Influence of QD array positioning in GaAs solar cell p-n junction on their photoelectric characteristics

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Abstract. In the work, the effect of In0.8Ga0.2As quantum dots position in the i-region of a GaAs solar cell on its spectral and photoelectric characteristics has been investigated. Three solar cell structures were obtained by metal-organic vapor-phase epitaxy, in which layers of quantum dots were placed in the middle of the i-region and also have been shifted to the base and the emitter. As a result, it has been shown that the solar cell with a quantum dot array shifted to the base demonstrates the smallest open-circuit voltage drop and, accordingly, a higher efficiency value.

1. Introduction

Today, solar cells (SCs) based on III-V semiconductors are the most efficient among such kinds of devices. In particular, multi-junction (MJ) SCs are widely used for both terrestrial and space applications. To improve the photoelectric characteristics of such SCs, approaches are being developed using quantum-sized structures, such as quantum wells, quantum dots (QDs), as well as their combinations [1-2]. There is a concept of MJSC with embedded arrays of QDs suggesting the possibility of achieving current matching between subcells of the MJ structure and, in the future, increasing its efficiency [3]. However, the main problem of embedding QD arrays into the SC structure is the open-circuit voltage (V_{oc}) drop appearing with an increase in the number of embedded QD rows [4]. It is considered, that the main reason for the V_{oc} drop is associated with the introduction of additional recombination levels into the band gap of the matrix material. As a result, a change in the current flow mechanisms in the structure appears leading to a change in dark saturation currents, which are the fundamental parameters of a p-n junction. However, special approaches to the design of the SC such as a change in the positioning of the QD array within the i-region of the p-n junction have a significant effect on the V_{oc} and efficiency [5-8].

In this work, the object of research was a GaAs SC with an embedded array of In0.8Ga0.2As QDs [9]. Such a GaAs SC with an increased photogenerated current via embedding a QD array into its heterostructure can be effectively used as a subcell in a MJSC to achieve the current balance [10]. In the paper, we have established the positioning of the QD array in the i-region at which the minimum V_{oc} drop has been demonstrated while maintaining the high internal quantum efficiency of the device.

2. Experimental procedure

To investigate the effect of QD positioning in the i-region of the SC on its photoelectric characteristics three SC structures were grown by metal-organic vapor-phase epitaxy technique: sample with QDs...
located in the middle of the i-region (QD-middle), sample with QD located in the i-region near the emitter (QD-emitter), and SC located in the i-region near the base (QD-base). The QD arrays in all SC samples contained 5 rows of QDs. Excluding the i-region design, the sequence of growth operations was the same for all experimental structures. Back surface field layer 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 array deposition. The In_{0.8}Ga_{0.2}As material was deposited and coherent islands were formed in the Stranski-Krastanov mode with a wetting layer formation. The growth rate was 0.167 ML/sec [11]. Then the epitaxial growth was stopped for a post-growth interruption step. At this step, the temperature was stabilized for several seconds. After that, the completely formed QDs were covered with GaAs capping 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 for each QD row. For all structures, the described sequence was repeated 5 times, in accordance with the number of QD rows in the array. Then the rest of i-GaAs layer, p-GaAs emitter, p-Al_{0.8}Ga_{0.2}As "window" and n+GaAs contact layer were grown at 700 °C. The amount of In_{0.8}Ga_{0.2}As material for the QDs formation was 2 ML (~0.6 nm).

For measuring the quantum yield the method described elsewhere [12] has been used. Dark saturation currents for diffusion and recombination current flow mechanisms (I_{0d} and I_{0r}) were calculated using the standard two-diode model, which was applied for solar cells with quantum-dimensional objects in [13].

3. Results and discussion

Internal quantum yield (Q_{int}) spectra have been obtained for AM1.5D spectral conditions. Q_{int} of all three samples is approximately at the same level of 90%. This shows the high quality of the GaAs matrix regardless of the QD array location (Fig. 1 a). Also the dependences demonstrate a noticeable broadening of the spectral photosensitivity over the GaAs absorption edge due to sub-bandgap photon absorption (Fig. 1 b). This range can be conditionally divided into two areas: the contribution of the wetting layer (880 - 950 nm) and the contribution of the QDs themselves (950 nm-). As it has been also described in other works [4, 6] the main contribution in photosensitivity beyond the GaAs absorption edge mostly comes from the spectral range of the QD wetting layer.

![Figure 1. Spectral characteristics of the internal quantum efficiency of experimental SC (a), as well as scaled spectral characteristics in the absorption region of embedded In_{0.8}Ga_{0.2}As QDs (b).](image-url)

The obtained Q_{int} spectra were used to calculate the contributions to the photogenerated current, as well as separately the contributions of the QD array (Table 1). Comparison of the calculated data shows that the positioning of the QD array at the "emitter - i-region" interface and also in the middle of i-region allows obtaining a greater increase in the photogenerated current on the QD absorption area (880 – 1100 nm). The contributions of QD-emitter and QD-middle samples demonstrate fairly close values of 0.29 and 0.30 mA/cm², respectively. Since the concentration of minority carriers in the emitter is two orders of magnitude higher than in the base, the change in the electric field of the p-n junction...
junction in this region is also much higher than at the “i-region - base” interface. Thus, most of the carriers recombine in the bulk GaAs material before reaching the region where the QD array is located. Recombination through QDs decreases which leads to a decrease in the contribution of sub-bandgap photons to the photogenerated current. Therefore, the QD-base sample demonstrates the smallest contribution of the QD absorption region among all three samples.

Table 1. Values of the photocurrents generated in SCs with different In\(_{0.8}\)Ga\(_{0.2}\)As QDs position relative to the centre of i-region.

| Sample     | \(I_p\), mA/cm\(^2\) | \(I_0\), mA/cm\(^2\) |
|------------|-----------------|-----------------|
|            | Total (300-1100 nm) | QDs (880-1100 nm) | \(I_{0D}\) | \(I_{0R}\) |
| QD-emitter | 32.61 0.29       | 6.0e-18         | 3.4e-09 |
| QD-middle  | 33.18 0.30       | 4.2e-18         | 2.6e-09 |
| QD-base    | 33.48 0.25       | 1.0e-18         | 8.0e-10 |

Figure 2. Photoelectric characteristics of SC with In\(_{0.8}\)Ga\(_{0.2}\)As QDs as a function of the concentration of solar radiation.

At the same time in the QD-emitter and QD-middle samples, the recombination through the QD array occurs much more intensively, prevailing over the recombination through the bulk GaAs material. Besides, the collection of photogenerated carriers from the QD array shifted to the emitter occurs much more efficiently due to the increased probability of their thermal activation from the QDs, and also due to the increased probability of tunneling through the entire QD array. As a result, the dark saturation currents \(I_{0D}\) and \(I_{0R}\) are largely determined by the material of the quantum dots (In\(_{0.8}\)Ga\(_{0.2}\)As). Indeed, the values obtained by approximating the experimental dependences of \(V_{oc}\) on solar concentration by standard two-diode model demonstrate a decrease in their values by almost half an order of magnitude as the QD moves from the emitter to the base. The \(V_{oc}\) value is directly related to the dark saturation current, so the voltage of the QD-base is more than 0.06 V higher than the other two samples.

In summary, the QD-base sample demonstrated the smallest contribution in the photogenerated current of sub-bandgap photons in the QD absorption region, but at the same time, a significantly higher \(V_{oc}\). This substantially influenced the efficiency value, which increased by an average of 3% in relation to the QD-emitter and QD-middle samples.
4. Conclusions
As a result, it has been shown that changing the QDs positioning in the i-region of the SC affects both the value of the photocurrent generated by the sub-bandgap photons and the value of the device voltage, which in turn is determined by the dark saturation currents. Wherein, both \( I_{0D} \) and \( I_{0R} \) saturation currents decreased as the QD array is shifted from the emitter to the base. In p-n junctions, \( I_{0D} \) is determined by the “band-to-band” recombination. Therefore, in the case of QD SCs, one can conclude of some change in the "effective" bandgap when the narrow-gap In\(_{0.8}\)Ga\(_{0.2}\)As is shifted from the "emitter - i-region" interface to the “i-region - base” interface of the GaAs SC. But there is also a correlated decrease in \( I_{0R} \) when the QDs are shifted from the emitter to the base. The recombination saturation current \( I_{0R} \) is determined by recombination through deep levels. The rate of this recombination has a maximum inside the space charge region. It can be concluded that the entire QD array is fully involved in recombination in the case of “QD-emitter” SC. In case of “i-region - base” interface the QD array is located the farthest from space charge region center, therefore saturation currents reduced by half an order of magnitude.

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