InAs quantum dots for cascade GaInP / GaAs / Ge solar cells

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Abstract. In the triple-junction InGaP/Ga(In)As/Ge solar cells there is an unused potential for increasing efficiency. The photocurrent of the lower (Ge) subcell greatly exceeds the photocurrents of the middle (GaAs) and upper (GaInP) subcells. It leads to recombination losses in the lower subcell. Integration of quantum dots arrays into the middle subcell allows improving the balance of photocurrents. It potentially allows increasing the efficiency of the device. Practical and theoretical studies in this paper allow to establish the optimal design of the quantum dots array providing the balance of photocurrents in InGaP/Ga(In)As/Ge solar cell.

1. Introduction
Today one of the most highly efficient solar PV converters are the triple-junction GaInP/Ga(In)As/Ge solar cells. In such solar cells, different parts of the solar spectrum are absorbed in p-n junctions with appropriate bandgap widths. Thus thermalization losses for charge carriers are reduced. One of the problems in the triple-junction solar cells is the uneven current generation in every single cascade. So the middle GaAs cascade generates the smallest current. The problem of current imbalance can be solved by increasing the current generation in the middle cascade due to the expansion of its spectral sensitivity [1]. It could be done due to the implant the array of InAs quantum dots (QDs).

The idea of spectral sensitivity widening is also used in the concept of an intermediate band solar cell. Together with the zone-zone absorption in the base material, there is two-photon absorption through the intermediate band. Such a concept assumes efficiency close to cascade solar cells. Intermediate band could be implemented using QDs and its development is carried out in many research centers. Thus the inclusion of QDs in solar cells is an actual topic for today.

2. Technology
Usually InAs QDs in a GaAs host material are grown by molecular beam epitaxy (MBE). Submonolayer growth and precision control of growth parameters allow forming structures with an array of high-quality quantum dots. However the industrial production of solar cells by the MBE method is not preferred. A massive solar cells manufacturing required creating devices of large area. Therefore, semiconductor solar cells are usually produced using metalorganic chemical vapour deposition (MOCVD) technology that provides high growth rate and a large area of devices grown in one process. However, the formation of InAs QDs by the MOCVD is poorly investigated. Therefore, for the GaAs solar cells the MOCVD technology of InAs QDs grows was developed. Photoluminescence parameters were close to the results obtained from MBE-grown QDs. MOCVD-developed samples demonstrate a separation of QDs by size. This was confirmed both in studies of
photoluminescence and atomic force microscopy [2]. The technology of QDs array growth was developed and the structures with 10 QDs layers are grown [3].

![Figure 1](image_url)

**Figure 1.** Characterization of the developed structure: a) photoluminescence research, b) atomic force microscopy, c) transmission electron microscopy

GaAs solar cells with quantum dots InAs were created on the base of the developed heterostructures. The QD solar cells demonstrate an increase in spectral sensitivity in the long-wavelength region. A solar cell with 10 QDs layers showed an increase in spectral sensitivity in terms of 1 QD layer, while the absorption edge of the main material (gallium arsenide) did not change.

3. **Theoretical research**

The average lateral size of the QDs obtained in the growth processes was about 12 nm, and the height was about 6 nm. InAs QD of this size in GaAs form a large number of localized energy levels in host bandgap. To calculate the internal quantum yield and therefore the photocurrent it is necessary to take into account the transitions between all the levels of QD.

Usually description of zincblende materials (InAs and GaAs) requires using the 8-band k-p model. In this model the Schrodinger equation contains the Hamiltonian matrix of 8x8 elements. The calculation of matrix elements between all the levels requires the use of a massive mathematical apparatus with considerable time spent on research. So for current tusk the calculation it takes about one month.

Therefore the Empiric k-p Hamiltonian method was used. The basis of this method is a 4-band approximation of the semiconductor energy structure. Here the Hamiltonian matrix of 4x4 elements is used in the Schrodinger equation. The Hamiltonian as a Hermitian matrix can be decomposed into eigenvalues and eigenvalues. In Empiric k-p Hamiltonian model, the eigenvalues of the classical 4-band Hamiltonian are replaced by empirical parabolic dependencies with effective masses. The total time for calculating the internal quantum yield of the 12x12x6 nm QD is about 2 hours. And the accuracy of the Empiric k-p Hamiltonian method is comparable to 8-band model [4]. However the accuracy of both methods is not so good near the GaAs absorption edge. So modified Empiric k-p Hamiltonian was used for current calculation. The QDs size dispersion, the wetting layer, and the filling of the first level of electrons in the quantum dot were taken into account in the modified model [5].

A simulation of the spectral internal quantum efficiency for a 12x12x6 nm quantum dot was carried out. The results together with the experimentally obtained data appear in Figure 2.
Figure 2. Internal quantum yield of InAs/GaAs QD solar cell. Dots are measured data (average value for 10-layer structure), solid lines are calculated data.

There is mismatch between calculated and measured data. It appears mainly because of QDs size separation. In calculation only one single size was used. In real material there is separation into two size and dispersion of size near them. Nevertheless small QDs do not give enough wide spectral sensitivity expansion. It is shown that an increase in the QD size leads to an increase in the photocurrent. An increase in the QD size of more than 50 nm does not lead to a noticeable increase in the photocurrent. The relation between QD size and calculated current density per layer appears in Figure 3.

Figure 3. Calculated current density per layer in InAs/GaAs QD solar cell. Dot is the current density value of designed structure.

The calculation show that 30 QDs layers of a size 12x12x6 nm generate a current of 2 mA/cm², which is sufficient to achieve a balance of photocurrents in a triple-junction solar cell. Thus, for
cascading solar cells, it is not necessary to develop a technology for storing more than 30 QD layers. 100 layers of quantum dots of the same size can absorb light almost as effectively as a solid material.

4. Conclusion

In this paper, we consider the prospects for using quantum dots in the triple-junction InGaP / Ga(In)As/Ge solar cells. The structures grown by the MOCVD method were chosen as a subject of consideration. The developed structures contained 10 layers of InAs quantum dots in the GaAs host material. Practical studies have shown that such structures can generate a photocurrent with a density of 0.07 mA/cm$^2$. Theoretical modeling of the solar cell parameters was carried out using the Empiric k-p Hamiltonian method. It revealed that an increase in QDs size leads to increase of the photocurrent, but the efficiency of photocurrent generation slows down as the size of the QD in the array increases. An increase in the QD size of more than 50 nm does not lead to a noticeable increase in the photocurrent. It was established that an array of 30 QDs of 12x12x6 nm in size provides the generation of an additional current of 2 mA/cm$^2$ for the GaAs subcell, equating it with the photocurrent of GaInP cascade.

References

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