The study of voltage loss reasons in GaAs solar cells with embedded InGaAs quantum dots

R A Salii¹, V V Evstropov², S A Mintairov², M A Mintairov¹, M V Nakhimovich², M Z Shvarts² and N A Kalyuzhnyy²

¹ Submicron Heterostructures for Microelectronics, Research & Engineering Center, 194021, St. Petersburg, Russia
² Ioffe Institute, Saint Petersburg, 194021, Russia

Abstract. In the work the effect of the number of In0.8Ga0.2As stacked quantum dots (QDs) embedded in a single-junction GaAs solar cell (SC) on its photoelectric characteristics has been studied. A series of GaAs SC structures, which differed by a number of embedded QD layers, were grown using metalorganic vapor phase epitaxy. By analyzing the electroluminescence spectra and the current–voltage characteristics of the obtained structures the main reason for the voltage loss in SC with QDs has been established which is an increase in recombination through the QD levels with an increase the number of QD layers.

1. Introduction
Solar cells (SC) based on A₃B₅ semiconductor heterostructures are one of the most effective solutions for solar energy conversion. During last two decades lattice-matched GaInP/GaAs/Ge SCs have been the most investigated structures for space applications. One of the factors limiting the efficiency of SC based on such material system is the current mismatch between GaInP, GaAs and Ge subcells [1]. Low photocurrent of middle GaAs subcell (figure 1a) reduces total short-circuit current of whole structure and limits the maximum achievable efficiency of the SC.

Figure 1. Structure and subcells’ quantum yield spectra for usual triple-junction SC (a) and current-matched triple junction SC with embedded QDs in GaAs subcell (b).
Recently, an approach that can provide an increase in the photocurrent of the middle GaAs subcell by embedding quantum dot (QD) arrays has been developed [2]. An increase in the photocurrent can be achieved due to the absorption of sub-bandgap photons by a QD array, which will make it possible achieving photocurrent balance between subcells of a multijunction structure (figure 1b). The increase in the photocurrent of middle subcell leads to an increase in the efficiency of the whole SC structure [3].

However, in SC with integrated InAs QD arrays there are a number of issues which do not allow achieving high efficiency. The main problem is a decrease in the open-circuit voltage ($V_{OC}$) [4]. Studies devoted to the introduction of QDs in a single-junction GaAs SC showed that, along with an increase in photocurrent the $V_{OC}$ loss occurs, which minimize the achieved advantage [5]. The aim of this work is to establish the main reason of such $V_{OC}$ loss using GaAs SC with embedded In$_{0.8}$Ga$_{0.2}$As QD arrays.

2. Experimental procedure
The GaAs SCs under study were grown using metalorganic vapor phase epitaxy. The samples differed in the number of QD layers in the array from 1 to 20. The growth was carried out according to the following technological process. Back potential barrier $n$-Al$_{0.3}$Ga$_{0.7}$As layer, $n$-GaAs base, and a part of GaAs $i$-region were grown at 700 °C. Then the reactor was cooled down to 520 °C for QD material deposition. The In$_{0.3}$Ga$_{0.7}$As material was deposited for growth of coherent islands in the Stranski-Krastanov mode. The growth rate was 0.167 ML/sec [6]. Then the epitaxial growth was stopped for a post-growth interruption step. At this step the structure was kept during several seconds at stabilized temperature equal to the QD growth temperature in order islands to completely form. After that, the formed QDs were covered with GaAs layer at the same temperature in order to protect islands from degradation during the subsequent reactor heating up to 600 °C for GaAs spacer layer growth. The GaAs spacer thickness was 35 nm. The process was repeated according to the number of embedded QD layers, and then the rest of $i$-GaAs layer, $p$-GaAs emitter, $p$-$Al_{0.3}Ga_{0.7}$As "window" and $n$-$GaAs$ contact layer were grown at 700 °C. The In$_{0.8}$Ga$_{0.2}$As material amount for the QDs formation was chosen according to the previous study and was 2 ML (~0.6 nm) [7].

To study the current flow mechanisms in a p-n junction with embedded QDs IV - curves and electroluminescence (EL) spectra were measured. Electroluminescence spectra have been measured using a fiber-optic spectrophotometer based on a 2048 elemental CCD detector matrix with high photometric sensitivity in the spectral range of 200–1100 nm and an optical resolution of 0.04–20 nm. The EL spectra were recorded at current density of 0.128 A/cm$^2$ using a stabilized current source. To prevent uncontrolled heating, the sample was mounted on a thermostatic surface with a digital temperature controller.

3. Results and discussion
EL spectra show three peaks (figure 2) which associated with bulk GaAs (1.42 eV), QDs wetting layer (WL) (~1.32 eV), and QDs (1.21-1.23 eV). The shape of the EL spectrum for 1-layer’ SC significantly differs from other spectra which allow assuming that QDs multilayering leads to a change in its physical properties. This fact is also confirmed by the fact that the shape of the spectra in the energy range of less than 1.42 eV is close to structures with 2 - 20 layers, and a change with increasing the layers number only affects the level of the peaks (figure 2).

The red-shift of WL and QD peaks is observed while the number of QDs layers increases from 2 to 20. The similar behavior was previously observed for SCs with other InGaAs nanostructures [8] and was explained by the redistribution of elastic strain between nanostructures and spacer layers. The structure with 1 QD layer also does not fit into this dynamics. It demonstrates WL and QD peaks whose energy is greater than that of all other structures (figure 2).

The obtained EL spectra demonstrate a noticeable effect of the number of QD layers on spectrum shape. As it increases, radiative recombination via the bulk GaAs decreases in comparison with recombination via QDs levels. For SC with one QD layer EL intensity of GaAs peak is 10 times and 20 times higher than that of WL and QD peaks respectively. At the same time for SC with 2 QD layers
it is three times higher and for 20-layers SC it is two times lower. This leads to the conclusion that the recombination via QDs during current flow gradually becomes dominating over recombination via GaAs with increasing the number of QD layers.

Figure 2. EL spectra normalized to GaAs EL peak for GaAs SCs with different numbers of In_{0.8}Ga_{0.2}As QDs layers recorded at current density of 0.128 A/cm², (curves) and calculated $E_A$ for unary current flow mechanism (vertical lines).

At the same time the dependences of $V_{OC}$ on the photocurrent ($J_g$) demonstrate a decrease of $V_{OC}$ with increasing QD layers (figure 3) which allows relating the value of $V_{OC}$ with the rate of recombination via QDs. It is known that a change in $V_{OC}$ ($\Delta V_{OC}$) indicates a change in the band gap of the p-n junction material [9]. This is due to the fact that the saturation current $J_0$, which determines $V_{OC}$, depends on a material energy gap ($E_g$). On the other hand, $J_0$ is determined by the rate of carrier recombination.

In p-n junctions with QDs, carriers can recombine both via the matrix and via QDs transitions. Since QDs have different $E_g$, $\Delta V_{OC}$ characterizes which part of the carriers combines via the bulk GaAs and which via the QDs. Thus, $\Delta V_{OC}$ characterizes an average energy ($E_A$) of carrier recombination. To calculate $\Delta V_{OC}$ we determined $J_0$ values for each sample by approximating the $V_{OC}$-$J_g$ dependences, which represents non-resistive dark IV-curve [10], using a two-diode model. The calculation has been made for the ideal Shockley (unary) component. The calculations were performed according to the procedure described in [10].

Using obtained values, the values of $E_A$ were found as the difference between the $E_g$ of GaAs and $q\cdot \Delta V_{OC}$. In figure 2 these values marked as vertical lines. It is seen that with an increase in the number of QD layers, $E_A$ shifts to the low-energy region, i.e. into the QDs absorption region.

It can be noted that the structure with one QD layer demonstrates insignificant VOC drop (figures 2 and 3). This correlates well with the low level of recombination via QD levels for this structure (figure 2). It can be said that with the introduction of one QD layer in the SC, recombination through the bulk GaAs dominates. A significant $V_{OC}$ drop occurs with the introduction of two QD layers, and after that an increase in the layers leads to a relatively slow decrease in the voltage (figure 2). For structures with 15 and 20 QD layers, $E_A$ is close to the long-wavelength edge of the QDs EL peak. This suggests that for these structures the recombination via QDs dominates, and a further increase in the number of QD layers should saturate the dynamics of the voltage drop.
Figure 3. $V_{OC}$-$J_g$ dependencies for GaAs SCs with different numbers of In$_{0.8}$Ga$_{0.2}$As QDs layers and for a reference solar cell (without QDs): symbols – experimental data, lines – two diodes model approximation.

Thus, the obtained data shows that the main mechanism affecting $V_{OC}$ loss in GaAs SC with QD arrays is an increase in recombination via QD levels caused by an increase in the number of QD layers in the array. The results should be taken into account for the structural design of both single and multi-junction solar cells.

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References
[1] Algora C and Rey-Stolle I 2016 Handbook of concentrator photovoltaic technology (John Wiley & Sons, The Atrium, Southern Gate, Chichester, West Sussex, UK)
[2] Luque A and Marti A 1997 Phys. Rev. Lett. 78 pp 5014–5017
[3] Kerestes C, Polly S, Forbes D, Bailey C, Podell A, Spann J, Patel P, Richards B, Sharps P and Hubbard S 2016 Progr. Photovolt. 22 1172
[4] Sogabe T, Shen Q, Yamaguchi K 2016 J. Phot. Ener. 6(4) 040901
[5] López N, Marti A, Luque A, Stanley C, Farmer C, Diaz P 2007 J. Sol. Ener. Eng.129 p 319
[6] Salii R A, Mintairov S A, Mintairov M A, Nadtochiy A M, Shvarts M Z and Kalyuzhnyy N A 2018 J. Phys.: Conf. Ser. 1038 012110
[7] Salii R A, Kosarev I S, Mintairov S A, Nadtochiy A M, Shvarts M Z and Kalyuzhnyy N A 2018 Semicond. 52 1 pp 870–876
[8] Mintairov S A, Evstropov V V, Kalyuzhny N A, Maximov M V, Mintairov M A, Nadtochiy A M, Pavlov N V, Shvarts M Z and Zhukov A E 2020 Appl. Phys. Express 13 015009
[9] King R R, Bhusari D, Boca A, Larrabee D, Liu X-Q, Hong W, Fetzer C M, Law D C, Karam N H 2010 Prog. Photovolt: Res. Appl. 19 797–812
[10] Mintairov M A, Evstropov V V, Shvarts M Z, Mintairov S A, Salii R A and Kalyuzhnyy N A 2016 AIP Conf. Proc. 1748 050003