ISSN 1063-7850, Technical Physics Letters, 2012, Vol. 38, No. 11, pp. 1024–1026. © Pleiades Publishing, Ltd., 2012.
Original Russian Text © S.A. Blokhin, A.M. Nadtochiy, S.A. Mintairov, N.A. Kalyuzhny, V.M. Emel'yanov, V.N. Nevedomsky, M.Z. Shvarts, M.V. Maximov, V.M. Lantratov, N.N. Ledentsov, V.M. Ustinov, 2012, published in Pis'ma v Zhurnal Tekhnicheskoi Fiziki, 2012, Vol. 38, No. 22, pp. 43–49.

Influence of the Position of InGaAs Quantum Dot Array on the Spectral Characteristics of AlGaAs/GaAs Photovoltaic Converters

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Received May 25, 2012

Abstract—Results of a comparative study of the internal quantum yield of AlGaAs/GaAs photovoltaic converters (PVCs) with variable position of the array of vertically coupled InGaAs quantum dots (QDs) are presented. It is established that the QD array placed immediately at the *i*-region/base interface does not change the PVC sensitivity compared to that for QDs arranged inside the *i*-region of the *p*–*n* junction. However, the QD array shifted to the base or the back potential barrier decreases the contribution of a base layer to the PVC photocurrent and reduces the photosensitivity of the QD-based medium.

DOI: 10.1134/S1063785012110193

Photovoltaic converters (PVCs) are among the most promising alternative energy sources. However, the low efficiency of PVCs, which is related to various mechanisms of losses, prevents their wide implementation in practice [1]. A traditional approach based on the serial connection of single-junction solar cells (SCs) with various bandgaps into multijunction (cascade) heterostructure PVCs provides only a partial solution to the problem [2]. In recent years, it has been proposed [3–5] to use zero-dimensional quantum-sized heterostructures (so-called quantum dots, QDs) for more effective matching of the absorption spectra of cascades, while retaining the pseudomorphous regime of PVC structure growth.

The present investigation has been devoted to complex optimization of an absorbing medium based on InGaAs QDs (QD medium) with the aim to increase the efficiency of photovoltaic energy conversion in these structures.

The task of ensuring effective collection and separation of charge carriers photogenerated in QDs is a key problem encountered in the development of high-efficiency photoelectric QD-media. Previously, we have demonstrated [6] that the main mechanism of carrier emission from isolated In(Ga)As quantum dots is based on thermal activation, whereas, in the case of vertically coupled QDs, the carriers are predominantly emitted by tunneling in a pulling field of the *p*–*n* junction. In this context, the question of optimum positioning of a QD medium in PVXCs is topical.

We have employed the principal design of an AlGaAs/GaAs heterostructure PVC based on the photovoltaic *p*–*n* junction in GaAs (*p*-emitter/*n*-base) with a *n*-AlGaAs back potential barrier and a thin *p*-AlGaAs broad-bandgap window [1] and prepared a series of samples with various positions of the QD medium. Al samples were grown by the method of molecular-beam epitaxy on Si-doped (001)-oriented GaAs substrates in a Riber MBE 49 setup. Self-assembled QDs were formed in the course of growth according to the Stranski–Krastanov mechanism [7]. The QD medium was represented by ten rows of InGaAs quantum dots separated by 10-nm-thick GaAs spacers and had a total thickness of 130 nm. Five variants of PVC structures have been prepared: (i) with QD medium inside the *i*-region of the *p*-*n* junction (*i*-QD-SC structure); (ii) with QD medium at the *i*-region/base interface (*i*-Base-QD-SC structure); (iii) with QD medium inside the base at a distance of 200 nm from the *i*-region (Base-QD-SC structure); (iv) with QD medium near the back potential barrier (BSF-QD-SC structure); and (v) without QD medium, but with the same total thickness (130 nm) of the *i*-region (Ref-SC).

The structural perfection of the synthesized QD arrays was studied by transmission electron microscopy (TEM) on a JEM-2100F (JEOL) instrument operating at an accelerating voltage of 200 kV. The lateral spatial resolution was 0.1 nm for all PVC structures with QD-media. The samples for TEM measure-

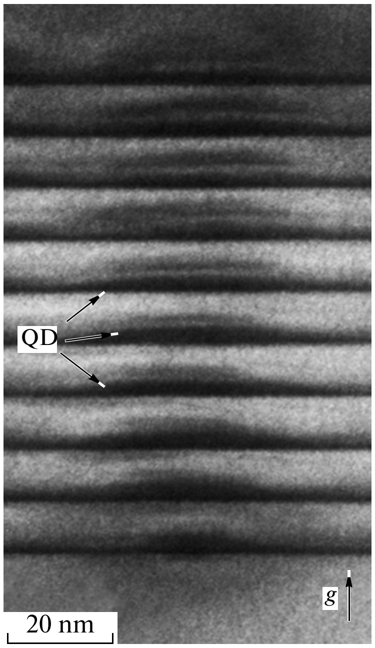

Fig. 1. Dark-field image of the (110) transverse section of vertically coupled InGaAs quantum dots in an *i*-QD-SC structure measured by TEM in a double-beam regime with operative diffraction vector $g = (002)$. The diffraction vector direction, which coincides with that of the structure growth, is indicated by arrow *g* in the bottom right corner. The $g = (002)$ reflection is composition-sensitive, whereby the bright contrast corresponds to GaAs layers and the dark contrast corresponds to InGaAs quantum dots (indicated by the QD arrows). Additional contrast above the QDs is related to elastic stresses that are manifested in the TEM image due to influence of the $g = (004)$ reflection on the primary beam intensity.

ments were prepared using the conventional procedure with mechanical polishing followed by 5-keV Ar^+ ion sputtering until perforation. Analysis of the obtained TEM images revealed strong correlation between the arrangement of QDs in various layers and showed vertical alignment (coupling) of QDs into columns, while the lateral dimensions and heights of QDs varied rather slightly (within ~10%) from bottom to top layers.

Figure 1 presents a typical image of vertically coupled InGaAs quantum dots as observed in the geometry of the (110) transverse section. Moreover, the TEM investigation showed the formation of neither dislocations in elastically stressed QD arrays nor extended defects related to the substrate. This result allows the density of threading dislocations to be estimated as being below 5×10^6 cm^{-2} (detection limit of TEM), which is evidence of a high structural perfection and the growth of dislocation-free QDs. It should be noted that the position of a QD medium relative to the *p*–*n* junction influences neither the density of defects nor the structural and optical characteristics of QD arrays.

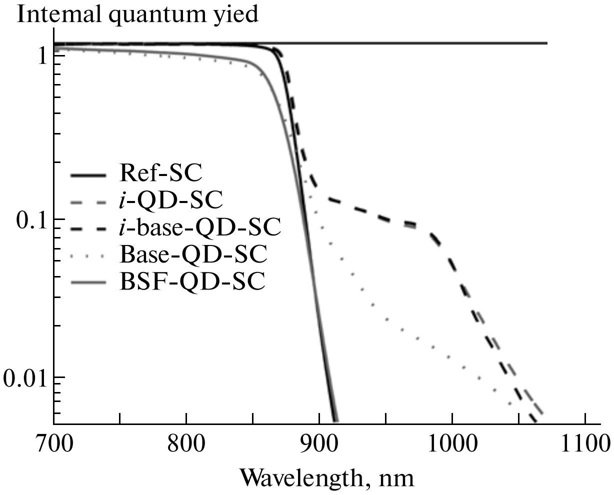

Fig. 2. Spectra of the internal quantum yield in AlGaAs/GaAs single-junction PVCs of various types.

Figure 2 shows typical spectra of the internal quantum yield of various PVCs measured in a 600–1100 nm wavelength range, in which contributions of the *i*-region and base layer to the photocurrent is significant. The introduction of a QD medium into the *i*-region (*i*-QD-SC and *i*-Base-QD-SC) leads to considerable expansion of the spectral range of PVC sensitivity (from 900 to 1080 nm) due to the separation of electron–hole pairs photogenerated in QDs via nonresonant tunneling between adjacent vertically coupled QDs within one column. The possibility of the spatial transfer of carriers via QD column and the action of a pulling field of the *p*–*n* junction ensure the effective transport of carriers between QD rows. It should be noted that the appearance of dislocations in the QD medium would lead to a decrease in the lifetime of carriers photogenerated in the *i*-region and *p*-emitter and, hence, to a drop in the internal quantum yield in the spectral range of GaAs photosensitivity [8, 9]. However, the results of TEM measurements and a good coincidence of the spectra of internal quantum yield of *i*-QD-SC and Ref-SC in the photosensitivity range of GaAs (<900 nm) show evidence of the dislocation-free growth of vertically coupled QDs and the retained high structural perfection of the *p*–*n* junction [7].

The QD medium placed directly at the *i*-region/base interface does not change the PVC sensitivity compared to that for QDs arranged inside the *i*-region of the *p*–*n* junction. However, a shift of the QD array to the base (at a distance of 200 nm from the *i*-region/base interface) or the back potential barrier, where the pulling field of the *p*–*n* junction (and, hence, the probability of carrier emission from QDs) decreases, results in a significant decrease of photocurrent in the spectral range of QD sensitivity. For the QD medium occurring at the back potential barrier, the PVC photosensitivity at wavelengths above 900 nm

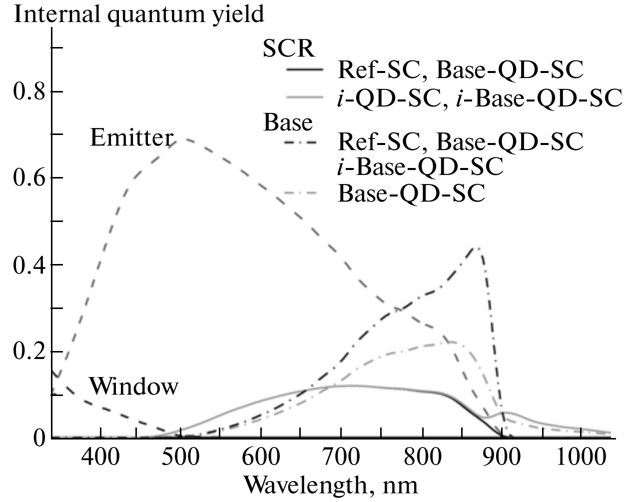

Fig. 3. Contributions of various layers to the spectral characteristics of AlGaAs/GaAs heterostructure PVCs with QD array (SCR = space-charge region).

vanishes because of a negligibly small rate of carrier emission from QDs in the absence of the pulling field of the *p*–*n* junction in this region of the structure. In both latter cases, the photocurrent also sharply drops in the spectral range of GaAs photosensitivity.

In order to quantitatively estimate the phenomena described above, we have numerically simulated the experimental spectral characteristics of PVCs using a method described in [10] so as to separate the contributions of various layers (broad-bandgap window, emitter, *i*-region, and base) to the total spectral characteristic. According to the results presented in Fig. 3, contributions from the emitter and broad-bandgap window are virtually identical for all modeled structures. At the same time, the *i*-region equally contributes to the internal quantum yield of PVCs without QDs in this region (Ref-SC, Base-QD-SC, BSF-QD-SC), while the structures with QD medium in the *i*-region (*i*-QD-SC, *i*-Base-QD-SC) exhibit long-wavelength photosensitivity at 870–1080 nm due to the photoeffect in the QD array. The QD medium arrangement within the base irrespective of the position (Base-QD-SC, BSF-QD-SC) leads to a significant decrease in the efficiency of carrier collection from the base, which is well consistent with experimental data. Since the TEM investigation did not reveal any increase of defects of the QD medium grown in the base layer, this behavior is apparently related to a hindered transport of carriers. Evidently, carriers photogenerated in the base and diffusing toward the *i*-region are trapped in the QDs and recombine in the absence of an effective pulling electric field.

Thus, we have analyzed the influence of the position of an array of vertically coupled InGaAs quantum dots in an AlGaAs/GaAs heterostructure on the internal quantum yield of the PVC based on this structure. It is established that the spectral characteristic of a PVC with the QD medium at the *i*-region/base interface is identical to that of the PVC with the QD medium inside the *i*-region and exhibits increased photosensitivity at 900–1080 nm as compared to that of the reference PVC without QDs. The shift of the QD array to the base or the back potential barrier decreases the efficiency of collecting carriers photogenerated in the base layer and diffusing to the *i*-region, which is caused by their trapping in the QD array. In both latter cases, the emission of carriers from QDs sharply drops because of the absence of a pulling field of the *p*–*n* junction, which results in degradation of the photosensitivity of PVCs with the QD medium.

Acknowledgments. The authors are grateful to A.R. Kovsh and S.S. Mikhrin for kindly providing epitaxial heterostructures.

This study was supported in part by the Ministry of Education and Science of the Russian Federation and by the Russian Foundation for Basic Research.

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Translated by P. Pozdeev