium charge carriers.

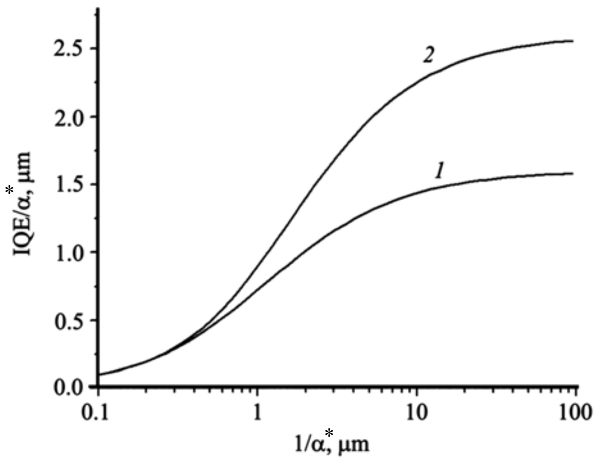


**Fig. 1.** Theoretical dependences of the internal quantum efficiency of short-circuit current IQE (in the region of no absorption in $Al_xGa_{1-x}As$) divided by the effective coefficient of light absorption $\alpha^*$ on $1/\alpha^*$. The following values of parameters $d_{p2}$, $w$ and $L_p$ are used: curve 1 – 0.5, 0.1 and 1; curve 2 – 1.5, 0.1 and 1, respectively.

Let us consider the case when (i) the photon energy is below the $Al_xGa_{1-x}As$ bandgap (so one can neglect light absorption in the $Al_xGa_{1-x}As$ layer of the thickness $d_{p1}$ and electron diffusion length $L_{n1}$, (ii) the *p*-GaAs layer thickness, $d_{p2}$, is small as compared to the electron diffusion length in this layer, $L_{n2}$, and (iii) the *n*-GaAs layer thickness is big as compared to the hole diffusion length in this layer, $L_p$. Then one can easily show that the spectral dependence of the short-circuit current density in an $Al_xGa_{1-x}As$–*p*-GaAs–*n*-GaAs-based SC illuminated with monochromatic light is of the following form:

$$J_{SC}(\alpha^*) = qI_0(\lambda)(1-R(\lambda))\times \times\frac{\alpha^* L_p + 1 - \exp(-\alpha^*(d_{p2}+w))}{\alpha^* L_p + 1}. \quad (1)$$

Here $\lambda$ is the light wavelength; $\alpha^*$ is the effective coefficient of light absorption in GaAs; $q$ is the electron charge; $I_0(\lambda)$ is the intensity of illumination; $R(\lambda)$ is the coefficient of light reflection; $w$ is the space-charge region (SCR) width.

It should be noted that for relief gallium arsenide SC the effective coefficient of light absorption $\alpha^* = f a$ ($f > 1$), i.e., $\alpha^*$ is somewhat larger than the $\alpha$ value in the case of normal light incidence onto the SC surface. The reason for this is that photon path is longer in the case of oblique incidence. The numerical coefficient $f$ depends on the relief type and degree of SC filling with it. In the ray optics approximation, it varies between 1 and 1.3 [6].

In the region of weak light absorption in GaAs, Eq. (1) for the spectral dependence of the short-circuit current density in an $Al_xGa_{1-x}As$–*p*-GaAs–*n*-GaAs-based SC becomes much simpler:

$$J_{SC}(\alpha^*) \approx qI_0(\lambda)(1-R(\lambda))\alpha^*(d_{p2}+w+L_p). \quad (2)$$

If the *p*-GaAs layer thickness is much over the electron diffusion length ($d_{p2} >> L_{n2}$), then the expression for the spectral dependence of short-circuit current density in the region of weak light absorption in GaAs can be obtained from Eq. (2) by replacing $d_{p2}$ with $L_{n2}$. This means that, if the strong inequality $d_{p2} << L_{n2}$ (or $d_{p2} >> L_{n2}$) is valid in the region of weak light absorption in GaAs, the ratio $J_{SC}(\alpha^*)/qI_0(\lambda)(1-R(\lambda))\alpha^*$ is equal to $(d_{p2}+w+L_p)$ (or $(L_{n2}+w+L_p)$).

Shown in Fig. 1 are the theoretical $IQE/\alpha^* = J_{SC}(\alpha^*)/qI_0(\lambda)(1-R(\lambda))\alpha^*$ curves plotted using Eq. (1). At small $\alpha^*$ values, they really go to the total value $(d_{p2}+w+L_p)$. It should be noted that one has to know the absolute values of $I_0(\lambda)$ and $R(\lambda)$ to realize experimentally the possibility of determination of the total value $(d_{p2}+w+L_p)$ (or $(L_{n2}+w+L_p)$).

Starting from Eq. (1), one can obtain for the inverse short-circuit current density normalized to the number of absorbed photons the following expression (in coordinates $\nu = 1/\alpha^*$):

$$qI_0(\lambda)(1-R(\lambda))/J_{SC}(\nu) = = \frac{L_p + \nu}{L_p + \nu(1-\exp(-(d_p+w)/\nu))}. \quad (3)$$

One can see that $\nu_x = -L_p$ at a point $\nu_x$ where $qI_0(\lambda)(1-R(\lambda))/J_{SC}(\nu) \to 0$.

Fig. 2a presents the theoretical curves of the inverse short-circuit current density on $\nu$ normalized to the number of absorbed photons (plotted using Eq. (3)) and their cut off lengths by the $\nu$ axis. One can see that the cut off length is over $\nu_x$, i.e., the cut off length magnitude exceeds $L_p$. Our analysis showed that the bigger is $(d_{p2}+w)$ as compared to $L_p$, the bigger is this distinction. And when $(d_{p2}+w) \le L_p$, the error in determination of $L_p$ in the range of its variation from 0.5 up to 5 μm does not exceed 30 %.

Thus, knowing the cut off length of the inverse short-circuit current density (normalized to the number of absorbed photons) on $\nu$ curve plotted in coordinates $1/\alpha$ enables one to determine the upper bound on the hole diffusion length $L_p$ in *n*-GaAs. The smaller is the total value of $(d_{p2}+w)$ (or $(L_{n2}+w)$) as compared to $L_p$, and the closer is $f$ to unity, the closer is the obtained value to $L_p$. Similar technique for determination of charge carrier diffusion length in surface-barrier

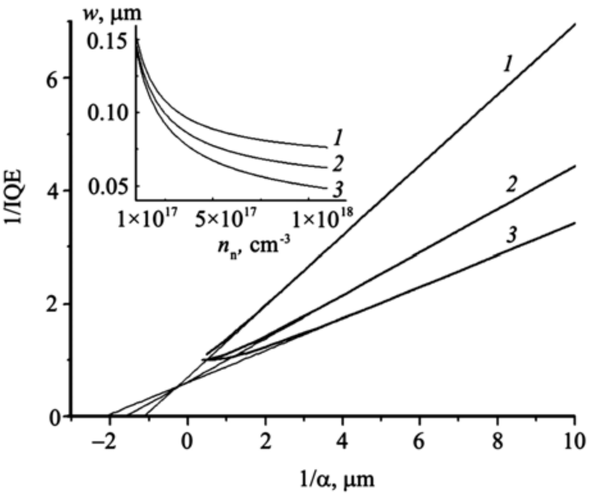


**Fig. 2a.** Theoretical dependences of the inverse internal quantum efficiency of short-circuit current 1/IQE (in the region of no absorption in $Al_xGa_{1-x}As$) on the inverse coefficient of light absorption. The following values of parameters $d_{p2}$, $w$ and $L_p$ are used: curve 1 – 0.5, 0.1 and 1; curve 2 – 1.5, 0.1 and 1; curve 3 – 1.5, 1 and 1, respectively. Inset: theoretical dependences of the SCR width $w$ in the gallium arsenide *p-n* junction on the doping level $n_n$ of the *n*-region at $T = 300$ K. $p_p$ value: curve 1 – $5\cdot10^{17}$; curve 2 – $10^{18}$; curve 3 – $5\cdot10^{18}$ cm$^{-3}$.

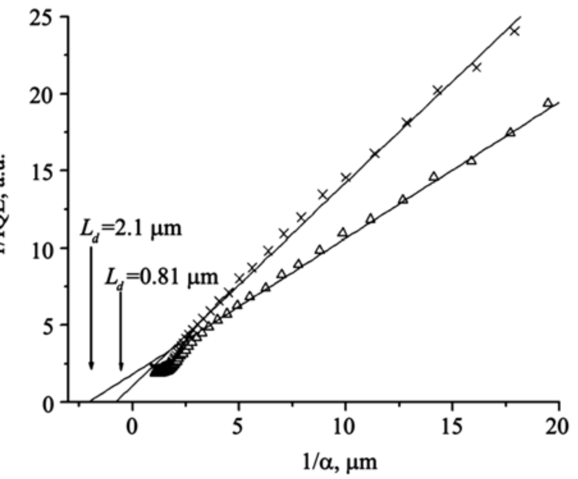


**Fig. 2b.** Experimental and (fitted to them) theoretical dependences of the inverse internal quantum efficiency of the short-circuit current $1/\mathrm{IQE}$ (in the region of no absorption in $Al_xGa_{1-x}As$) on the inverse coefficient of light absorption. $L_p$ value: curve 1 – 0.81; curve 2 – 2.1 μm.

structures from spectral dependences of small-signal photovoltage was proposed earlier in [7].

The SCR width $w$ depends on the doping level in the *p*- and *n*-GaAs regions. In optimized SC made on the basis of $Al_xGa_{1-x}As$–*p*-GaAs–*n*-GaAs heterojunction, $w$ lies, as a rule, below $d_{p2}$ and $L_p$. A $w$ value can be determined if one knows the doping levels. Shown in Fig. 2a (inset) are the $w$ dependences on the doping level in *n*-GaAs (at different values of the doping level in *p*-GaAs region) calculated at $T = 300$ K from the following expression:

$$w = \left[3.75\times10^5 \frac{n_n + p_p}{n_n p_p} \ln\left(\frac{n_n p_p}{n_i^2}\right)\right]^{1/2} \text{ [cm].} \qquad (4)$$

Here $n_n$ ($p_p$) is the equilibrium concentration of electrons (holes) in the *n*(*p*)-GaAs region (measured in cm$^{-3}$); $n_i$ is the charge carrier concentration in intrinsic GaAs (also measured in cm$^{-3}$). One can see from Fig. 2a (inset) that $w$ varies from $1.5\cdot10^{-5}$ down to $5\cdot10^{-6}$ cm as $n_n$ increases from $10^{17}$ up to $10^{18}$ cm$^{-3}$ (this corresponds to the results obtained from the capacitance measurements, with allowance made for a higher doping degree in the *p*-GaAs layer) and is less than $L_p$ by a factor of at least three.

Shown in Fig. 2b are the experimental spectral curves 1/IQE (the inverse short-circuit current $I_{SC}$ normalized to the same number of incident photons) as function of $1/\alpha$. The $L_p$ values for different SC samples (obtained from the cut off length on the abscissa) are presented in Table 1. One can see that, for the SC samples studied, these values lie between 0.5 and 2 μm. And, correspondingly, the hole diffusion velocity $V_p = D_p / L_{p2}$ varies from $1.4\cdot10^5$ down to $3.5\cdot10^4$ cm/s for different samples (at $D_p = 7$ cm$^2$/s).

**Table 1. The experimental cutoff values for the inverse short-circuit current $I_{SC}$ (normalized to the same number of incident photons) vs $1/\alpha$ curves (D – dendrite-like, QG – quasi-grating-like).**

| Sample N | Interface relief | Cutoff, μm |
|---|---|---|
| 129 | flat | 2.1 |
| 42p | flat | 2.5 |
| 44p | flat | 1.5 |
| 45p | flat | 2.2 |
| Mc-1 | flat | 0.81 |
| M-21 | D | 1.8 |
| M-22 | D | 1.26 |
| M01-C2.1 | QG | 1.85 |
| M02-C2 | QG | 3 |

**Table 2. Some parameters of SC samples with flat and relief interfaces between the *p*- and *n*-regions (D – dendrite-like, QG – quasi-grating-like).**

| Sample N | Structure | Interface relief | $x$ | $d_{p1}$, μm | $\tau_{n1}$, $10^{-10}$ s | $d_{p2}$, μm | $\tau_{n2}$, $10^{-10}$ s | $\tau_p$, $10^{-10}$ s |
|---|---|---|---|---|---|---|---|---|
| 145AK | heterojunction | QG | 0.47 | 2 | 0.5–1 | 1.6–2 | 4–10 | 15 |
| 146AK | heterojunction | flat | 0.73 | 2 | 0.3 | 2 | 1.2 | 3 |
| MO-13C1 | *p-n* junction | D | | | | 1.3 | 2 | 1 |
| MO-10C1 | *p-n* junction | flat | | | | 1.5 | 0.5 | 0.3 |

Both the hole diffusion length and diffusion velocity values determined from them are higher than those obtained in [3]. This seems to be due to better quality of the LPE-grown *n*-GaAs layer.

### 3. Mechanisms of photosensitivity formation in relief $Al_xGa_{1-x}As$–GaAs-based solar cells

We investigated the spectral characteristics of photosensitivity inherent to a number of SC samples made using $Al_xGa_{1-x}As$–*p*-GaAs–*n*-GaAs system and gallium arsenide *p-n* junctions (without a wide-gap window). We studied experimentally the spectral dependences of the external quantum efficiency and coefficient of light reflection from the illuminated sample surfaces, as well as measured short-circuit current under AM0 conditions. Then we calculated the spectral dependence of the internal quantum efficiency of photocurrent from the above data. After this the experimentally obtained spectral dependences for internal quantum efficiency were fitted to the theoretical ones presented in [6].

A comparison between the results of measurements for relief and flat SC samples was performed for the samples obtained using the same LPE technique. The experimental and theoretical spectral dependences of the internal quantum efficiency of photocurrent for two samples (with relief and flat interfaces) of SC made using the $Al_xGa_{1-x}As$–*p*-GaAs–*n*-GaAs system are shown in Fig. 3.

Before presenting the parameters obtained and discussing the results, let us dwell on the principal aspects of classification of spectral dependences of the external quantum efficiency in the $Al_xGa_{1-x}As$–*p*-GaAs–*n*-GaAs system by its response value and shape. First of all, to achieve the internal quantum efficiency value close to unity practically in the whole photosensitivity region of GaAs, as well as $Al_xGa_{1-x}As$, the following inequalities are to be fulfilled: $d_{p1}/L_{n1} < 1$ and $d_{p2}/L_{n2} < 1$.

If the inequalities $d_{p1}/L_{n1} > 1$ and $d_{p2}/L_{n2} < 1$ are fulfilled, then the maximal value (close to unity) of the internal quantum efficiency is achieved in the GaAs absorption region only; in the $Al_xGa_{1-x}As$ absorption region the quantum efficiency decreases as light wavelength goes down. The stronger is the inequality $d_{p1}/L_{n1} > 1$, the more abrupt is drop of photosensitivity. This is related to the fact that, as the ratio $d_{p1}/L_{n1}$ increases, more and more electron-hole pairs produced in the $Al_xGa_{1-x}As$ layer recombine before reaching the *p-n* junction. As the aluminum fraction in the $Al_xGa_{1-x}As$ layer (i.e., $x$ value) grows, the spectral width of the photosensitivity increases, up to its peak at $x = 1$.

If the inequalities $d_{p1}/L_{n1} > 1$ and $d_{p2}/L_{n2} > 1$ are fulfilled (i.e., the thicknesses of $Al_xGa_{1-x}As$ and GaAs layers are big as compared to the electron diffusion lengths in them), then the internal quantum efficiency is below unity over the whole spectral range of photosensitivity. The stronger are the above inequalities, the smaller is its maximal value.

In the case of SC made on the basis of gallium arsenide *p-n* junctions, the *p*-layer thickness should be less than the electron diffusion length in it for providing the maximal value of the internal quantum efficiency (close to unity).

The value $S$ of the surface recombination velocity at the illuminated SC surface may for sure provide a high-energy drop of photosensitivity only if the thickness of the $Al_xGa_{1-x}As$ layer in SC with a heterojunction, or the *p*-GaAs layer thickness in gallium arsenide photoconverters, is small as compared to the electron diffusion length in the corresponding layer. If the above thicknesses are comparable to the corresponding diffusion lengths, then high-energy drop of photosensitivity may be determined by surface recombination velocity and, as well, by recombination of the electron-hole pairs produced in the bulk of the corresponding layer. And in the case when the layer thicknesses far exceed the corresponding electron diffusion length, low-energy drop of photosensitivity is provided by recombination of the electron-hole pairs produced in the bulk of the corresponding layer only.

Table 2 presents, in pairs, the photosensitivity characteristics of four typical samples of SC made using the $Al_xGa_{1-x}As$–*p*-GaAs–*n*-GaAs and *p*-GaAs–*n*-GaAs systems, with relief and flat interfaces. The data on the aluminum content $x$ and *p*-$Al_xGa_{1-x}As$ layer thickness were obtained from X-ray studies. The hole diffusion

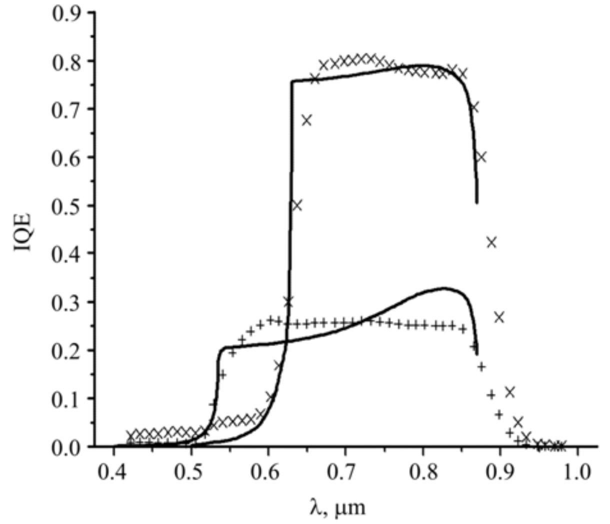


**Fig. 3.** Experimental and (fitted to them) theoretical dependences of the internal quantum efficiency of the short-circuit current on the wavelength of incident light for SC with relief (× – sample N 145 AK) and flat (+ – sample N 146 AK) interfaces.

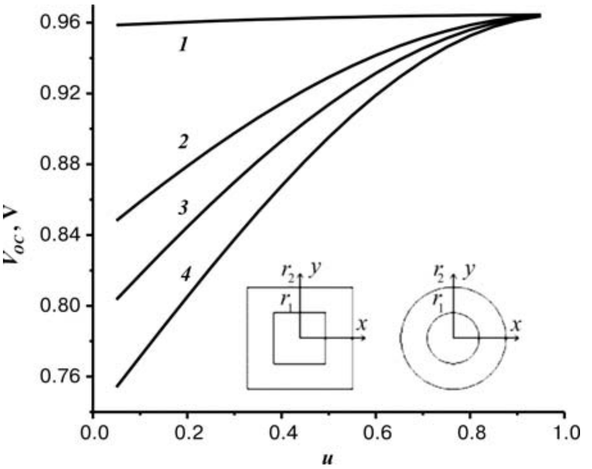


**Fig. 4.** Theoretical dependences of the open-circuit voltage in relief SC at linear (curves 1) and exponential (curves 2–4) decay of the hole concentration in the *p*-layer under relief on the ratio $u = A_p / A$ between the areas of relief and flat regions. $m = 10^{-7}$ (1); $\cdot 10^{-7}$ (2); $10^{-9}$ (3); $10^{-11}$ (4). Insets (a) and (b): cells for relief and flat regions when the relief building blocks are square and disk.

lengths in *n*-GaAs were determined from the cut off length of the inverse quantum efficiency as a function of the inverse absorption coefficient. From their values, we calculated the hole lifetimes in *n*-GaAs. Other parameters were determined by fitting the experimental and theoretical values for spectral dependences of the internal quantum efficiency in different samples.

One can see from Table 2 that charge carrier lifetimes in *p*- and *n*-layers of relief SC are longer than those in SC with flat surface. We believe that this is related to the fact that, when relief is formed with anisotropic etching, the areas with high defect concentrations are etched off primarily.

Our estimations of charge carrier diffusion lengths in *p*-layers (using the obtained charge carrier lifetimes and diffusion coefficient values taken from handbooks) showed that their typical values vary between 0.1 and 1 μm. In all the cases (except for the sample N 145AK where the diffusion length in the *p*-GaAs layer was about 2 μm) the inequalities $d_{p1} / L_{n1} > 1$ and $d_{p2} / L_{n2} > 1$ are valid, i.e., the maximal values of the internal quantum efficiency are below unity. The photosensitivity region of the relief sample N 145AK is much narrower than that of the sample N 146AK with flat surface. This fact is related to a big decrease of *x* for the relief sample as compared to that for the flat sample.

Due to the above reasons, we managed to estimate the surface recombination velocity $S$ for the relief sample N MO-13C1 of gallium arsenide SC. It turned out to be close to $5 \cdot 10^5$ cm/s. This value exceeds the typical ones for relief SC with Schottky contact. The reason for this fact seems to be as follows. In the case of a *p-n* junction, the planes where recombination and separation of electron-hole pairs by electric field do not coincide, contrary to the case of a SC with Schottky contact where surface recombination occurs in the high electric field region.

The maximal internal quantum efficiency (≈ 0.8) was achieved for the relief sample N 145AK. To further increase this value and extend the photosensitivity region, one should decrease thicknesses of *p*-layers of $Al_xGa_{1-x}As$ and GaAs (particularly that of *p*-$Al_xGa_{1-x}As$) down to their optimal values.

## 4. Theoretical analysis of open-circuit voltage in solar cells with relief interfaces

We studied experimentally open-circuit voltage $V_{OC}$ in microrelief SC made on the basis of the $Al_xGa_{1-x}As$–*p*-GaAs–*n*-GaAs system using LPE-technique. It was found that in some cases $V_{OC}$ values decreased (down to 0.6–0.7 V) as compared to those obtained for SC with flat interface. One of possible explanations for such decrease is an assumption that wetting of a relief substrate with a solution-melt went down. As a result, the hole concentrations in *p*-GaAs layers decreased. In this case, one can apply the "spotty" structure model of microrelief interface to analyze the effect of $V_{OC}$ reduction.

According to the "spotty" structure model of microrelief interface, SC of different areas and with different $\overline{V}_{OC}$ values are connected in parallel. Then the expression for the open-circuit voltage averaged over surface is of the following form:

$$\bar{V}_{OC} = \left( \sum_{i=1}^{n} \frac{A_i}{A} \cdot \frac{1}{V_i} \right)^{-1} . \quad (5)$$

Here $A_i$ is the area of the $i$-th structure element with the $i$-th value of the hole concentration in the $p$-GaAs layer, and $A$ is the total area. When obtaining Eq. (5), it was also assumed that the short-circuit current density is the same for all SC.

In what follows, we shall use a specific dependence of the hole concentration $p$ in the $p$-GaAs layer inside the relief region on the coordinate $y$ that is parallel to the interface plane. Let relief be a tetrahedral pyramid with square base (see Fig. 4, inset a). We consider the following two cases: $p$ value is continuously decreasing from relief edge toward its middle part according to the linear or exponential law:

$$p(x) = p_{\rm fl}(1 - k_1 x)\,, \qquad p(y) = p_{\rm fl}(1 - k_1 y) \quad (6)$$

$$p(x) = p_{\rm fl}\exp(-k_2 x)\,, \quad p(y) = p_{\rm fl}\exp(-k_2 y)\,, \quad (7)$$

where $p_{\rm fl}$ is the hole concentration at the grain edge or in the areas with flat interface; $k_1$ and $k_2$ are some coefficients. At the relief center (at the point $x = 0$, $y = 0$) the hole concentration is less than $p_{\rm fl}$ by a factor $m$.

With allowance made for the above and assuming that all the cells with relief are identical, one may present Eq. (5) in the following way:

$$\bar{V}_{OC} = \left( u \frac{1}{V_p} + \int_0^{\sqrt{1-u}} \int_0^{\sqrt{1-u}} \frac{dxdy}{V(p(x,y))} \right)^{-1} . \quad (8)$$

Here $u = A_p / A$ where $A_p$ is the flat section area. $V(p(x,y)$ is determined from the condition of vanishing of the total current under illumination (the open-circuit mode):

$$I_{\rm ph} = I_d(p(x,y))\exp\left(\frac{qV(p(x,y))}{kT}\right) + I_r(p(x,y))\exp\left(\frac{qV(p(x,y))}{2kT}\right), \quad (9)$$

where $I_{\rm ph}$, $I_d$ and $I_r$ are, correspondingly, the densities of the (short-circuit) photocurrent and dark saturation currents of the diffusion and recombination components of the total current. The quantities $I_d$ and $I_r$ are defined as in [6]

$$I_d = \left[ \frac{qn_i^2}{p} \frac{D_n}{L_n} \frac{\sinh(d_2/L_n) + (SL_n/D_n)\cosh(d_2/L_n)}{(SL_n/D_n)\sinh(d_2/L_n) + \cosh(d_2/L_n)} + \frac{qn_i^2}{n_n} \frac{D_p}{L_p} \right], \quad (10)$$

$$I_r \approx \frac{qw(p)n_i}{\tau_p} \frac{\pi}{2} \frac{kT}{q(V_b - \bar{V}_{OC})}\,, \quad (11)$$

where $n_i$ is the electron concentration in intrinsic gallium arsenide; $w$ is the SCR width determined from Eq. (4); $V_b$ is the barrier height in $p$-$n$ junction.

The dependences of $\bar{V}_{OC}$ on the ratio between the areas of flat and relief sections are shown in Fig. 4. One can see (curve 1) that, when the hole concentration varies linearly with coordinate in the relief region, relative decrease of $\bar{V}_{OC}$ is small (does not exceed 1.5 %). If the hole concentration in the $p$-region under relief decreases exponentially, then $\bar{V}_{OC}$ decay is much more considerable: the smaller is $m$ (the ratio between the hole concentrations in the plane, or at a point, in the middle of relief and at flat sections), the more pronounced is that decay (curves 2, 3 and 4).

For the sake of comparison, the dependences of $\bar{V}_{OC}$ on the ratio between the areas of flat and relief sections when relief sections are polyhedral pyramids whose bases are close to discs are also shown in Fig. 4. Curve 1 corresponds to linear decrease of the hole concentration towards the middle part of the relief, while curves 2, 3 and 4 – correspond to exponential decrease. The dependences $\bar{V}_{OC}(u)$ are the same for square and round regions of the relief. This is related to the fact in both cases the ratios between the flat and relief areas are the same.

The $\bar{V}_{OC}$ values obtained in the "spotty" surface model enable one to qualitatively explain open-circuit voltage spreading that is observed experimentally in the case of microrelief AlGaAs–GaAs interface.

## 5. Conclusions

We studied, both experimentally and theoretically, the spectral dependences of internal quantum efficiency of photocurrent in relief SC made on the basis of the $Al_xGa_{1-x}As$–$p$-GaAs–$n$-GaAs system. From a comparison between the experimental results and theoretical expressions, we obtained the values of both the electron diffusion length in the $p$-layers of $Al_xGa_{1-x}As$ and GaAs and thicknesses of these layers, as well as the hole diffusion length in the $n$-GaAs layer. It is shown that one should reduce the thicknesses of $p$-$Al_xGa_{1-x}As$ and $p$-GaAs layers down to the optimal values to extend the photosensitivity spectral region and increase the internal quantum efficiency in the SC samples obtained with the same LPE-technique.

A theoretical analysis is made of the "spotty" model of open-circuit voltage formation in relief SC made on the basis of $Al_xGa_{1-x}As$–$p$-GaAs–$n$-GaAs system. This model enables one to give qualitative explanation for reduction of open-circuit voltage in relief SC as compared to the case of flat interface.

**Acknowledgment**

This work was partially supported by the STCU Grant U-56(J).

*References*

1. N.L. Dmitruk, I.B. Mamontova, Photoelectric converters of solar radiation with textured surface // *Optoelektronika i Poluprovodnikovaya Tekhnika* **35**, p. 67-90 (2000).
2. Zh.I. Alferov, V.M. Andreev, V.D. Rumyantsev, Trends and prospects for development of solar photoenergetics // *Phys. Tekhn. Poluprov*. **34** (8), p. 937-947 (2004).
3. N.L. Dmitruk, O.Yu. Borkovskaya, S.V. Mamykin, Measuring of minority charge carrier diffusion length using actual Schottky barriers // *Phys. Tekhn. Poluprov.* **31** (7), p. 781-785 (1997).
4. N.L. Dmitruk, O.Yu. Borkovskaya, I.B.Mamontova, S.V. Mamykin, Texturized interface as a basis of surface-barrier heterostructure for solar cells application // *Solar Energy Materials and Solar Cells*. **60,** p. 379-390 (2000).
5. N.L. Dmitruk, O.Yu. Borkovskaya, I.N. Dmitruk, S.V. Mamykin, Zs.J. Horvath, I.B. Mamontova // Morphology and interfacial properties of microrelief metal-semiconductor interface // *Appl. Surf. Sci*. **190,** p. 455-460 (2002).
6. O.Yu. Borkovskaya, N.L. Dmitruk, V.G. Lyapin, A.V. Sachenko, Computer simulation of the photocurrent collection coefficient in solar cells based on the textured thin-film AlGaAs–GaAs heterostructure // *Thin Solid Films* **451-452,** p. 402 (2004).
7. N.L. Dmitruk, Yu.V. Kryuchenko, V.G. Popov, V.G. Litovchenko, M.A. Stepanova, Diffusion length determination by the surface photovoltage method // *Phys. status solidi* (*a*) **124**, p. 183-189 (1991).