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PHYSICS
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Properties of Interfaces in GaInP Solar Cells

A. S. Gudovskikh[a]^, N. A. Kalyuzhnyy[b], V. M. Lantratov[b], S. A. Mintairov[b], M. Z. Shvarts[b], and V. M. Andreev[a,b]

[a] *St. Petersburg Physics and Technology Centre for Research and Education, Russian Academy of Sciences, St. Petersburg, 195220 Russia*

^e-mail: gudovskikh@edu.ioffe.ru

[b] *Ioffe Physicotechnical Institute, Russian Academy of Sciences, St. Petersburg, 194021 Russia*

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Abstract—The effect of the properties of interfaces with Group-III phosphides on characteristics of GaInP solar cells has been studied. It is shown that the large valence band offset at the *p*-GaAs/*p*-AlInP interface imposes fundamental limitations on the use of *p*-AlInP layers as a wide-band-gap window in *p*–*n* structures of solar cells operating at ratios of high solar light concentration. It is demonstrated that characteristics of *p*–*n* solar cells can be, in principle, improved by using a double-layer wide-band-gap window constituted by *p*-$Al_{0.8}Ga_{0.2}As$ and *p*-$(Al_{0.6}Ga_{0.4})_{0.51}In_{0.49}P$ layers.

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1. INTRODUCTION

The development of solar power engineering requires that characteristics of photoconverters (solar cells) should be permanently improved to raise the solar energy's conversion efficiency. One of the most successful ways to raise the efficiency of solar cells (SCs) is to use multijunction (cascaded) III–V heterostructures. Cascaded solar cells of this kind have efficiencies exceeding 40% in conversion of a concentrated solar light, which makes these cells promising for use in photoelectric units with light concentrators [1].

In GaInP/GaAs/Ge multijunction solar cells, ternary compounds of Group-III phosphides (GaInP and AlInP) are among the best suitable candidates for fabrication of the upper junction. However, the properties of interfaces in heterostructures are of key importance in the operation of devices of this kind. The influence of interface properties on characteristics of GaInP photoelectric converters was demonstrated in [2]. It has also been experimentally shown that SCs based on *n*-GaAs/*n*-AlInP/*n*-GaInP/*p*-GaInP/*p*-GaAs structures (henceforth, *n*–*p* structures) have a higher efficiency, compared with SCs based on *p*-GaAs/*p*-AlInP/*p*-GaInP/*n*-GaInP/*n*-GaAs structures (henceforth, *p*–*n* structures). The main specific feature of *p*–*n* structures is that they have a bend in the load's current–voltage (I–V) characteristic near the open-circuit voltage (V_{oc}), which leads to a decrease in the fill factor (*FF*) and, consequently, in the SC efficiency [2, 3]. In [4], we demonstrated that the occurrence of the bend may be due to properties of interfaces in *p*-GaAs/*p*-AlInP/*p*-GaInP. In this communication, we report results of an additional experimental study, in which specific features of solar cell operation under exposure to a concentrated solar light were taken into account, and ways to improve SCs based on *p*–*n* structures are demonstrated. The interest in improvement of *p*–*n* structures is also caused by the promise using SCs transparent in the IR spectral range in high-efficiency, mechanically joined multijunction photoconverters [5].

2. EXPERIMENT AND SIMULATION

Experimental heterostructures based on a ternary compound $Ga_{0.52}In_{0.42}P$ (henceforth, GaInP) were grown by metal-organic chemical vapor deposition (MOCVD) on *p*- and *n*-type GaAs substrates. As a wide-gap window served 30- and 15-nm-thick $Al_{0.53}In_{0.47}P$ layers (henceforth, AlInP) or $Al_{0.8}Ga_{0.2}As$ layers. The topology of the upper contact grid was formed by photolithography, selective etching of the upper contact layer of GaAs, and deposition of Au:Ge/Ni/Au and Ag:Mn/Ni/Au systems as contacts to *n*- and *p*-type layers, respectively. A double-layer ZnS/MgF_2 antireflection coating was deposited onto the wide-gap window. The design of the contacts was optimized for operation of SCs under exposure to a 100-fold concentrated solar light. The degree of the photoactive region's shadowing by the contact grid was 8%. A more detailed description of the structure's fabrication process can be found in [6].

A computer simulation of I–V characteristics of the heterostructures was performed using the AFORS-HET v.2.2 software package developed at Hahn-Meitner-Institut Berlin GmbH (HMI) [7]. In the simula-

Table 1. Parameters of materials for heterostructure layers

Material	E_g, eV	χ, eV	μ_n/μ_p
GaAs	1.42 [8]	4.07 [8]	1000/50 [8]
GaInP	1.85 [9]	4.01 [11]	500/30 [13, 14]
AlInP	2.35 [10]	3.78 [11]	100/10
$Al_{0.8}Ga_{0.2}As$	2.09 [9]	3.53 [12]	500/30 [15]
$Al_{0.4}Ga_{0.6}As$	1.92 [9]	3.63 [12]	500/30
$(Al_{0.6}Ga_{0.4})_{0.51}In_{0.49}P$	2.26 [9]	3.83 [9]	100/50

Note: E_g is the energy gap; χ, electron affinity; and μ_n and μ_p, electron and hole mobilities in $cm^2 V^{-1} s^{-1}$.

tion, we used a 1D structure "GaAs contact layer/wide-gap window/junction in InGaP/GaAs substrate," with a surface recombination rate at the interface between the semiconductor and the metallic electrode taken to be 10^7 cm s^{-1} for electrons and holes. The main parameters of the materials, used in the calculation, are listed in Table 1. The same carrier lifetime in the bulk of the material (10^{-8} s [16]) was taken for all the semiconductor layers. I–V characteristics under illumination were calculated with allowance for the typical experimental reflectance spectrum of the antireflection coating and the 8% loss for shading by the contact grid. In the first stage of the calculation, the surface density of states was disregarded. The layer's parameters used in the calculation (Table 2) were chosen on the basis of analysis of data for the structures.

In the second stage of the simulation, we examined the effect of the density of states at the "wide-gap window (AlInP or $Al_{0.8}Ga_{0.2}As$)/GaInP emitter" interface. The interface was described by introducing a very thin ($d = 1$ nm) defective GaInP layer (with an energy gap $E_g = 1.85$ eV) between the GaInP emitter and the wide-gap window. The density-of-states distribution (g_{it}) in this defective layer was assumed to be constant, with states in the lower part of the energy gap being of the donor type, and those in the upper half, of the acceptor type. The capture's cross section for electrons and holes was taken to be 10^{-14} cm^2. The density of surface states, $D_{it} = g_{it}d$ was varied within the range 10^7–5×10^{13} cm^{-2} eV^{-1}. Preliminary results of our simulation demonstrated that the effect of the density of states at the "GaAs contact layer/wide-gap window" interface on characteristics of solar cells is negligible up to $D_{it} = 10^{13}$ cm^{-2} eV^{-1} and these surface states were disregarded in what follows.

3. RESULTS AND DISCUSSION

3.1. Solar Cells with an AlInP and AlGaAs Wide-Gap Windows

Figure 1 shows typical experimental I–V characteristics of solar cells of *n–p* and *p–n* types with an AlInP wide-gap window (30 nm thick), measured under exposure to unconcentrated light. The main distinctive feature of the *p–n* structures is that the I–V characteristics have a bend at the V_{oc} point, which leads to a substantial decrease in the fill factor of the I–V characteristic ($FF = 0.75$) and in the SC efficiency (11.58% against 14.27% for the *n–p* structure). It was shown in [4] that the occurrence of this bend is due to a high potential barrier for holes (~0.54 eV), formed in the region of the wide-gap window. The band diagram of this region, calculated for the conditions of thermodynamic equilibrium, is shown in Fig. 2a. The potential barrier is formed because of the large valence band's offset (ΔE_v) at the GaAs/AlInP interface. The I–V characteristics obtained in our simulation (Fig. 3) rather well reproduce the shape of the experimental I–V characteristics for both *n–p* and *p–n* structures.

It is possible to preclude the appearance of the bend in I–V characteristics of *p–n* structures by raising the doping level of the *p*-AlInP window, or making the window thinner, or using a *p*-$Al_{0.8}Ga_{0.2}As$ layer as the wide-gap window [4]. Deposition of heavily doped *p*-AlInP layers (with a doping level exceeding 2×10^{17} cm^{-3}) is a rather complicated technological task that requires an additional study of the growth conditions. Therefore, we fabricated, in the initial stage, structures with a thinner *p*-AlInP layer (15 nm) and a *p*-$Al_{0.8}Ga_{0.2}As$ window. The I–V characteristics calculated for these two variants are shown in Fig. 3. Com-

Table 2. Doping levels (in cm^{-3}) and thicknesses (nm) of layers, used in the calculation

Layer	*n–p* structure with a window (AlInP)	*p–n* structure with a window (AlInP)	*p–n* structure with a window (AlGaAs)
Contact GaAs	$2 \times 10^{18}/300$	$10^{19}/300$	$10^{19}/300$
Window	AlInP	AlInP	$Al_{0.8}Ga_{0.2}As$
	$5 \times 10^{18}/30$	$2 \times 10^{17}/(30$ and $15)$	$2 \times 10^{17}/30$
GaInP emitter	$2 \times 10^{18}/50$	$4 \times 10^{17}/130$	$4 \times 10^{17}/130$
GaInP base	$10^{17}/800$	$10^{17}/920$	$10^{17}/920$
GaInP BSF	$10^{18}/50$	$2 \times 10^{18}/50$	$2 \times 10^{18}/50$
Buffer GaAs	$2 \times 10^{18}/150$	$2 \times 10^{18}/150$	$2 \times 10^{18}/150$

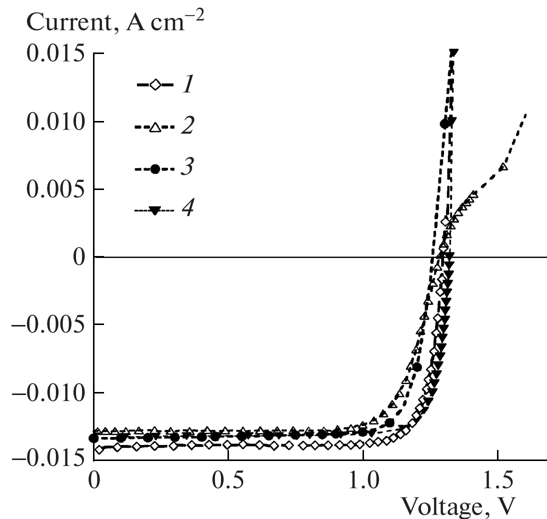

Fig. 1. Experimental *I–V* characteristics for four types of solar cells fabricated in the study: (*1*, *2*) *n–p* and *p–n* structures with a 30-nm-thick AlInP window, respectively; (*3*) *p–n* structures with a 15-nm-thick AlInP window; and (*4*) *p–n* structure with an $Al_{0.8}Ga_{0.2}As$ window. Illumination conditions: AM1.5D, 100 mW/cm^2.

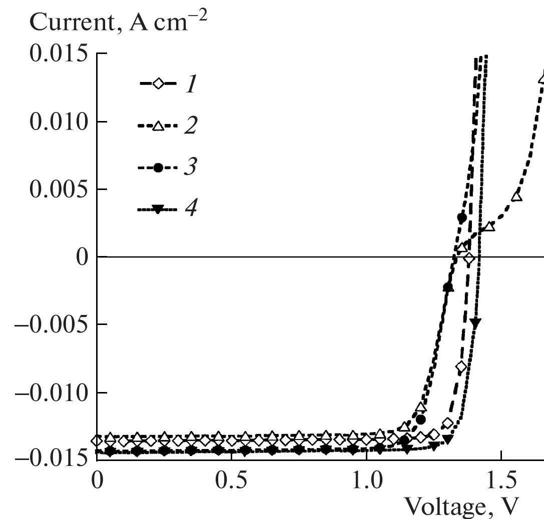

Fig. 3. Calculated *I–V* characteristics of (*1*) *n–p* and (*2*) *p–n* structures with a 30-nm-thick AlInP window, (*3*) *p–n* structure with a 15-nm-thick AlInP window, and (*4*) *p–n* structure with a $Al_{0.8}Ga_{0.2}As$ window. Illumination conditions AM1.5D, 100 mW/cm^2.

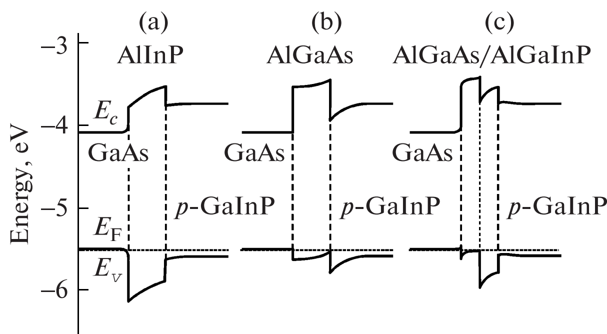

Fig. 2. Calculated band diagrams under thermodynamic equilibrium conditions for *p–n* structures with (a) *p*-AlInP, (b) *p*-$Al_{0.8}Ga_{0.2}As$, and (c) $Al_{0.8}Ga_{0.2}As/(Al_{0.6}Ga_{0.4})_{0.51}In_{0.49}P$ windows. E_c, conduction band; E_v, valence band; and E_F, Fermi level.

parison of the I–V characteristics in Figs. 1 and 3 (curves *3* and *4*) shows that the simulation results for a low illumination level are in a rather good agreement with experimental data. In both cases, there is no bend in I–V characteristics and the short-circuit current and the fill factor of the I–V characteristics somewhat increase, compared with the structure with a 30-nm-thick *p*-AlInP window (curve *2*), for which the bend is observed at low illumination levels as well. Also in accordance with the calculation results for the structure with the *p*-$Al_{0.8}Ga_{0.2}As$ window, an increase in the open-circuit voltage is observed.

When, however, these heterostructures are used in solar cells converting concentrated light, of greatest interest are their characteristics at high illumination levels. It can be seen in Fig. 4 (curve *1*) that, for a solar cell with a 15-nm-thick *p*-AlInP window, a bend in the I–V characteristic is observed at an eightfold concentration. A similar behavior is also observed for the calculated I–V characteristics (curve *2* in Fig. 4). In a simulation for a heavily doped *p*-AlInP layer (10^{19} cm^{-3}), a bend in the I–V characteristics is also observed at ratios of large solar light concentration. Thus, a *p*-GaAs/*p*-AlInP interface should not be used for SCs based on *p–n* structures and intended for conversion of concentrated light.

A heterostructure with a *p*-$Al_{0.8}Ga_{0.2}As$ window has a considerably more favorable band diagram as it regards making lower the barrier for holes (Fig. 2b). The smaller valence band's offset at the GaAs/$Al_{0.8}Ga_{0.2}As$ and $Al_{0.8}Ga_{0.2}As$/GaInP interfaces results in the fact that a low barrier for holes (and a substantially higher barrier for electrons) are formed on the side of the *p*-emitter. As a consequence, larger values of the open-circuit voltage (V_{oc}) and short-circuit current (J_{sc}) are observed, compared with the *p–n* SC with a *p*-AlInP window (Fig. 3), and there are no bends in the I–V characteristics at concentration ratios of up to 75 (curve *3* in Fig. 4). This is in exact agreement with the simulation results (curve *4* in Fig. 4). However, the basic distinctive feature of solar cells with an $Al_{0.8}Ga_{0.2}As$ window, that we fabricated, is that the values of J_{sc} and V_{oc} are smaller as compared with the calculation results, which also manifests itself under exposure to concentrated light. The reason why parameters of the SC with a *p*-$Al_{0.8}Ga_{0.2}As$ window are poorer is the recombination loss at the *p*-$Al_{0.8}Ga_{0.2}As$/*p*-GaInP interface, because, according to the simulation results, the transport across this interface has an increased sensitivity to surface states.

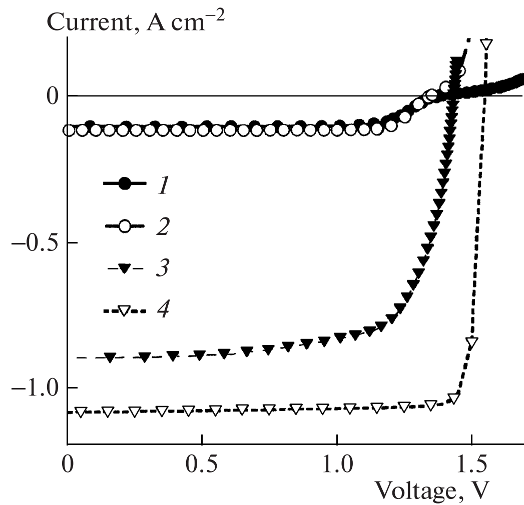

Fig. 4. (*1*, *3*) Experimental and (*2*, *4*) calculated *I–V* characteristics of *p–n* structures with (*1*, *2*) a 15-nm-thick *p*-AlInP window at a solar light concentration ratio of 8 and (*3*, *4*) *p*-$Al_{0.8}Ga_{0.2}As$ window at a concentration ratio of 75.

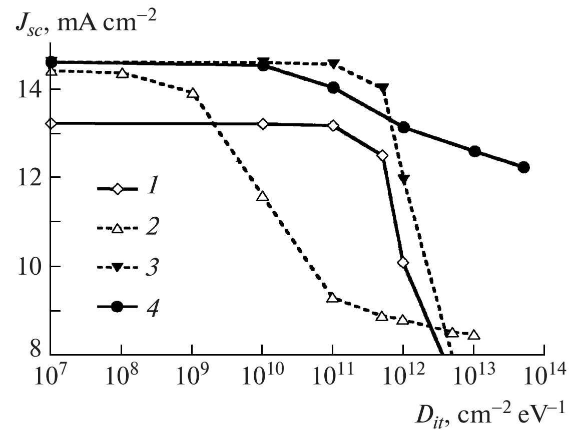

Fig. 5. Calculated dependences of J_{sc} on D_{it} at the window/emitter interface for (*1*) *p–n* structure with an AlInP window and (*2*) *p–n* structure with an $Al_{0.8}Ga_{0.2}As$ window and calculated dependences of J_{sc} on D_{it} at (*3*) $(Al_{0.6}Ga_{0.4})_{0.51}In_{0.49}P$/GaInP and (*4*) $Al_{0.8}Ga_{0.2}As/(Al_{0.6}Ga_{0.4})_{0.51}In_{0.49}P$ interfaces for a *p–n* structure with an $Al_{0.8}Ga_{0.2}As/(Al_{0.6}Ga_{0.4})_{0.51}In_{0.49}P$ window. Illumination conditions: AM1.5D, 100 mW/cm^2.

Figure 5 shows the results of the calculation of how the short-circuit current density depends on the surface-state density (D_{it}) for *p–n* structures with wide-gap windows *p*-AlInP (curve *1*) and *p*-$Al_{0.8}Ga_{0.2}As$ (curve *2*). It can be seen that J_{sc} for the structure with the *p*-$Al_{0.8}Ga_{0.2}As$ window is considerably more dependent on the surface-state density and starts to noticeably decrease even at $D_{it} = 10^9$ cm^{-2} eV^{-1}. This feature is due to the specific band structure of the *p*-$Al_{0.8}Ga_{0.2}As$/*p*-GaInP interface. It follows from the band diagram calculated for an SC of this kind under thermal equilibrium conditions (Fig. 2b) that the considerable conduction band's offset (ΔE_c) at the $Al_{0.8}Ga_{0.2}As$/GaInP interface causes substantial band bending in the *p*-GaInP emitter. Thus, an electric field dragging electrons from the *p*-emitter to the interface is created and stimulates carrier recombination there. For comparison: a more favorable situation was observed at the *p*-AlInP/*p*-GaInP interface (Fig. 2a), where the band bending in *p*-GaInP is considerably less pronounced, which leads to a lower sensitivity of the SC parameters to the value of D_{it} at this interface (curve *1* in Fig. 5). The assumption of an increased recombination level at the $Al_{0.8}Ga_{0.2}As$/GaInP interface is confirmed by the spectral characteristics of the SC measured in the study. A spectral sensitivity analysis demonstrated that the external quantum yield in the short-wavelength part of the spectrum is substantially lower for the SC with a *p*-$Al_{0.8}Ga_{0.2}As$ window, compared with that having a *p*-AlInP window. This indicates that a recombination loss occurs in the region adjacent to the emitter and, what is the most probable, at the *p*-$Al_{0.8}Ga_{0.2}As$/*p*-GaInP interface.

Thus, our study demonstrated that the considerable valence band's offset at the interface between the *p*-GaAs and *p*-AlInP makes using this combination of layers in SCs operating at ratios of high solar light concentration absolutely impossible. The problem can be obviated by using a *p*-$Al_{0.8}Ga_{0.2}As$ layer as the wide-gap window adjacent to the *p*-GaAs contact layer. However, doing so leads to a steep rise in the influence of surface states at the *p*-$Al_{0.8}Ga_{0.2}As$/*p*-GaInP interface and impairs the SC characteristics.

3.2. Solar Cells with an AlGaAs/AlGaInP Window

A possible trade-off decision is to use a double-layer window constituted of an upper layer of a *p*-AlGaAs ternary compound, adjacent to the *p*-GaAs contact layer and a lower layer of a ternary (AlInP) or quaternary (AlGaInP) solid solution. The band structure of the double-layer window constituted by *p*-$Al_{0.8}Ga_{0.2}As$ and *p*-$(Al_{0.6}Ga_{0.4})_{0.51}In_{0.49}P$ layers is shown in Fig. 2c. The small valence band's offset at the *p*-GaAs/*p*-$Al_{0.8}Ga_{0.2}As$ interface makes it possible to lower the potential barrier for holes coming from the emitter side to a value sufficient for an efficient SC operation at rations of high solar light concentration. At the same time, the absence of band bending at the *p*-$(Al_{0.6}Ga_{0.4})_{0.51}In_{0.49}P$/*p*-GaInP interface leads to a low sensitivity of SC parameters to the surface-state density at this interface (curve *3* in Fig. 5). Figure 5 also shows calculated dependences of J_{sc} on D_{it} at the $Al_{0.8}Ga_{0.2}As/(Al_{0.6}Ga_{0.4})_{0.51}In_{0.49}P$ interface (curve *4*). According to the calculated results, the density of states at this interface only slightly affects the SC characteristics because of the small thickness of the $(Al_{0.6}Ga_{0.4})_{0.51}In_{0.49}P$ layer (15 nm), even though there is band bending in the $(Al_{0.6}Ga_{0.4})_{0.51}In_{0.49}P$ layer at the

Table 3. Calculated parameters of SCs with different types of windows under exposure to AM1.5D at a concentration ratio of 1000

Window (doping level, cm^{-3})	V_{oc}, V	J_{sc}, A cm^{-2}	*FF*, %	Efficiency, %
$AlInP(2 \times 10^{17})$	1.35	14.22	70.39	13.49
$Al_{0.4}Ga_{0.6}As(10^{18})/AlInP(2 \times 10^{17})$	1.5	14.17	65.46	13.88
$Al_{0.8}Ga_{0.2}As(5 \times 10^{17})/AlInP(2 \times 10^{17})$	1.56	14.64	63.46	14.48
$Al_{0.4}Ga_{0.6}As(10^{18})/(Al_{0.6}Ga_{0.4})_{0.51}In_{0.49}P(10^{18})$	1.53	13.8	83.96	17.75
$Al_{0.8}Ga_{0.2}As(5 \times 10^{17})/(Al_{0.6}Ga_{0.4})_{0.51}In_{0.49}P(10^{18})$	1.59	14.48	84.01	19.35

interface with $Al_{0.8}Ga_{0.2}As$, which leads to recombination of a considerable part of electrons generated in this layer.

We calculated SC characteristics for various combinations of layers in the double-layer window for a concentrated solar light (concentration ratio 1000). The results obtained are listed in Table 3. The effect of the surface-state density on SC parameters was taken into account by using the value $D_{it} = 10^{11}$ cm^{-2} eV^{-1} at the interfaces between the two layers of the window and between the lower layer of the window and the emitter. This value was chosen with a certain excess over the upper limit to D_{it}, obtained from a comparison of the experimental I–V characteristics with the simulation results for structures with an $Al_{0.8}Ga_{0.2}As$ window [(2–5) × 10^{10} cm^{-2} eV^{-1}]. For comparison, the table lists data for a structure with a 30-nm-thick *p*-AlInP window, for which the calculated efficiency is 13.49%. Use of a double window constituted by $Al_{0.4}Ga_{0.6}As$ and AlInP layers (both 15 nm thick) enables a slight increase in efficiency because of the higher V_{oc}. With $Al_{0.8}Ga_{0.2}As$ used as the upper layer, the SC efficiency can be additionally raised. A more substantial increase in efficiency is observed when the lower layer is composed of a quaternary compound $(Al_{0.6}Ga_{0.4})_{0.51}In_{0.49}P$. The optimal solution is a double heterostructure with a window constituted by $Al_{0.8}Ga_{0.2}As$ and $(Al_{0.6}Ga_{0.4})_{0.51}In_{0.49}P$ layers, in which case the SC efficiency can be raised to 19.35% (Table 3). The I–V characteristic of an SC based on this structure has no bends up to concentration ratios of 1000. Thus, according to the results of our theoretical calculation, the combination of $Al_{0.8}Ga_{0.2}As$ and $(Al_{0.6}Ga_{0.4})_{0.51}In_{0.49}P$ layers is of greatest interest for fabrication of a wide-gap window for SCs based on *p–n* structures, intended to operate at ratios of high solar light concentration. According to the calculation results, an efficiency of 17% can be achieved under exposure to unconcentrated solar light (AM1.5) with SCs based on structures of this kind, which exceeds theoretical estimates for other types of SCs at comparable values of D_{it} [4].

4. CONCLUSIONS

A computer simulation of GaInP solar cells demonstrated the importance of interface parameters, with a good correlation achieved between the calculation results and experimental data. It was shown that the substantial valence band offset at the *p*-GaAs/*p*-AlInP interface in *p–n* structures impairs characteristics of solar cells based on these structures. The use of a *p*-$Al_{0.8}Ga_{0.2}As$ layer as a window creates conditions for a barrier-free transport of holes; however, the band structure at the *p*-$Al_{0.8}Ga_{0.2}As$/*p*-GaInP interface results in a substantially stronger influence of the surface-state density on the transport across this interface, which, in the end, strongly impairs the SC parameters. Theoretical estimates demonstrated that a double-layer wide-gap window constituted by $Al_{0.8}Ga_{0.2}As$ and $(Al_{0.6}Ga_{0.4})_{0.51}In_{0.49}P$ layers shows promise for use in solar cells. This combination of layers makes it possible, on the one hand, to lower the barrier for holes, and on the other hand, to diminish the effect of the surface-state density at the interface between the wide-gap window and the emitter on parameters of I–V characteristics and to provide a substantial increase in the efficiency of solar cells based on a *p–n* junction.

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REFERENCES

1. R. R. King, D. C. Law, K. M. Edmondson, C. M. Fetzer, G. S. Kinsey, H. Yoon, D. D. Krut, J. H. Ermer, R. A. Sherif, and N. H. Karam, in *Proc. of the 4th Intern. Conf. Solar Concentrators* (El Escorial, Spain, 2007).
2. S. R. Kurtz, J. M. Olson, D. J. Friedman, J. F. Geisz, K. A. Bertness, and A. E. Kibbler, in *Proc. of the Compound Semiconductor Surface Passivation and Novel Device Processing Symp.*, Ed. by H. Hasegawa, M. Hong, Z. H. Lu, and S. J. Pearton (Mater. Res. Soc., Warrendale, 1999), p. 95.
3. S. I. Wojtczuk, S. M. Vernon, and M. M. Sanfacon, in *Proc. of the 23th IEEE Photovoltaic Specialists Conf.* (1993), p. 655.
4. A. S. Gudovskikh, N. A. Kaluzhniy, V. M. Lantranov, S. A. Mintairov, M. Z. Shvarts, and V. M. Andreev, Thin Sol. Films **516**, 6739 (2008).

5. M. Z. Shvarts, P. Y. Gazaryan, N. A. Kaluzhniy, V. P. Khvostikov, V. M. Lantranov, S. A. Mintairov, S. V. Sorokina, and N. K. Timoshina, in *Proc. of the 21th Eur. Photovoltaic Solar Energy Conf.* (Dresden, 2006).
6. V. M. Lantratov, N. A. Kalyuzhnyĭ, S. A. Mintairov, N. Kh. Timoshina, M. Z. Shvarts, and V. M. Andreev, Fiz. Tekh. Poluprovodn. **41**, 751 (2007) [Semiconductors **41**, 727 (2007)].
7. R. Stangl, M. Kriegel, and M. Schmidt, in *Proc. of the 4th World Conf. Photovoltaic Energy Conversion, WCPEC-4* (Hawaii, USA, 2006).
8. S. M. Sze, *Physics of Semiconductor Devices* (Wiley, New York, 1981).
9. I. Vurgaftman, J. R. Meyer, and L. R. Ram-Mohan, J. Appl. Phys. **89**, 5815 (2001).
10. D. P. Bour, J. R. Shealy, G. W. Wicks, and W. J. Schaff, Appl. Phys. Lett. **50**, 615 (1987).
11. C.-S. Jiang, D. J. Friedman, H. R. Moutinho, and M. M. Al-Jassim, in *Proc. of the IEEE 4th World Conf. on Photovoltaic Energy Conversion, 2006* (Waikoloa, Hawaii, 2006), p. 853.
12. S. Adachi, J. Appl. Phys. **58**, R1 (1985).
13. T. Shitara and K. Eberl, Appl. Phys. Lett. **65**, 356 (1994).
14. M. Ikeda and K. Kaneko, J. Appl. Phys. **66**, 5285 (1989).
15. D. C. Look, D. K. Lorance, J. R. Sizelove, C. E. Stutz, K. R. Evans, and D. W. Whitson, J. Appl. Phys. **71**, 260 (1992).
16. M.-J. Yang, M. Yamaguchi, T. Takamoto, E. Ikeda, H. Kurita, and M. Ohmori, Sol. Energy Mater. Solar Cells **45**, 331 (1997).

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