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Optical properties of In$_{0.8}$Ga$_{0.2}$As quantum dots in GaAs photovoltaic convertors

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Abstract. In the work, GaAs photovoltaic convertor structures with embedded In$_{0.8}$Ga$_{0.2}$As arrays of quantum dots (QDs) have been obtained by metalorganic vapor-phase epitaxy. Spectral characteristic of internal quantum yield showed two spectral peaks at 930 and 985 nm of photosensitivity beyond the GaAs absorption edge. A theoretical calculation of the band transitions in the nanoheterostructure showed that the peak at 930 nm corresponds to the electron–heavy-hole band transition in the wetting layer of QDs, while the long-wavelength peak at 985 nm corresponds to InGaAs QDs. Contributions of both QDs and wetting layer to the total photocurrent of the devices with the different number of QDs have been calculated.

1. Introduction

Photovoltaic converters (PVCs) based on AlIIIBV semiconductor heterostructures are ones of the most effective solutions among renewable energy sources. However, today, in this field of photovoltaics, there are still a number of unresolved problems related to various fundamental loss mechanisms that prevent the efficiency of such PVCs from approaching the theoretical limit [1]. At the present time, one of the most successful approaches allowing to significantly reduce the fundamental losses are multijunction solar cells [2], in particular, based on the lattice-matched InGaP/GaAs/Ge material system. In such PVCs, the efficiency increases due to absorbing radiation of different parts of the solar spectrum by different subcells of a multijunction structure.

However, multijunction PVCs still have several unsolved issues such as current mismatch between their subcells due to low photogenerated current of the middle GaAs junction. It reduces total current of the whole structure and limits the maximum achievable efficiency of a PVC. One of the ways to solve the problem is the embedding the quantum-size objects in GaAs to create a subbandgap, what allows absorbing radiation of an additional part of the solar spectrum increasing the photogenerated current of the GaAs subcell. Also, in the last two decades, the models describing one-junction based PVC with an intermediate band (IB) is actively developing. Theoretically, IB PVCs allow absorbing radiation of a wide solar spectrum due to multiphoton absorption processes in semiconductor structures based on a single p-n junction [4]. For practical realization of both multijunction PVCs with current balance and IB PVC, the arrays of InAs quantum dots (QDs) embedded in GaAs [5] can be proposed.

The aim of this work is to obtain GaAs PVCs with embedded In$_{0.8}$Ga$_{0.2}$As QD arrays, which have better relaxation parameters in the GaAs matrix compared with classic InAs QDs. The electro-optical properties of In$_{0.8}$Ga$_{0.2}$As QDs are investigated, and their contribution to GaAs PVC photocurrent is determined.
2. Experimental procedure
All structures were grown by metalorganic vapor-phase epitaxy (MOVPE) on a R&D installation with a horizontal type reactor at low pressure (100mbar). A series of structures of single-junction GaAs PVCs differed by the number of embedded QD layers in a wide range from 1 to 20 layers. The schematic structure of experimental samples is shown in Fig. 1. The growth carried out according to the following technological process: after growing the $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ rear potential barrier, the n-GaAs base and a part of the GaAs i-region were grown at 700°C, and then the reactor was cooled down to QD material deposition temperature of 520°C. Then, the $\text{In}_{0.2}\text{Ga}_{0.8}\text{As}$ material was deposited for nucleation of coherent islands in the Stransi-Krastanov mode \[6\] with forming a wetting layer (WL). After that, the QDs were covered with GaAs cap layer at the same temperature in order to protect them from degradation during the subsequent reactor heating to the GaAs spacer layer growth temperature (600°C). The GaAs spacer thickness was 35 nm. The process repeated according to the number of embedded QD layers, and then the rest of the i-GaAs and p-GaAs emitter, $\text{Al}_{0.8}\text{Ga}_{0.2}\text{As}$ "window" and n+GaAs contact layer were grown at the temperature of 700°C. The amount of the $\text{In}_{0.8}\text{Ga}_{0.2}\text{As}$ material for QDs formation was chosen according to the previous study, which was devoted to determination of the maximum photoluminescence (PL) intensity of $\text{In}_{0.8}\text{Ga}_{0.2}\text{As}/\text{GaAs}$ heterostructures and was 2 ML (~6 Å) \[7\]. Also a reference structure without QD layers (reference GaAs PVC) was created.

PVCs based on grown structures were created by expedited procedure due to forming metallic front and rear contacts and subsequent etching the p+GaAs contact layer from the photoactive surface.

![Figure 1. GaAs PVC experimental structure](image)

A multifunctional installation has been used for measuring the internal quantum efficiency (IQE) of the PVCs. The measuring hardware included an unblocked ultra-violet halogen light source, a grating monochromator with 2 nm/mm dispersion within 300–1200 nm wavelength scanning range, and an optical chopper of 90 Hz and high sensitivity lock-in electronics. The IQE measurement was controlled by a laptop. The lock-in technique allows weakling output signals at the QD sensitivity range to be detected confidently.

3. Results and discussion
Fig. 2a shows the spectral characteristics of IQE of a PVC with QD arrays in comparison with GaAs PVC reference sample. Embedding the $\text{In}_{0.8}\text{Ga}_{0.2}\text{As}$ QD layer into aGaAs PVC does not lead to the IQE drop in the GaAs absorption range up to 20 InGaAs QD layers. This indicates an improvement in
the quality of the active region with the InGaAs QDs due to better relaxation of the medium in comparison with InAs QDs grown by MOVPE [8, 9].

In the long-wavelength part of the spectrum beyond the GaAs absorption edge (in the range of 880 – 1100 nm) a sharp peak at 930 nm and a long-wavelength peak in the region of ~985 nm have been observed (Fig. 2 b).

Figure 2. Spectral characteristics of the internal quantum yield of a GaAs PVC with embedded In$_{0.8}$Ga$_{0.2}$As QD arrays, a – whole spectra, b – scaled part of QDs contribution.

To identify spectral peaks, a model of QW was suggested for describing WL. Theoretical calculation of energy transitions for InGaAs/GaAs QW based on model-solid theory [10] was carried out. According to the model calculation, the position of the spectral peak at 930nm (1.33eV) corresponds to the electron–heavy-hole (Ee-Ehh) transition in the In$_{0.8}$Ga$_{0.2}$As wetting layer (Fig.2b “WL Ee-Ehh”). The upper estimate of the WL thickness is 5.2Å (Fig.3). For such a thickness, the energy of electron–light-hole (Ee-Elh) transition is 1.39eV (892 nm) (Fig.2b “WL Ee-Elh”), so it is not observed on the spectral characteristic due to overlapping by the blurred GaAs absorption edge [11] in the range of 870 – 900 nm. Thus, the spectral peak at ~985 nm obviously corresponds to the contribution of QDs (Fig. 2 b “QDs”).

Figure 3. Theoretical calculation of energy transitions in a InGaAs/GaAs QW.
Fig.4 shows a linear increase of the maximum internal quantum yield (IQY) values for both WL peak (Ee-Ehh transition) and QD peak with increasing the quantity of QD arrays. The obtained data correlate with both current contribution of QDs and the total current contribution of QDs and WL versus a number of embedded QD arrays for AM0 and AM1.5 solar spectra after normalizing to one layer (Fig.5). These contributions were calculated separately according to the data obtained in analyzing the spectral characteristics and classification of the spectral peaks described above. The total maximum WL and QD contribution to the photocurrent of a PVC with 20 QD layers in the active region was 1.2 mA/cm² and 1.03 mA/cm² for the AM0 and AM1.5 spectra, respectively. The contribution of QDs remains constant (~0.006 mA/cm²) with increasing the number of embedded QD layers in the PVC structure (Fig.5, blue and magenta curves). Total contribution of WL and QDs normalized to one QD layer slightly decreased from 0.06 mA/cm² (structure with 1 and 3 QD layers) to 0.05 mA/cm² (structures with 5 - 20 QD layers) for the AM0 spectra, and from 0.05 mA/cm² (structure with 1 and 3 QD layers) to 0.04 mA/cm² (structures with 5 - 20 QD layers) for the AM1.5 spectra (Fig.5, black and red curves). Thus, the total contribution of QD and WL decreases with increasing the number of QD layers up to 5 and then practically does not change with the QD layer increase up to 20.

![Graph 1](image1.png)

**Figure 4.** Maximum values of IQY for WL peak at 930 nm (black line) and QDs peak at 965 nm (red lone).

![Graph 2](image2.png)

**Figure 5.** Total photocurrent contribution per one layer for WL and QDs (black and red curves for AM0 and AM1.5 spectra, respectively) and QDs photocurrent contribution (blue and magenta lines for AM0 and AM1.5 spectra, respectively).

This indicates that the quality of the QD array remains practically unchanged, what correlates with the data on the quality of the GaAs p-n junction with embedded QD arrays discussed above.

**Conclusions**

In the work, an experimental analysis of In0.8Ga0.2As QD arrays formation in the GaAs matrix by the MOVPE in the Stranski-Krastanov mode was carried out. The internal quantum yield of the reference GaAs PVC, as well as the PVCs with embedded 1, 3, 5, 7, 10, 15 and 20 layers of InGaAs QDs was measured. It has been shown that the p-n junction quality is practically the same even for 20 QD layers embedded in the PVC structure. It has been demonstrated that the main contribution to the photogenerated current of a PVC is done by the WL of the QDs, as shown through classification of the spectral peaks of IQY by theoretical calculations of the energy transitions by the InGaAs/GaAs quantum well model. It is established that, with increasing the number of embedded QD layers, their contribution to the photocurrent became constant after staking more than 5 QD layers up to 20 QD layers in an array. The total maximum WL and QD contribution to the photocurrent of a PVC with 20 QD layers in the active region was 1.20 mA/cm² and 1.03 mA/cm² for the AM0 and AM1.5 spectra,
respectively. The developed MOVPE for growing In\textsubscript{0.8}Ga\textsubscript{0.2}As QD arrays is promising for both IB SCs and multijunction SCs with improved current balance.

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