Conference materials
UDC 620.3, 620.9, 539.23, 621.315.592
DOI: https://doi.org/10.18721/JPM.161.170

Influence of GaP compensating layers on the characteristics of GaAs photovoltaic converters with InGaAs quantum dot arrays

R.A. Salii [1]✉, M.A. Mintairov [1], S.A. Mintairov [1],
M.V. Nakhimovich [1], M.Z. Shvarts [1], N.A. Kalyuzhnyy [1]

[1] Ioffe Institute, Saint-Petersburg, Russia
✉ r.saliy@mail.ioffe.ru

Abstract. In this work, we studied the influence of GaP compensating layers on the characteristics of GaAs solar cells with InGaAs quantum dot arrays. An increase in the overall level of quantum efficiency in the absorption range of quantum dots (870–1000 nm) by more than 10% has been demonstrated when GaP layers are embedded in GaAs intermediate layer (spacer) of a quantum dot array. It was also shown that in this case a noticeable increase in the open-circuit voltage can be achieved at high solar concentration.

Keywords: GaAs, InGaAs, GaP, solar cell, quantum dots, MOVPE

Citation: Salii R.A., Mintairov M.A., Mintairov S.A., Nakhimovich M.V., Shvarts M.Z., Kalyuzhnyy N.A., Influence of GaP compensating layers on the characteristics of GaAs photovoltaic converters with InGaAs quantum dot arrays. St. Petersburg State Polytechnical University Journal. Physics and Mathematics. 16 (1.1) (2023) 411–415. DOI: https://doi.org/10.18721/JPM.161.170

Материалы конференции
УДК 620.3, 620.9, 539.23, 621.315.592
DOI: https://doi.org/10.18721/JPM.161.170

Влияние компенсирующих слоев GaP на характеристики фотопреобразователей GaAs со встроенными массивами квантовых точек InGaAs

Р.А. Салий [1]✉, М.А. Минтаиров [1], С.А. Минтаиров [1],
М.В. Нахимович [1], М.З. Шварц [1], Н.А. Калюжный [1]

[1] Физико-технический институт им. А.Ф. Иоффе РАН, Санкт-Петербург, Россия
✉ r.saliy@mail.ioffe.ru

Аннотация. В настоящей работе было исследовано влияние параметров компенсирующих слоев GaP на фотоэлектрические характеристики фотопреобразователей на GaAs с квантовыми точками InGaAs. Продемонстрировано увеличение общего уровня квантовой эффективности в области поглощения квантовых точек (870-1000 нм) более чем на 10% при встраивании слоев GaP в промежуточные слои массива квантовых точек. Также показано, что в этом случае при высоких кратностях солнечного излучения может быть достигнуто заметное увеличение напряжения холостого хода.

Ключевые слова: GaAs, InGaAs, GaP, фотопреобразователь, квантовые точки, МОГФЭ

Ссылка при цитировании: Салий Р.А., Минтаиров М.А., Минтаиров С.А., Нахимович М.В., Шварц М.З., Калюжный Н.А. Влияние компенсирующих слоев GaP на характеристики фотопреобразователей GaAs со встроенными массивами квантовых точек InGaAs // Научно-технические ведомости СПбГПУ. Физико-математические науки. 2023. Т. 16. № 1.1. С. 411–415. DOI: https://doi.org/10.18721/JPM.161.170

Introduction

Today, quantum dots (QDs) based on InAs-InGaAs materials are of great interest for various fields of semiconductor electronics. They have already shown their efficiency for lasers [1–3] and are being actively studied in the context of their application in III-V solar cells (SCs) to increase the photocurrent [4, 5]. One of the main problems when embedding arrays of QDs in a SC is the voltage (in particular, open circuit voltage (V_{OC})) drop appearing in the photovoltaic device [6]. The main reason for this drop is the additional recombination levels which are created by QDs in the band gap of the SC matrix material [7]. This leads to a decrease in average "effective" band gap in p-n junction area and, consequently, the dark saturation currents of the p-n-junction increase, on which the voltage directly depends. In addition, it is well known that in order to increase the absorption efficiency of QDs, it is necessary to grow a large number of QD rows in an QD array. In case of SC dozens of QD rows usually embedded in i-region of a device. This creates structural stresses (tensile stresses) in the semiconductor crystal lattice and local defects can be formed. At low photogenerated current (low solar radiation concentration) structural imperfection additionally leads to a decrease in device voltage due to the appearance of a tunnel current flow mechanism in the p-n junction of the structure.

In the present work we studied the effect of V_{OC} drop in single-junction GaAs SC with embedded InGaAs QDs. We used an approach of the incorporation of thin (up to 1 nm) wide-gap GaP layers into each layer of QD array. Interleaving layers of InGaAs QDs through an intermediate GaAs layer (spacer), in which GaP layers are embedded should allow compensating the increase in the effective band gap near the p-n junction. Thus, the main goal of embedding these layers between QD layers is to reduce the value of dark saturation currents, on which the value of V_{OC} strictly depends. These layers also are intended for compensating the tensile stresses created by the QD layers and eliminating of a tunneling current flow mechanism, which can additionally lead to a decrease in V_{OC}. The influence of the parameters of the GaP compensating layers on the photoelectric and spectral characteristics of GaAs SCs with QDs is studied on experimental structures described.

Materials and Methods

Four SC structures with different configuration of the QD array were grown by metalorganic vapor-phase epitaxy. The QD arrays in all SC samples contained 15 rows of QDs. Excluding the i-region design, the sequence of growth operations was the same for all experimental structures. Back surface field 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 [8]. 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 value of the standard thickness of the spacer layer used for such QDs in our earlier works is about 40 nm [9]. In the framework of this work, we used both 40 nm spacer layer and a thinner one. Four structures were grown, differing in the parameters of spacer layers: a reference sample without compensating GaP layers with a spacer layer thickness of 13 nm; two samples with 5 and 10 Å GaP layers, embedded in 13 nm GaAs spacer layers; and a sample with 10 Å thick GaP layers embedded in a 40 nm GaAs spacer layer. The total thickness of the i-region was 1000 nm. The schematic structure of samples with GaP compensating layers embedded in GaAs spacer of QD arrays shown in figure 1.

For all structures, the described sequence was repeated 15 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 p-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), since this is the optimal amount of material determined for the composition [8]. For measuring the quantum yield and photovoltaic parameters the method described elsewhere [10] has been used.

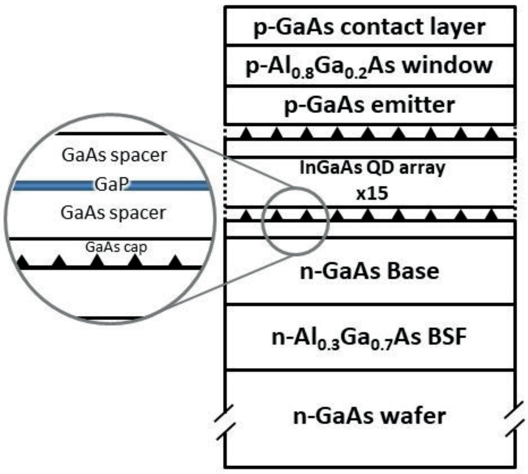

Fig. 1. The schematic structure of GaAs SC with GaP compensating layers in QD arrays

Results and Discussion

Internal quantum yield (Q_{int}) spectra have been obtained for AM1.5D spectral conditions. The obtained Q_{int} dependences showed that the use of compensating GaP layers makes it possible increasing the overall level of quantum efficiency by more than 10% in the GaAs absorption range (Fig. 2). This indicates a general improvement in the quality of the QD array.

The spectral dependences demonstrate broadening of the photosensitivity and Q_{int} increasing over the GaAs absorption edge due to sub-bandgap photon absorption (Fig. 2, on inset). In this case, the best effect of the embedding of GaP layers is demonstrated by a sample with a GaAs spacer and GaP layer thicknesses of 40 nm and 10 Å, respectively. Presumably, the combination of relatively thick GaAs spacer and GaP compensating layer makes it possible maintaining the high quality of the QD array and ensure efficient separation of carriers generated via sub-bandgap photon absorption.

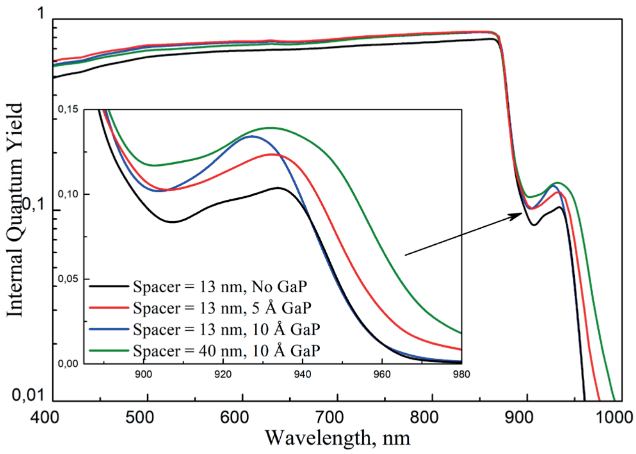

Fig. 2. Spectral characteristics of the internal quantum yield of experimental SC, as well as scaled spectral characteristics in the absorption region of embedded $In_{0.8}Ga_{0.2}As$ QDs (on inset)

At different values of the concentration of solar radiation V_{OC} value was measured (Fig. 3). For all samples V_{OC} increases uniformly with concentrations of solar radiation. The V_{OC} value for SC with GaP compensating layer thickness of 10 Å and GaAs spacer layer thickness of 13 nm is ~ 0.06 V greater, which is 7% more than for reference QD SC without GaP compensating layers. At the same time the separation of GaP layers by a wider spacer layer (40 nm) in the QD array also levels out the compensating effect (Fig. 3, *b*) from voltage point of view, in spite of that such an array design showed the best photoresponse (inset in Fig. 2).

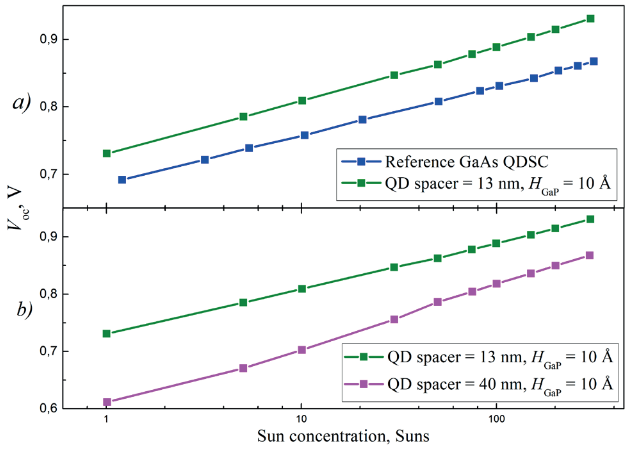

Fig. 3. V_{OC} at different values of the concentration of solar radiation

Conclusion

It was shown that thin GaP layers embedded in the GaAs SCs with InGaAs QD arrays can be used for both compensating local tensile stresses in the semiconductor crystal lattice and compensating the voltage drop (dark saturation currents increase) caused by decrease in average "effective" band gap in p-n junction area with QDs. Indeed, GaP layers embedded in QD arrays via 13 nm thick GaAs spacer layers, improve the average effective band gap and demonstrate more than 7% increase in V_{OC} in comparisons with samples without compensating layers. From the structural quality point of view, the GaAs SCs with compensating GaP layers showed increasing the overall level of quantum efficiency by more than 10% in the GaAs absorption range and quantum efficiency increasing as well as spectral broadening over the GaAs absorption edge. Wherein, the best spectral improving was demonstrated by SC with a 40 nm GaAs spacer. To further improve the parameters of the SCs with QDs by embedding compensating layers, it is necessary to optimize the GaP parameters and determine their position relative to the center of the GaAs spacer layer.

REFERENCES

1. **Mintairov S.A., Kalyuzhnyy N.A., Maximov M.V., Nadtochiy A.M., Rouvimov S., Zhukov A.E.,** GaAs quantum well-dots solar cells with spectral response extended to 1100 nm, Electronic Letters 51 (20) (2015) 1602–1604.

2. **Mikhrin S.S., Zhukov A.E., Kovsh A.R., Maleev N.A., Vasil'ev A.P., Semenova E.S., Ustinov V.M., Kulagina M.M., Nikitina E.V., Soshnikov I.P., Shernyakov Yu.M., Livshits D.A., Kryjanovskaya N.V., Sizov D.S., Maksimov M.V., Tsatsul'nikov A.F., Ledentsov N.N., Bimberg D., Alferov Zh.I.,** High efficiency (ηD > 80%) long wavelength (λ > 1.25 μm) quantum dot diode lasers on GaAs substrates, Semiconductors 36 (11) (2002) 1315–1321.

3. **Kovsh A., Krestnikov I., Livshits D., Mikhrin S., Weimert J., Zhukov A.,** Quantum dot laser with 75nm broad spectrum of emission, Optics Letters, 32(7) (2007) 793–795.

4. **López N., Martí A., Luque A., Stanley C., Farmer C., Diaz P.,** Experimental analysis of the operation of quantum dot intermediate band solar cells, Journal of Solar Energy Engineering, 129 (3) (2007) 319–322.

5. **Kalyuzhnyy N.A., Mintairov S.A., Salii R.A., Nadtochiy A.M., Payusov A.S., Brunkov P.N., Nevedomsky V.N., Shvarts M.Z., Marti A., Andreev V.M., Luque A.,** Increasing the quantum efficiency of InAs/GaAs QD arrays for solar cells grown by MOVPE without using strain-balance technology, Progress in Photovoltaics 24 (9) (2016) 1261–1271.

6. **Nadtochiy A.M., Blokhin S.A., Kuz'menkov A.G., Maksimov M.V., Maleev N.A., Troshkov S.I., Ledentsov N.N., Ustinov V.M., Mutig A., Bimberg D.,** Decreasing parasitic capacitance in vertical-cavity surface-emitting laser with selectively oxidized aperture, Technical Physics Letters 38 (2012) 106–109.

7. **Sogabe T., Shen Q., Yamaguchi K.,** Recent progress on quantum dot solar cells: A review, Journal of Photonics for Energy 6 (4) (2016).

8. **Salii R.A., Mintairov S.A., Nadtochiy A.M., Nevedomsky V.N., Shvarts M.Z., Kalyuzhnyy N.A.,** Comparative Analysis of the Optical and Physical Properties of InAs and $In_{0.8}Ga_{0.2}As$ Quantum Dots and Solar Cells Based on them, Semiconductors 54 (10) (2020) 1267–1275.

9. **Salii R.A., Mintairov M.A., Mintairov S.A., Nakhimovich M.V., Shvarts M.Z., Kalyuzhnyy N.A.,** Influence of QD array positioning in GaAs solar cell p-n junction on their photoelectric characteristics, Journal of Physics: Conference Series 2103 (2021).

10. **Levina S.A., Emelyanov V.M., Filimonov E.D., Mintairov M.A., Shvarts M.Z., Andreev V.M.,** Cascade optical coupling and quantum efficiency measurements of MJ SCs, Solar Energy Materials and Solar Cells 213 (2020).

THE AUTHORS

SALII Roman A.
r.saliy@mail.ioffe.ru

MINTAIROV Mikhail A.
mamint@mail.ioffe.ru
ORCID: 0000-0002-3481-477X

MINTAIROV Sergey A.
mintairov@scell.ioffe.ru
ORCID: 0000-0002-6176-6291

NAKHIMOVICH Maria V.
nmar@mail.ioffe.ru

SHVARTS Maxim Z.
shvarts@scell.ioffe.ru
ORCID: 0000-0002-2230-7770

KALYUZHNYY Nikolay A.
nickk@mail.ioffe.ru
ORCID: 0000-0001-8443-4663

Received 28.10.2022. Approved after reviewing 14.11.2022. Accepted 16.11.2022.