The dependence of recombination in GaAs solar cells on the number of included GaInAs quantum objects

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Abstract. The experimental characteristics of GaAs $p$-$i$-$n$ structures with InGaAs quantum objects (QOs) have been investigated. The study of electroluminescence spectra has shown that an increase of the number of QOs layers leads to relative increase in electroluminescence intensity from QOs and decrease it from the GaAs matrix. The observed increase in QOs recombination has resulted in a drop of open circuit voltage. It has been shown that recombination through deep levels in the QOs begins to dominate over recombination in the matrix at lower number of QOs layers than that through band-to-band recombination.

1. Introduction
The use of quantum-sized objects (quantum dots, quantum wells, and others) in multi-junction solar cells is a promising way for solving the problem of the imbalance of subcells’ photocurrents. This is achieved due to the fact that the quantum objects (QO) absorb additional photons and, as a result, can increase the photocurrent ($J_g$). However, the inclusion of QOs in a subcell always leads to a decrease in its open circuit voltage ($V_{oc}$). This has been observed for all types of QOs: quantum dots [1-3], quantum wells [4-6], wires [7] and others [8-11]. The main reason for the voltage drop is an additional recombination in the QOs [3, 8-11]. We studied these processes in [9–11]. In [8, 9, 11], a model that describes the increase in the saturation current ($J_0$) when introducing a different number of QOs rows ($r$) into a $p$-$n$ junction was proposed. In [11], the experimental data has allowed to obtain the values of diffusion (unary, diode coefficient $A = 1$) saturation currents which sublinearly depended on $r$ with the coefficient $r_s$. The reason for the sublinearity is that when a small number of QO rows is introduced, the recombination through QOs transitions does not dominate over the recombination in the bulk matrix material. With an increase in the $r$, the recombination in QOs increases and in the matrix decreases.

In this work we continue the study for obtaining recombination (binary, $A = 2$) saturation currents for the same samples as in [11]. We have found that the binary saturation current grows faster with increasing $r$ than the unary one and, when $r = 20$, the recombination through deep levels in the QOs, which determines the binary component [12], dominates over recombination in matrix, in contrast to band-to-band recombination which determines the unary component.
2. Unary and binary saturation currents and recombination energies

All structures under study were grown in a low pressure metalorganic vapors phase epitaxy reactor using (100) $n$-GaAs substrates. Details on structure growth are described in [13]. Saturation currents ($J_{01}$ - unary, $J_{02}$ - binary) were determined, as in [8], by approximation of the experimental $V_{OC} - J_g$ dependencies using two-diode model (figure 1).

![Figure 1](image1.png)

**Figure 1.** Open circuit voltage vs photocurrent ($V_{OC} - J_g$) dependencies for GaAs solar cells with InGaAs QOs and for a reference solar cell (without QOs): symbols – experimental data, lines – two diode model approximation

We used the obtained values of $J_{01}$ and $J_{02}$ to determine the decrease of $V_{OC}$ in comparison with a reference solar cell. In the regions where one of the current flow mechanisms dominates, for a given $J_g$ the following expression is valid:

$$
\Delta V_{OC} = V_{OC}^{\text{ref}} - V_{OC}^{\text{QO}} = \frac{A \cdot k \cdot T}{q} \ln \left( \frac{J_g}{J_g^{\text{ref}}} \right) - \frac{A \cdot k \cdot T}{q} \ln \left( \frac{J_g}{J_g^{\text{QO}}} \right) = \frac{A \cdot k \cdot T}{q} \ln \left( \frac{J_g^{\text{ref}}}{J_g^{\text{QO}}} \right) \tag{1}
$$

where, $k$ – the Boltzmann constant, $q$ – the electron charge, $T$ – the absolute temperature. The value of $\Delta V_{OC}$ allows one to determine average recombination energy. If matrix recombination dominates ($\Delta V_{OC} = 0$), the ratio $J_g^{(QO)}/J_g^{\text{ref}}$ tends to 1 for both unary and binary components. On the other hand, the ratio tends to infinity, when the recombination through QOs dominates and $\Delta V_{OC}$ approaches the constant $\Delta E_g/q$, where $\Delta E_g$ characterizes the difference between the band gap of the matrix and the QO [9]. The averaged energy of recombination can be obtained by the following expression:

$$
E_A = E_g^{\text{ref}} - q \cdot \Delta V_{OC} \tag{2}
$$

Figure 2 shows the measured electroluminescence spectra obtained at the same current density of 0.128 A/cm$^2$ for all samples. The spectra represent two peaks: one for GaAs matrix (photon energy 1.43 eV) characterizing GaAs bandgap energy and the other for QOs (1.19-1.21 eV) characterizing
QOs transition energy. The figure also shows calculated values of $E_{A1}$ for unary (zone-to-zone) and $E_{A2}$ for binary (through deep levels) recombination obtained using expressions (1) and (2) (figure 2, vertical lines). It is seen that the introduction of one QOs row abruptly changes the averaged recombination energy while with a further increase in the number of rows the energy approaches its position at the QOs peak. The faster drop in $E_{A2}$ in comparison with $E_{A1}$, in general, can be explained by the fact that the recombination rates responsible for unary and binary mechanisms have a different distribution over $p$-$i$-$n$ structure [14].

To calculate the behavior of the averaged energy, we used the model described in[11]. The model has been applied to the dependences $E_{A1}$ and $E_{A2}$ on the number of QO rows. The result is shown on figure 3. A linear change in the QO effective band gap $E_{g}^{OO}$ was taken into account for the calculations.

It is seen that the model adequately describes the experimental data. As a result of the approximation, an $r_{s}$ parameter was obtained. Within the proposed model this parameter characterizes the number of QO rows at which the recombination in QOs completely dominates over the recombination in a matrix. For the unary component $r_{s1} = 140$, for the binary $r_{s2} = 22$. Thus, an increase in the number of QOs rows, included in the space charge region of the $p$-$i$-$n$ junction, has greater impact on the recombination through deep levels than on band-to-band recombination.
Figure 3. Dependences of averaged recombination energies for the unary $E_{A1}$ and binary $E_{A2}$ components and dependence of QOs effective band gap $E_{g \, QO}$ on the number of QO rows: symbols - experimentally obtained data, lines - approximation according to the model described in [11] for $E_{A1}$ and $E_{A2}$ and by linear approximation for $E_{g \, QO}$.

3. Conclusions
The photovoltaic and electroluminescent characteristics of solar cells with a different number of InGaAs QOs rows have been investigated. The increase of QOs rows reduces the recombination through a matrix and increases the recombination through QOs. This affecting the electroluminescence spectrum as well as open circuit voltage vs photocurrent characteristics. A two-diode model have been used to describe the experimental characteristics, voltage drop, and averaged recombination energies. The use of the previously developed model has allowed to conclude that the introduction of QOs in the solar cell has a stronger effect on recombination through deep levels than on band-to-band recombination.

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