GaSb STRUCTURES WITH QUANTUM DOTS IN SPACE CHARGE REGION

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ABSTRACT: In the paper, an attempt is described to increase conductivity and to exclude the effect of the tunnel junction on the multi-junction solar cells (MJSC) characteristics. Investigations have been carried out on creation of p^+- n^+ and p-n junctions, as connecting elements in a MJSC, in the space charge region (SCR) of which a layer of quantum dots (QD) is introduced. Epitaxial GaSb - based structures were fabricated by the MOCVD technique. In p-n junctions with quantum dots, a significant (by three orders of magnitude) increase of the forward current has been observed, which can be explained by formation the local channels for the charge carrier flow. It has been observed the reduction of the resistance of the I-V characteristic forward branch in p^+-n^+ junctions with QDs more than in 2 times compared with that in p^+-n^+ junctions without QDs.

Keywords: Quantum Dots, Multi-junctions Solar Cell, GaSb.

1 INTRODUCTION

The last decade is marked by an active introduction into practice of multijunction solar cells (MJSC) based on the III-V compounds [1,2] with the number of photovoltaic junctions more than two. This became feasible due to development of the MOCVD technology for wide-band (AlGaInP, GaAs) and narrow-band (InGaAs, Ge) materials. For example, in triple-junction cells based on Ge/(In)GaAs/InGaP/AlInP structures, three photoactive p-n junctions are commutated in monolithic heterostructure by means of two tunnel junctions. The number of connecting tunnel diodes rises with the number of p-n junctions and the entire structure resistance as well as optical losses increase. This lowers down the photogenerated current [3] and results in the efficiency drop at the concentrated sunlight. One of the feasible approaches to solving this problem sorting a layer of quantum dots in the space charge region (SCR) [4]. In this case, it is a possible to lower down the extremely high doping levels of p^{++} and n^{++} layers in tunnel junctions, to decrease the effect degradation of the tunnel junctions between the rear narrow-band photovoltaic junctions due to the electrically active impurity diffusion during the both the epitaxial growth of the top wide-band cascades and action of radiation [5], and also to reduce the entire structure resistance.

2 EXPERIMENTAL PROCEDURES

The GaSb-based structures with QD layer in the SCR have been fabricated by the MOCVD technique. The structures based on GaSb have been chosen as a part of narrow-bandgap tandem cell structures AlGaAsSb/GaSb/InGaAsSb for efficient conversion of IR band (λ > 900 nm) of solar spectrum.

The layer were grown on n-GaSb substrates oriented in the (100) plane and doped with Te with electron concentration of $(3\text{-}5)*10^{17}$ cm^{-3} and Ge with hole concentration of $(1\text{-}5)*10^{18}$ cm^{-3}. Triethyl gallium (TEGa) was used as the gallium source and trimethyl antimony (TMSb) – as the antimony source. Silan (SiH_4) was used as a source for acceptor impurity and a quantum dot's material. Diethyl tellurium (DETe) was used as a source for donor impurity.

The structure was the following (Fig. 1):

- n-GaSb substrate doped with Te with electron concentration of $(3\text{-}5)\cdot10^{17}$см$^{-3}$;
- epitaxial n^+GaSb layer doped with Te with electron concentration higher then $1\cdot10^{18}$см$^{-3}$. The layer thickness was about 0.7 µm;
- layer of quantum dots made of Si;
- epitaxial p^+GaSb layer doped with Si up to the hole concentration of $1\cdot10^{18}$ cm^{-3}, the layer thickness was about 1 µm.

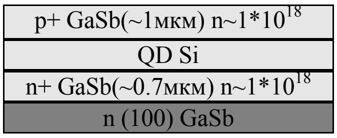

Figure 1: Schematic of a structure with heavily doped p^+ - n^+ junction including a layer of quantum dots in the SCR.

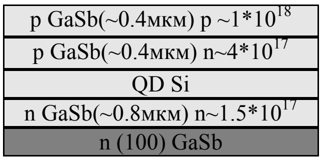

Figure 2: Schematic of a p-n junction structure with lower doping levels and with quantum dots in the SCR.

To elucidate the feasibility to use as connecting element between MJ SC cascades, p-n junction structures were grown with lower doping levels, in the SCR of which quantum dots were created. Fig.2 presents the schematic of the obtained structure:

- n-GaSb substrate doped with Te with the electron concentration of $(3\text{-}5)\cdot10^{17}$см$^{-3}$;
- epitaxial n-GaSb layer doped with Te with the electron concentration $1.5\cdot10^{15}$см$^{-3}$. This level is optimum one for the basic layers of photovoltaic junctions. The layer thickness was 0.8 µm.;
- Si layer of quantum dots;

- epitaxial p-GaSb layer doped with Si with the hole concentration higher than $4\cdot10^{17}$см$^{-3}$. The layer thickness was 0.4 µm;
- undercontact epitaxial p-GaSb layer doped with Si with the hole concentration higher than $1\cdot10^{18}$см$^{-3}$. The layer thickness was about 0.4 µm.

To estimate the quality of the junctions, two other types of structure were grown:

A) With heavily doped junction (Fig.3).

The p-n junction was connected with a substrate by means of a heavily doped junction. The structure was the following one:

- p-type substrate doped with Ge with the hole concentration of (1.2-1.5)$\cdot10^{18}$cm^{-3};
- epitaxial p+GaSb layer doped with Si with the hole concentration higher than $1\cdot10^{18}$cm^{-3}. The layer thickness was about 100 nm;
- epitaxial n+GaSb layer doped with Te with the electron concentration higher than $1\cdot10^{18}$см$^{-3}$. The layer thickness was about 100 nm;
- epitaxial n-GaSb layer doped with Te with the electron concentration up to $1.5\cdot10^{17}$cm^{-3}. The layer thickness was about 1.5 µm;
- epitaxial p-GaSb layer doped with Si with the hole concentration up to $7\cdot10^{17}$cm^{-3}. The layer thickness was about 1.5 µm.

p GaSb(~1,5мкм) p ~7*10^{17}
n GaSb(~1,5мкм) n~1.5*10^{17}
n+ GaSb(~0.1мкм) n~1*10^{18}
p+ GaSb(~0.1мкм) n~1*10^{18}
p (100) GaSb

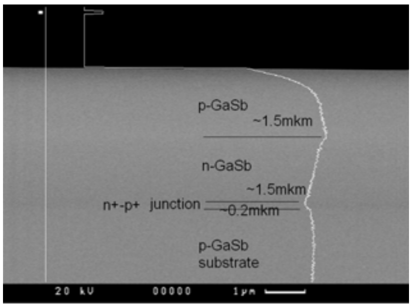

Figure 3: The structure with a heavily doped p$^+$-n$^+$ junction.

B) With a layer of quantum dots (Fig. 4).

The p-n junction was connected with a substrate by means of a layer of quantum dots. The structure was the following one:

- n-type substrate doped with Te with the electron concentration of (3-5)$\cdot10^{17}$cm^{-3};
- Si layer of quantum dots;
- epitaxial n-GaSb layer doped with Te with the electron concentration up to $1.5\cdot10^{17}$cm^{-3}. The layer thickness was about 1.5 µm;
- epitaxial p-GaSb layer doped with Si with the hole concentration up to $7\cdot10^{17}$cm^{-3}. The layer thickness was about 1.5 µm.

p GaSb(~1,5мкм) p ~7*10^{17}
n GaSb(~1,5мкм) n~1.5*10^{17}
QD Si
(100) GaSb

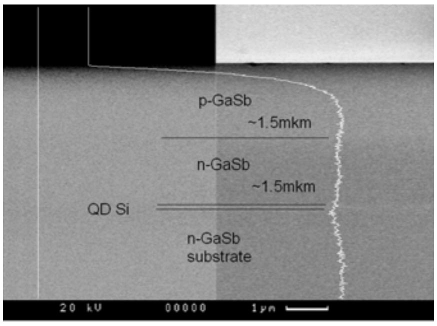

Figure 4: The structure with quantum dots.

3 RESULTS AND DISCUSSION.

The dark current-voltage characteristics of the structures and are presented in Fig.5 and 6.

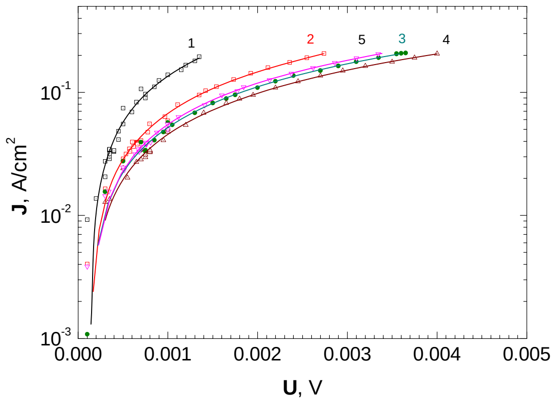

Figure 5: Dark current-voltage characteristics of the GaSb structures (300 K): 1, 2 – heavily doped p$^+$ - n$^+$ junctions, in the SCR of which Si quantum dots were grown; 3 – p-n junctions with grown Si quantum dots in their SCR, 4, 5 – heavily doped p$^+$ - n$^+$ junctions.

It is seen from the Fig.5 that the forward current in the structures of heavily doped GaSb diodes with Si quantum dots rises compared with heavily doped structures without QDs. In comparing the current values on the forward branch of the I –V characteristic (Fig.6) in GaSb p-n junctions and in p-n junctions with quantum dots at 0.01 – 0.02 V, a significant, by 3 orders of magnitude, rise of the forward current in the structures with quantum dots has been observed. This is explained by formation of local tunnel channels in the SCR in the structure with quantum dots. Note that the resistivity in the p-n junction structure with Si quantum dots in the SCR is nearly equal to that in the structures of heavily doped junctions and is less than 20 mOhm·cm^2 at the forward current density of 200 mA/cm^2.

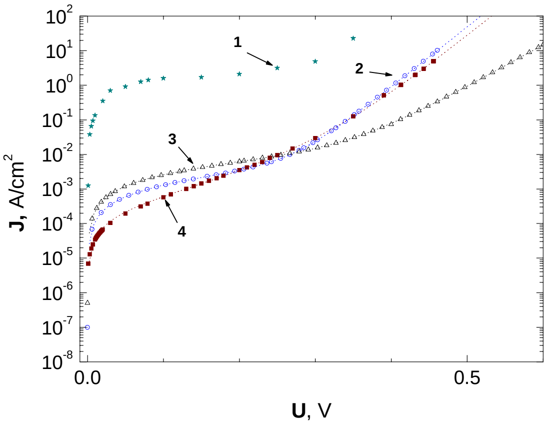

Figure 6: Dark current-voltage characteristic of GaSb structures: 1 – GaSb p-n junction with Si quantum dots in the SCR obtained by the MOCVD technique; 2 – GaSb p-n junction grown by the MOCVD technique on a heavily doped GaSb p^+ - n^+ junction; 3 – GaSb p-n junction grown on a layer of Si quantum dots by the MOCVD technique; 4 – GaSb p-n junction obtained by Zn diffusion into a substrate.

The dark *J-V* characteristics of the following structures: GaSb p-n junction grown by the MOCVD on a heavily doped GaSb p^+ - n^+ junction (Fig.3); GaSb p-n junction grown on a layer of Si quantum dots by the MOCVD technique (Fig.4); photovoltaic GaSb p-n junction obtained by Zn diffusion into a GaSb substrate, are presented in Fig.6. These I-V curves have been obtained from the combination of measurements of current-voltage, and open circuit voltage under laser radiation (λ=1.3 μm), [6]. Practically, for all studied structures, the dark *J-V* characteristic in the current density range of 10^{-8} – 10^{1} A/cm^2 are approximated by a sum of three components of an exponential shape

$$J = J_0(\exp\frac{qV_j}{AkT} - 1)$$

and has, correspondingly, three components: tunneling-trap one (diode coefficient $A > 2$), recombination one (Sah, Noyce, Shockley), ($A = 2$) and diffusion one ($A = 1$). The current boundary between the recombination and diffusion components for the GaSb p-n junctions grown on heavily doped GaSb p^+ - n^+ junction and for the photovoltaic GaSb p-n junction obtained by Zn diffusion was ~ 0.1 A/cm^2 and diffusion preexponential factors (J_{0d}) were correspondingly, 10^{-7} and $5.6 \cdot 10^{-8}$ A/cm^2. The lowest value of the preexponential factor was in the p-n junctions grown on a layer with Si quantum dots and was $J_{0d} \approx 5 \cdot 10^{-7}$ A/cm^2, i.e. it exceeded this value by an order of magnitude compared with the p-n junction obtained by Zn diffusion into a substrate. In the p-n junction structure grown on the layer of Si quantum dots, a combination of the recombination and diffusion mechanisms of current flow at the current densities of $\geq 10^{-1}$A/cm^2 is observed. This can be explained by residual growth defects in the GaSb p-n structure grown directly on the layer with Si quantum dots.

4 CONCLUSION

Heavily doped p^+ - n^+ junction in GaSb and p-n junctions with a layer of quantum dots in the SCR have been obtained. Increase of the forward current in GaSb structures of heavily doped diodes with Si quantum dots in the SCR was observed compared with structures without QDs. The current value on p-n junction with quantum dots SCR at voltages of 0.01-0.02 V are by 3 orders of magnitude higher than the current without QDs. In the structure with Si quantum dots in the SCR, the resistivity is nearly equal to that in the structures of heavily doped junctions and is less than 20 mOhm·cm^2 at the forward current densities of 200 mA/cm^2.

As follows from above, replace of tunnel junctions in a MJSC by a layer with quantum dots is feasible. In this case, the negative effect of heavily doped layer of tunnel p^{++} - n^{++} junctions decreases, and the number of grown layers in a MJSC reduces.

Introduction of quantum dots for commutating the p-n junction in a MJSC is more natural compared with the approach, at which semimetal islands are used for this purpose [7], bearing in mind also technological feasibilities for forming such a structure by the MOCVD technique.

At present, the works on creating the layers with quantum dots in GaAs and in solid solutions based on GaAs are in progress for application in the MJSC structures.

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