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High Power GaSb PV Cells With Nanocrystalline Si Inclusions In The Space Charge Region

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Abstract. In the work, a new model of connecting elements for monolithic multijunction solar cells (SCs) based on $A^{III}B^{V}$ compounds has been proposed, where, instead of tunneling p^{++}-n^{++} junction, connecting elements – layers with nanocrystalline inclusions in space charge region (SCR) have been elaborated. Such connecting elements exclude the effect of peak current and decrease the series resistance of the whole structure, which is particularly important in converting highly concentrated sunlight. Technological regimes for fabricating such junctions and results of their study are presented. The nanocrystalline silicon objects were formed in the SCR of GaSb p^{++}-n^{++} and *p-n* junctions. To estimate the effect of the nanocrystalline Si objects on defect formation during the production of the photoactive GaSb *p-n* junctions, structures where the base *n*-layer of photoactive GaSb *p-n* junctions was connected to the GaSb substrate by the usual way, through a p^{++}-n^{++} junction or by means of a layer with nanocrystalline Si objects were studied. Measurements for obtaining both dark and light *I-V* characteristics were carried out at room temperature within the current density range of 10^{-8} - 10^{2} A/cm^2. Measurements for obtaining light load *I-V* characteristics were carried out at illumination by monochromatic radiation (λ = 1.3 μm, $h\nu$ = 0.95 eV) up to 5 W/cm^2 power. The investigations carried out have shown that introduction of nanocrystalline Si inclusions into the SCR of *p-n* junctions allows excluding the negative effect of peak current up to current densities of about 50 A/cm^2 and decreasing the ohmic resistance of the serially connected *p-n* junctions down to about 0,01 Ohm·cm^2.

Keywords: Solar cells, Nanocrystals structure.
PACS: 88.40.hj, 61.46.Hk

INTRODUCTION

Recently, the highest efficiency values at conversion of concentrated sunlight have been achieved in triplejunction SCs based on $A^{III}B^{V}$ compounds. In such monolithic multijunction SCs, three photoactive *p-n* junctions with moderately doped photoactive layers are sequentially commutated by tunneling p^{++}-n^{++} junctions with a extremely high doping level.

In raising the sunlight concentration ratio, the generated photocurrent may exceed the peak current of the tunneling junction, which will result in the increase of the resistance of the whole structure, the reduction of the photogenerated current and a drop in efficiency of the multijunction solar cells (MJ SC).

Increasing the number of photovoltaic *p-n* junctions in MJ SC, the number of connecting elements – tunneling p^{++}-n^{++} junctions rises, which, in turn, increases the effects of peak current and resistance of the whole MJ SC structure [1].

One of the feasible approaches to solving this problem is the introduction of quantum dots, for example, into the SCR of the tunneling p^{++}-n^{++} junctions or substituting for them by a layer of quantum dots (QD) between adjacent photoactive *p-n* junctions connected in series in monolithic MJ SC [1]. In this case, the *p-n* junction is not a rectifying one and ensures current flow along the conduction channels in the layer of QDs or nanocrystalline inclusions. In this case, it is possible to decrease substantially the extremely high doping levels of p^{++} and n^{++} layers in the tunneling junctions and the effect of smearing out the doping profile of the tunneling junctions caused by diffusion of electrically active impurities during the following growth next photovoltaic *p-n* junction of wider-band materials.

The first steps in solving this problem were attempted by creating nanocrystalline Si inclusions in the SCR of GaSb tunneling and photovoltaic *p-n* junctions. The analysis of their *I-V* characteristics has shown a substantial rise in conduction of the forward branch of the characteristic of such structures [2].

EXPERIMENTAL PROCEDURE

SCs based on GaSb and its solid solutions are of a definite interest not only for converting the long

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wavelength part of the sunlight, but also in developing MJ SCs based on $A^{II}B^{VI}$ and $A^{III}B^{V}$ compounds [3]. In the present work, structures based on GaSb have been chosen as model objects for the investigations.

The structures have been fabricated by the MOCVD technique on an AIX-200 installation operated at lessened pressure. TEGa and TMSb were used as sources, and also SiH_4 and DETe – as doping impurity sources. The growth temperature was 600°C and the reactor pressure – 100 mbar. The crystalline objects, which were grown in the SCRs of the connecting junctions, consisted of Si. As substrates, *n*-GaSb(Te) (100) with an donor concentration of $(1\text{-}5)\cdot 10^{17}$ cm^{-3} and *p*-GaSb(Ge) (100) with an acceptor concentration of $(1.1\text{-}3)\cdot 10^{18}$ cm^{-3} were used.

To analyze the dimensions and forms of the Si inclusions, technological experiments on growing Si nanocrystals on *n*-GaSb substrates (100) doped with Te at concentrations of $(1\text{-}5)\cdot 10^{17}$ cm^{-3} at a growth temperature of 600°C and growth time of 30 min were performed.

The following structures were obtained and investigated:

1. Tunneling p^{++}-n^{++} junctions without inclusions;
2. Tunneling p^{++}-n^{++} junctions with nanocrystalline Si inclusions in the SCR;
3. *p-n* junctions with nanocrystalline Si inclusions in the SCR.

The structure of connecting *p-n* junctions consisted of epitaxial *n*-GaSb layers with donor concentrations within the range of $(1\text{-}5)\cdot 10^{18}$ cm^{-3} and thicknesses of 0.8-1.0 μm and *p*-GaSb layers with acceptor concentrations within the range of $(1\text{-}6)\cdot 10^{18}$ cm^{-3} and thicknesses of 0.8-1.0 μm. The layer of nanocrystalline Si inclusions in the SCR of the *p-n* junction had a thickness of 10 to 30 nm.

No less important is the conservation of good quality characteristics of the photoactive junctions grown on the structures of the connecting elements with nanocrystalline Si inclusions. To investigate the effect of possible defects from introduction of Si nanocrystals on the characteristics of the "above" photosensitive *p-n* structure, structures were fabricated and investigated:

1. Photosensitive *p-n* junctions
2. Photosensitive *p-n* junctions connected with the substrate by a p^{++}-n^{++} junction;
3. Photosensitive *p-n* junctions connected with the substrate by a *p-n* junction with nanocrystalline Si inclusions in the SCR.

The photosensitive *p-n* junction has been grown on a *n*-GaSb (100) substrate. Its structure consisted of epitaxial *n*-GaSb layers (electron concentration of $1.5\cdot 10^{17}$ cm^{-3}, thickness of 1.5 μm) and *p*-GaSb (hole concentration of $(7\text{-}9)\cdot 10^{17}$ cm^{-3}, thickness of 1.5 μm).

RESULTS AND DISCUSSION

Fig. 1 presents a picture and statistics of Si nanocrystals grown on *n*-GaSb substrates (100) doped with Te obtained by means of an AFM microscope. It is seen from the analysis of obtained data that, at the growth temperature of 600°C during 30 min., Si nanocrystals are growing with the dimensions: height 1-5 nm and width 10-70 nm.

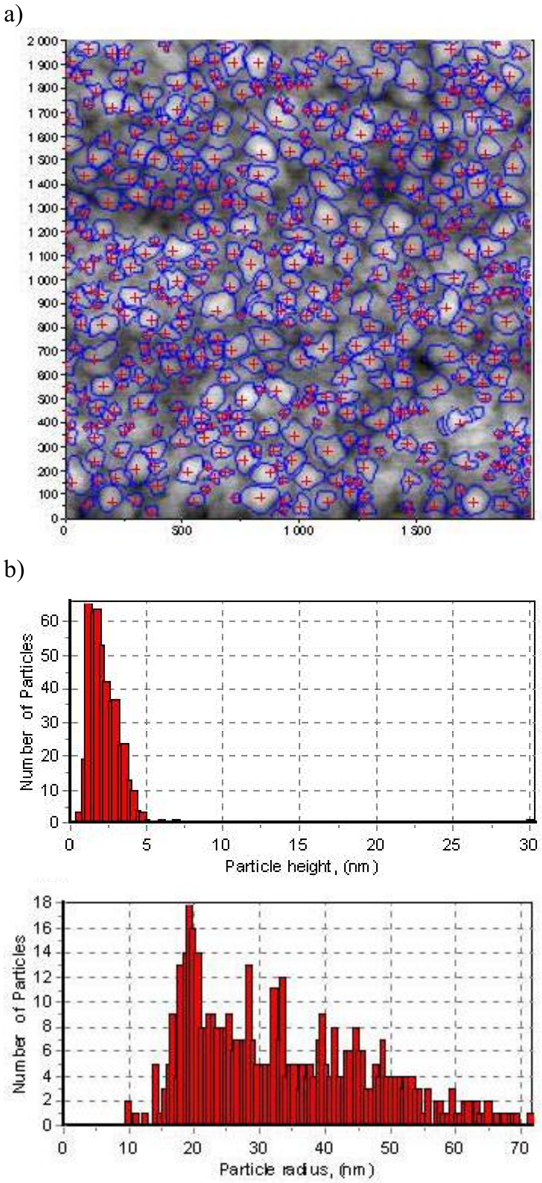


FIGURE 1. The data has been obtained by means of an AFM microscope: a) – picture of Si nanocrystals grown on the surface of the *n*-GaSb(Te) (100), (growth temperature 600°C, growth time 30 min.);
b) – statistics of linear dimensions of nanocrystals.

Forward dark *I-V* characteristics of the three formed connecting junctions were obtained and analyzed. It is seen from the data presented in

Fig. 1 that a barrier in the *p-n* junctions with nanocrystalline objects in the SCR is absent, and their *I-V* characteristics are similar to that of a resistance with resistivity less than 15 mOhm·cm^2 up to a current density of about 50 A/cm^2, as opposed to the case of the investigated tunneling junction with the peak current of about 13 A/cm^2.

Fig. 3 presents the spectral characteristics of the investigated photoactive structures (Fig. 2). The shapes of the obtained spectral characteristics are explained by the fact that the SC structure was not optimized and had no antireflection coatings, since, first of all, the problem of minimizing the effect of growth defects appearing from the layer of Si nanocrystals on the characteristics of the “grown” photoactive *p-n* structure had to be solved.

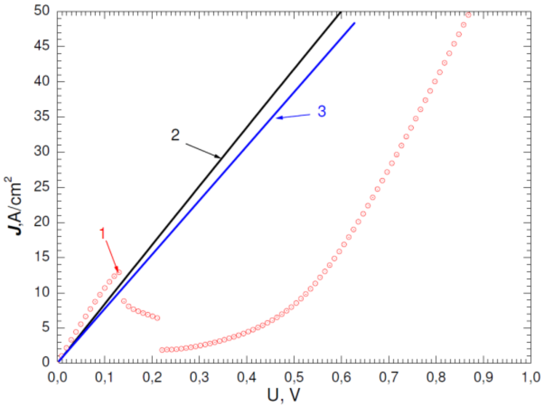


FIGURE 2. Dark *I-V* characteristics of GaSb structures: 1 – tunneling p^{++}-n^{++} junction;
2 – tunneling p^{++}-n^{++} junction with nanocrystalline Si inclusions in the SCR; 3 – p^{+}-n^{+} junction with nanocrystalline Si inclusions in the SCR.

It is clear from Fig. 3 that the spectral characteristics of the investigated structures (Fig. 4) are almost the same. This indicates that the defects arising for growing the photoactive *p-n* structure on the layer with Si nanocrystals may be compensated, and their effect on photovoltaic characteristics may be attenuated.

Measurements of the dark and light *I-V* characteristics were carried out at room temperature in the current density range of 10^{-8}-10^{2} A/cm^2. The load *I-V* characteristics were obtained at illumination by a semiconductor laser ($\lambda = 1.3$ µm, $h\nu = 0.95$ eV) creating irradiance up to 5 W/cm^2.

Fig. 4 presents the forward branches of the experimental dark *I-V* characteristics presented in Fig. 2: curve 1 – photoactive GaSb *p-n* junction on an *n*-GaSb substrate; curve 2 - photoactive GaSb *p-n* junction on a tunneling p^{++}-n^{++} junction, and curve 3 – photoactive GaSb *p-n* junction on a layer with nanocrystalline Si inclusions. That forms curves 2 and 3 are almost the same indicates that the connecting element with nanocrystalline Si inclusions does not lead to the deterioration of quality of the material of the photosensitive GaSb *p-n* junction layers.

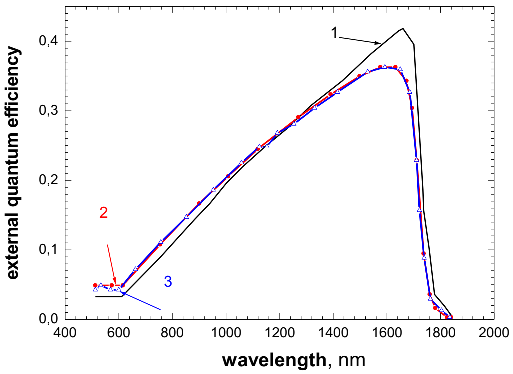


FIGURE 3. External quantum yield of GaSb photoactive *p-n* junctions: 1 – junction obtained on a *n*-GaSb substrate; 2 – *p-n* junction with a base *n*-layer connected with *p*-substrate by a tunneling p^{++}-n^{++} junction; 3 – *p-n* junction connected with a *p*-substrate by a layer with nanocrystalline Si inclusions.

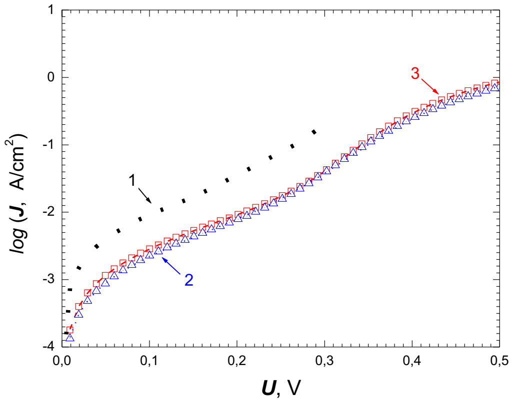
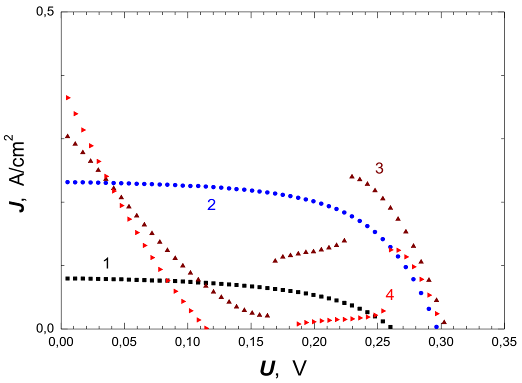


FIGURE 4. Dark forward *I-V* characteristics of GaSb structures: 1 – photoactive GaSb *p-n* junction grown on an *n*–GaSb substrate; 2 – photoactive GaSb *p-n* junction connected with a *p*–GaSb substrate by a tunneling p^{++}-n^{++} junction;
3 – photosensitive GaSb *p-n* junction connected with a *p*-GaSb substrate by a tunneling junction with Si nanocrystals in the SCR.

Fig. 5a and 5b present the load *I-V* characteristics of epitaxial structures with a photosensitive GaSb *p-n* junction connected to a *p*-GaSb substrate: a) – photosensitive GaSb *p-n* junction connected to a *p*-GaSb substrate by a tunneling p^{++}-n^{++} junction; b) – connected by a layer of Si nanocrystals. Note that in the structure, in which the photosensitive *p-n* junction is connected with the *p*-GaSb substrate by a tunneling p^{++}-n^{++} junction, a drastic increase of the structure resistance is observed with raising the laser illumination power (Fig. 5a, curves 2 and 3) owing to that the photocurrent exceeds the peak current of the tunneling junction. It seems, there is the effect of smearing out the doping profile of the tunneling junctions caused by diffusion of electrically active impurities during the following growth of the photoactive GaSb *p-n* junction. Whereas in the structure, where the photoactive GaSb *p-n* junction is connected with the substrate by a layer with nanocrystalline Si inclusions (Fig. 5b) this is not observed at photocurrent more than 0.5 A/cm^2.

a)



b)

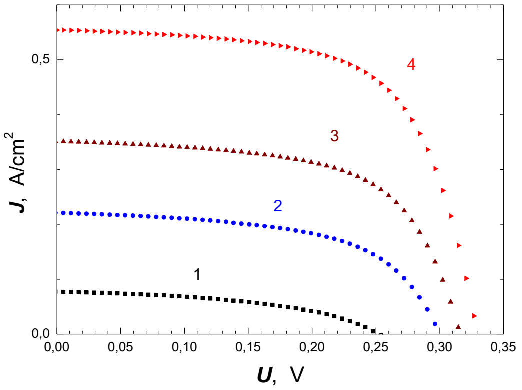


FIGURE 5. Load *I-V* characteristics of investigated (Fig. 2) structures at illumination by a laser ($\lambda = 1.3$ µm, $h\nu = 0.95$ eV): a) – photosensitive GaSb *p-n* junction connected with a *p*-GaSb substrate by a tunneling p^{++}-n^{++} junction; b) – connected by a layer of Si nanocrystals. For both figures, the presented curves are 1 – at $J_{sc} = 0.08$ A/cm^2; 2 – 0.23 A/cm^2;
3 – 0.35 A/cm^2; 4a – 0.4 A/cm^2 and 4b – 0.56 A/cm^2.

CONCLUSION

A technology for fabricating connecting elements by the MOCVD technique for MJ SC *p-n* junctions with nanocrystalline inclusions in the SCR has been elaborated. A Russian patent for this technological solution has been obtained [4]. As a result of carried out investigations, a new model of connecting elements, which can be applied for monolithic MJ SCs based on A^{III}B^{V} compounds, has been demonstrated. In the epitaxial structures based on A^{III}B^{V} compounds fabricated by the MOCVD technique, connecting elements – *p-n* junctions with nanocrystalline inclusions in the SCR instead of tunneling p^{++}-n^{++} junctions have been elaborated. An analysis of dark and load *I-V* characteristics of both conventional tunneling p^{++}-n^{++} junctions and new connecting elements based on structures with Si nanocrystals in the SCR of GaSb *p-n* junctions has been carried out. It has been shown that introduction of Si nanocrystals into the GaSb *p-n* junction SCR allows excluding the effect of peak current of the connecting tunneling junctions ensuring the resistivity of the photoactive *p-n* junctions in a MJ SC connected in series of the value of about 0.01 Ohm·cm^2 up to the current densities of about 50 A/cm^2. The obtained characteristics of the connecting elements with a layer of nanocrystalline objects in the SCR demonstrate the prospect and feasibility for their use in MJ SCs intended for conversion of highly concentrated sunlight.

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