ISSN 1063-7826, Semiconductors, 2013, Vol. 47, No. 12, pp. 1652–1655. © Pleiades Publishing, Ltd., 2013.
Original Russian Text © V.S. Kalinovsky, R.V. Levin, B.V. Pushniy, M.N. Mizerov, V.D. Rumyantsev, V.M. Andreev, 2013, published in Fizika i Tekhnika Poluprovodnikov, 2013, Vol. 47, No. 12, pp. 1677–1680.

PHYSICS OF SEMICONDUCTOR DEVICES

Fabrication and Study of p–n Structures with Crystalline Inclusions in the Space-Charge Region

V. S. Kalinovsky[a], **R. V. Levin**[a], **B. V. Pushniy**[b]^, **M. N. Mizerov**[b],
V. D. Rumyantsev[a], **and V. M. Andreev**[a]

[a] *Ioffe Physical–Technical Institute, Russian Academy of Sciences, ul. Politekhnicheskaya 26, St. Petersburg, 194021 Russia*
[b] *Submicron Heterostructures for Microelectronics, Research and Engineering Center, Russian Academy of Sciences, ul. Politekhnicheskaya 26, St. Petersburg, 194021 Russia*
^e-mail: pushnyi@vpegroup.ioffe.ru

Submitted April 15, 2013; accepted for publication May 23, 2013

Abstract—A new model of connecting elements for monolithic multijunction solar cells based on III–V compounds is proposed, in which p–n junctions with crystalline inclusions of a foreign semiconductor material in the space-charge region are used instead of p^{++}–n^{++} tunnel junctions. The study shows that the introduction of crystalline inclusions to the space-charge region of the p–n junction in a GaSb-based structure allows current densities of ~50 A/cm^2 at an ohmic loss of ~0.01 Ω cm^2. The obtained characteristics of the connecting elements with crystalline inclusions show their applicability to multijunction solar cells for concentrated light conversion.

DOI: 10.1134/S1063782613120105

1. INTRODUCTION

Recently, the highest efficiency of concentrated sunlight conversion was achieved in three-junction solar photoconverters (PC) based on III–V materials. In such PCs, three photoactive p–n junctions formed by layers with moderate doping are connected in series by two p^{++}–n^{++} tunneljunctions formed by layers with extremely high doping levels [1, 2]. As the sunlight concentration multiplicity is increased, the generated photocurrent can exceed the peak current of the tunnel junctions, which results in an increase in the resistance of the entire structure and a decrease in the photoconversion efficiency [3].

A possible means for solving the issue with connecting elements is the introduction of arrays of crystalline inclusions into the space-charge region (SCR) of the p^{++}–n^{++} tunnel junctions or the simple formation of a layer of crystal arrays between adjacent photoactive p–n junctions in monolithic photoconverters [1]. In the former case, the extremely high doping levels of p^{++} and n^{++} layers in tunnel junctions can be lowered; thus, the effect of the doping-profile spread in tunnel junctions, caused by the diffusion of electrically active impurities upon further growth of the structure, can be reduced. In the latter case, tunnel junctions can be completely excluded and the mechanism of ohmic current flow over conductivity channels in a crystalline-inclusion layer in a p–n junction SCR can be facilitated. In [4], the properties of tunnel and photovoltaic GaSb p–n junctions with crystalline Si inclusions introduced into their SCR were studied for the first time. An analysis of the dark current–voltage characteristics showed a significant decrease in the ohmic loss in such structures.

In this paper, we present data on technological conditions of the growth of connecting junctions and the results of studying the photoelectric parameters of the grown structures. The crystalline silicon objects were formed in the SCR of both tunnel p^{++}–n^{++} and p–n junctions (with a lower doping level) based on GaSb.

2. STRUCTURE GROWTH TECHNOLOGY

As a model p–n junction, the GaSb junction was chosen. Photosensitive devices based on GaSb and its alloys are of particular interest not only for long-wavelength sunlight conversion [5], but also in developing PCs using other II–VI and III–V materials [6].

The material for developing conductivity channels in the SCR should satisfy the following conditions.

(i) Low absorption of optical radiation converted by underlying narrower-gap cascades;

(ii) the crystal material should form only isolated crystals with the scale larger than the SCR thickness at the p–n junction boundary.

For photoactive GaSb p–n junctions, silicon satisfies these conditions. It has a wider band gap than gallium antimonide, hence, low light absorption in the GaSb photosensitivity region.

All structures of GaSb were grown by metal-organic chemical vapor deposition (MOCVD) using an AIX-200 setup operating at a reduced pressure. As the Ga and Sb sources, triethylgallium (TEGa) and

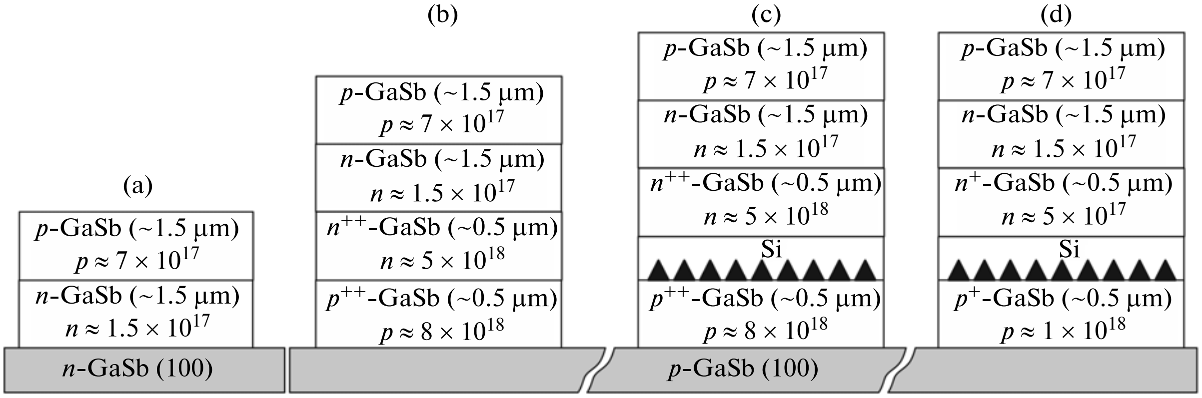

Fig. 1. Schematic representation of the studied structures: (a) p–n junction grown on an n-GaSb(Te) substrate; (b) p–n junction with an n-type base connected to a p^{++}–n^{++} tunnel junction with a p-GaSb(Ge) substrate; (c) p–n junction connected with a p-GaSb(Ge) substrate by a tunnel junction to crystalline silicon inclusions in the SCR; (d) p–n junction connected to a p-GaSb(Ge) substrate by a layer with an array of silicon crystalline inclusions.

trimethylantimony (TMSb) were used; as the dopant sources, silane (SiH_4) and diethyltellurium (DETe) were used. The growth temperature was 600°C, the reactor pressure was 100 mbar. As the substrates, n-GaSb(Te) (100) wafers with an electron concentration of $(1–5) \times 10^{17}$ cm^{-3} or p-GaSb(Ge) (100) wafers with a hole concentration of $(1.0–3) \times 10^{18}$ cm^{-3} were used.

Figure 1 shows the types of the studied structures. All structures were grown under the same conditions.

The structure of the connecting junctions included an n-GaSb epitaxial layer with a donor concentration of $(1–5) \times 10^{18}$ cm^{-3} 0.8–1.0 μm thick and a p-GaSb layer with an acceptor concentration of $(1–6) \times 10^{18}$ cm^{-3} 0.8–1.0 μm thick. The Si-inclusion layer thickness in the SCR of the p–n junctions corresponded to the SCR thickness. Control samples of the structures with a single photoactive p–n junction were grown on an n-GaSb (100) substrate. The photoactive p–n junction structure consisted of n-GaSb and p-GaSb epitaxial layers 1.5 μm thick with a donor concentrations of 1.5×10^{17} and an acceptor concentration $(7–9) \times 10^{17}$ cm^{-3}, respectively.

When growing the structures under study, it is important to retain the qualitative characteristics of the photoactive junctions grown over the layers containing crystalline Si inclusions.

To analyze the Si-inclusion sizes and shape, technological experiments on Si crystal growth on an n-GaSb substrate surface were performed. It became possible to vary the Si-inclusion size by varying the time of epitaxial-structure exposure to the silane flow, providing low ohmic loss in the connecting p–n junctions. The following conditions of crystal growth were chosen as optimal for the study: the temperature $T_g = 600°C$ and time $t_g = 30$ min.

Figure 2 shows a micrograph and statistical data for the Si crystals in the SCR, obtained using an atomic-force microscope. The data presented show that Si crystals 1–5 nm high and 10–70 nm wide are formed under the chosen growth conditions.

3. RESULTS OF STUDYING THE CURRENT–VOLTAGE CHARACTERISTICS

The dark current–voltage (I–V) characteristics were measured at room temperature in the current density range of 10^{-8}–10^{2} A/cm^2. First, the I–V characteristics of the GaSb structures grown on the n-type substrate were measured. These structures model the connecting p–n junctions of various types: the p^{++}–n^{++} tunnel junction, the p^{++}–n^{++} junction with Si crystals in the SCR, and the connecting p–n junction with Si crystals in the SCR. We can see in Fig. 3 that there is no potential barrier in the p–n junctions with crystalline inclusions; their I–V characteristic is similar to the ohmic resistance with $R_S < 15$ mΩ cm^2 up to current densities of 50 A/cm^2. The ordinary GaSb tunnel junction under these conditions exhibited a peak current of ~13 A/cm^2. Figure 4 shows the spectral characteristics of the photosensitivity of the structures with p–n junctions. We can see that the spectral characteristics of the studied structures differ from each other only in the long-wavelength region, where the slightly higher sensitivity of the samples grown on the n-type substrate is explained by the fact that carriers are collected not only from the relatively thin n-base, but also from the substrate. The coincidence of the curves in other spectral regions shows that defects appearing during photoactive p–n structure growth on the layer of Si crystals (curve *3*) are significantly compensated, and their effect on the spectral characteristics of the grown photoactive p–n junction is almost lacking.

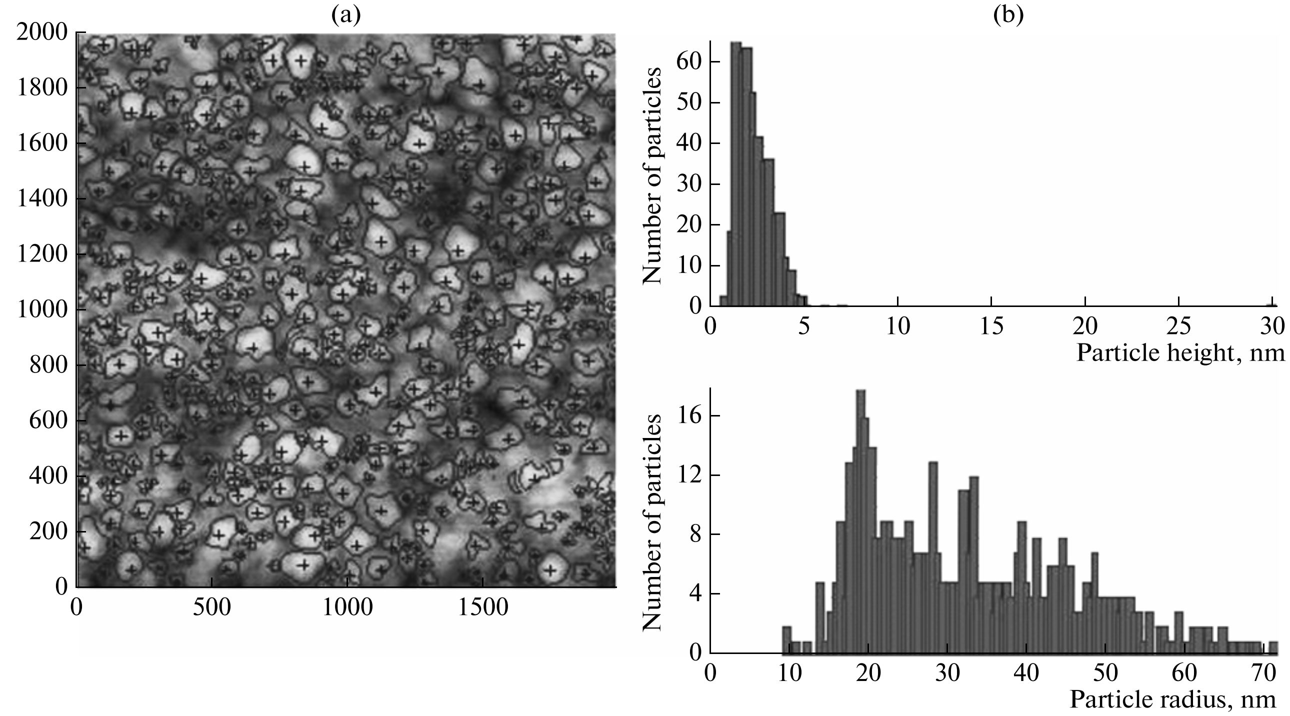

Fig. 2. Data obtained using an atomic-force microscope: (a) Si crystals formed on an n-GaSb(Te) (100) substrate surface at T_g = 600°C for t_g = 30 min, (b) statistics of linear sizes over the Si crystal height and width.

Figure 5 shows the forward portions of the dark I–V characteristics (semilog scale) for structures similar to those shown in Fig. 4 (curve numbers in Figs. 4 and 5 are identical). In all studied structures, we can distinguish three current-flow mechanisms: the tunnel-trap (excess) one with a diode factor of $A > 2$ and the preexponential factor $J_{0t} = (2 \times 10^{-4}$–$2.8 \times 10^{-3})$ A/cm^2; the recombination mechanism with $A = 2$ and $J_{0r} = (4 \times 10^{-5}$–$4.5 \times 10^{-5})$ A/cm^2; and the diffusion one with $A = 1$ and $J_{0d} = (3.6 \times 10^{-7}$–$4.4 \times 10^{-7})$ A/cm^2. The

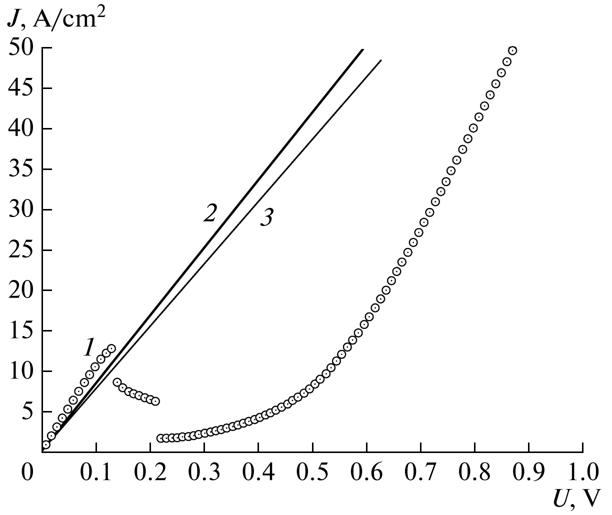

Fig. 3. Dark current–voltage characteristics of GaSb structures: (*1*) p^{++}–n^{++} tunnel junction, (*2*) p^{++}–n^{++} junction with Si crystals in its SCR, and (*3*) connecting p–n junction with Si crystals in the SCR.

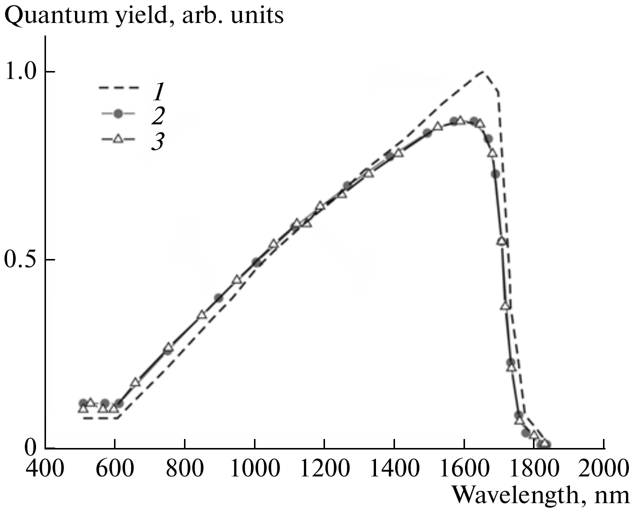

Fig. 4. External quantum yield of GaSb photoactive p–n junctions (*1*) p–n junction grown on an n-GaSb (100) substrate, (*2*) p–n junction with a base n-layer connected to a p-GaSb (100) substrate by a p^{++}–n^{++} tunnel junction, and (*3*) p–n junction with a base n-type layer connected to a p-GaSb (100) substrate by a layer with Si crystalline inclusions.

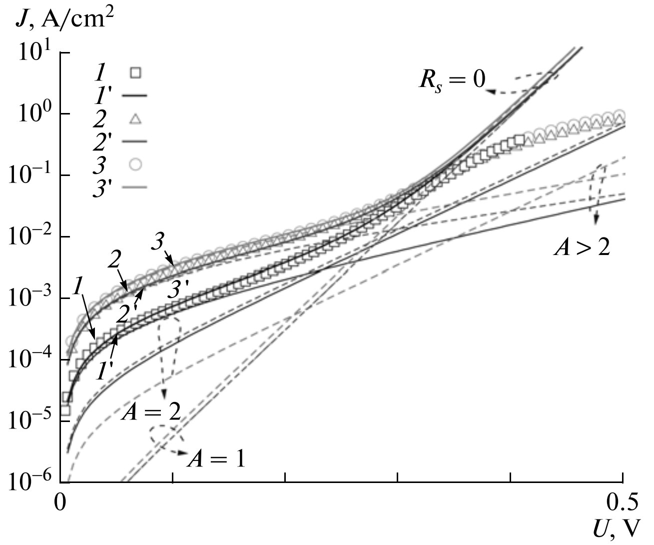

Fig. 5. Forward portions of dark *I–V* characteristics of the studied GaSb structures: (*1*) and (*1*') experimental *I–V* characteristic and *I–V* characteristic as a result of fitting at $R_S = 0$ for the photoactive GaSb *p–n* junction with an *n*-type base layer grown on an *n*-GaSb substrate; (*2*) and (*2*') the same in the case of the *n*-type base layer connected to the substrate via a p^{++}–n^{++} tunnel junction; (*3*) and (*3*') the same in the case of an *n*-type base layer connected to the substrate via a *p–n* junction with Si crystals in the SCR.

almost complete coincidence of curves *2* and *3* and the close resemblance pre-exponential factors J_{0r} and J_{0d} for the "recombination" and "diffusion" portions of the *I–V* characteristics of the studied structures suggests that the introduction of a connecting element with crystalline Si inclusions does not lead to significant degradation of the material quality in the upper photoactive GaSb *p–n* junction.

4. CONCLUSIONS

As a result of the study, a new type of connecting element was demonstrated, which is applicable to monolithic solar cells and photoconverters of high-power optical radiation, based on III–V compounds. This technological solution is protected by a patent of the Russian Federation [7].

In GaSb epitaxial structures grown by the MOCVD method, instead of p^{++}–n^{++} tunnel junctions, a connecting element such as a *p–n* junction with crystalline inclusions in the space-charge region was used.

It was shown that the introduction of Si crystals into the SCR of GaSb *p–n* junctions eliminates the adverse effect of the peak current of the connecting tunnel junctions up to current densities of ~50 A/cm^2 and provides low ohmic resistance of reverse connected parasitic *p–n* junctions of ~0.01 Ω cm^2.

ACKNOWLEDGMENTS

The authors are grateful to G.V. Il'menkov for helpful discussions and N.Kh. Timoshina for assistance in measurements.

This study was supported in part by the Ministry of Education and Science of the Russian Federation (State contract no. 14.516.11.0011) and the project of the Scientific and Technical Information Department of the Russian Academy of Sciences for 2012–2013.

REFERENCES

1. Zh. I. Alferov, V. M. Andreev, and V. D. Rumyantsev, Semiconductors **38**, 899 (2004).
2. H. Karam Nasser, A. Sherif Raed, and R. King Richard, Springer Ser. Opt. Sci. **40**, 199 (2008).
3. V. M. Andreev, E. A. Ionova, V. R. Larionov, V. D. Rumyantsev, M. Z. Shvarts, and G. Glenn, in *Proceedings of the IEEE 4th World Conference on Photovoltaic Energy Conversion, May 7–12, 2006, Hawaii*, pp. 799–802.
4. V. M. Andreev, V. S. Kalinovsky, R. V. Levin, B. V. Pushniy, and V. D. Rumyantsev, in *Proceedings of the 24th European Photovoltaic Solar Energy Conference, Sept. 21–25, 2009, Hamburg, Germany*, p. 740.
5. V. M. Andreev, V. V. Evstropov, V. S. Kalinovskii, V. M. Lantratov, and V. P. Khvostikov, Semiconductors **43**, 644 (2009).
6. S.-N. Wu, D. Ding, S. R. Johnson, S.-Q. Yu, and Y.-H. Zhang, Prog. Photovolt.: Res. Appl. **18**, 328 (2010).
7. RF Patent No. RU106443U1 (2011).

Translated by A. Kazantsev