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ԵՐԵՎԱՆ, 23-25 ՀՈՒՆԻՍ

SEMICONDUCTOR
MICRO- AND NANOELECTRONICS

PROCEEDINGS OF THE ELEVENTH INTERNATIONAL
CONFERENCE
YEREVAN, ARMENIA, JUNE 23-25

ԿԻՍԱՀԱՂՈՐԴՉԱՅԻՆ

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Միջազգային
Տասնմեկերորդ Գիտաժողով

SEMICONDUCTOR
MICRO- AND ANOELECTRONICS

The Eleventh International Conference

ԵՐԵՎԱՆ 2017 YEREVAN
ARMENIA

Երևան

ԵՊՀ հրատարակչություն

2017

OPTOELECTRONIC PROPERTIES OF InAsSbP QUANTUM DOT PHOTOCONDUCTIVE CELLS

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1. Introduction

In recent years, quantum dots (QDs) have been intensively studied for applications in transistors, solar cells, LEDs, photodetectors, quantum computing systems, etc. The manipulation of the matter at the nanoscale is the key challenge of nanotechnology. Because of quantum confinement effects quantum nanostructures can be considered as artificial atoms and like the natural atoms show a discrete spectrum of energy levels [1]. More than natural atoms, their electronic and optical properties can be tuned on demand adjusting structural parameters, such as size, composition and morphology. For instance, the authors of [2] theoretically showed that the absorption edge of ellipsoidal QDs depends on their semiaxis. The latter parameter is very important to control the properties of nanostructures, as tiny variations in morphology can cause significant changes [3]. The mid-wavelength infrared (MWIR) region of 3-5 μm has many important applications. The importance of this range is related to the atmosphere transmission, appropriate absorption spectra of several industrial gases, etc. Due to QDs peculiarities, QD based photodetectors are expected to show fascinating operation. To satisfy the demands of the state-of-the-art infrared photodetectors, quantum well infrared photodetectors (QWIP) and quantum dot infrared photodetectors (QDIP) are of great interest. QDIPs are predicted to have superior performances compared to QWIPs [4, 5], such as sensitivity to normal incidence infrared radiation, low dark current, high responsivity and detectivity. In addition, this technology is important in remote sensing, chemical and biological detection, as well as in photovoltaic (PV) [6] and thermo-PV (TPV) applications [7]. Some researchers use long-wavelength infrared (LWIR) QDIPs for spectroscopic applications. Bhattacharya et al. presented several heterostructure designs to obtain improved responsibility for InGaAs/GaAlAs mid- and far-infrared QDIPs [8]. HgCdTe (MCT) is a well-established alloy, which has been the dominant system for MWIR and LWIR infrared photodetectors. However, MCT suffers from instability and non-uniformity problems over large area due to the high Hg vapor pressure. Theoretical studies predicted that only type-II superlattice photodiodes and QDIPs are expected to compete with HgCdTe photodiodes [9]. Another potential material system for MWIR applications is InAs-InSb-InP. This quaternary system has been applied to grow diode heterostructures [10, 11]. In recent years, InAsSbP QDs have been successfully grown on InAs substrates for the purpose of MWIR application too [11-17].

In this paper, we report our efforts to fabricate and investigate MWIR photoconductive cells with InAsSbP QDs grown on the surface of an n-InAs(100) substrate. The results of structural characterization, as well as optoelectronic properties of fabricated photodetectors are presented.

2. Experiment

To grow InAsSbP QDs on InAs substrates, we used a modified liquid phase epitaxy (MLPE) technique. The growth process was performed in a slide-boat crucible under a hydrogen atmosphere purified by a palladium filter. The liquid phase consisted of In (7N) solvent and InAs, InP, Sb (6N) solutes was used to nucleate QDs. The substrate used was n–InAs industrial single crystal with 11 mm in diameter, (100) orientation, background electron concentration of 2×10^{16} cm^{-3}, and electron mobility of 40.000 $cm^2V^{-1}s^{-1}$ at 78 K. The QDs were grown in Stranski-Krastanow mode [18, 19] by providing appropriate lattice mismatch between the substrate and wetting layer. To investigate the morphology and crystalline properties of grown nanostructures, atomic force microscope (AFM) and scanning tunneling microscope (STM) were used. MWIR photodetectors were fabricated in the form of photoconductive cells (PCC). Actually, the QD PCC consists of InAs substrate and InAsSbP QDs grown on its surface (Fig. 1). The capacitance-voltage characteristic of the QD PCC was measured by a high precision LCR meter (QuadTech-1920). In addition, an infrared He-Ne laser was used to investigate the relative conductivity change of fabricated photodetector at different wavelengths. The photoresponse spectrum measurements were performed by an IRS-21 spectrometer.

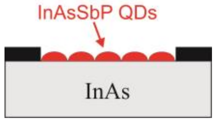

Fig. 1. Schematic of the QD PCC.

3. Results and discussion

The oblique view AFM image of grown QDs is presented in Fig. 2(a). Additional studies have shown that the average surface density and heights of the QDs are in the range of $(4\text{-}8)\times10^{9}$ cm^{-2} and 0.5-21 nm, respectively. In average, the diameter of the QD exceeds the height by about 3 times. The STM image of a single InAsSbP QD is presented in Fig. 2(b).

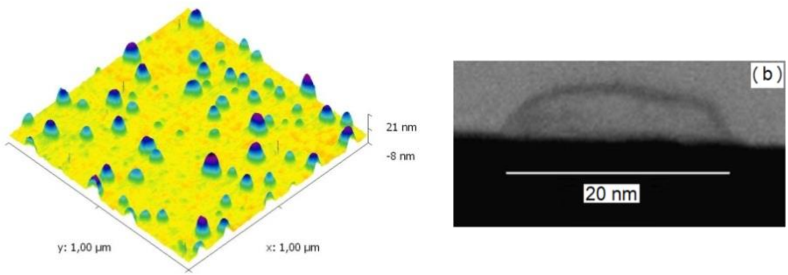

Fig. 2. (a) - AFM image of InAsSbP QDs (oblique view), (b) - STM image of a single InAsSbP QD.

The capacitance-voltage characteristics (C-V) of the QD PCC were measured at signal frequency of 10^6 Hz (Fig. 3). In the figure, the arrows show the voltage change direction during the measurement. One can notice that a capacitance hysteresis is revealed, i.e. at increasing and decreasing of voltage the value of capacitance does not remain the same (see Fig. 3). The remnant capacitance (ΔC) is 270 pF. Detected hysteresis can be explained by the remnant polarization occurred in type-II InAsSbP QDs [12, 16] due to spatial separation of electrons and holes.

The photoresponse spectrum of fabricated photodetector was measured at room temperature applying biases up to 6 mV. It was found that the spectrum is extended up to 4 μm with main peak at 3.48 μm (Fig. 4). This peak coincides with the energy bandgap of InAs (E_g=0.355 eV) at room temperature. The observed additional peaks are the results of charge carrier transitions via energy levels created by InAsSbP QDs. Figure 5 shows the dependence of the relative surface conductance ($\Delta\sigma/\sigma_d$) of the QD PCC on power density under irradiation at different wavelengths, where $\Delta\sigma$ is the change of conductance under irradiation and the dark conductance σ_d.

In the case of irradiation at 1.15 μm, the relative surface conductance change of up to 16 % was measured. As for 3.39 μm, the relative surface conductance change was found to be up to 7 % (Fig. 5(b)). Note that the intensity range of radiation at different wavelengths is different. To make a comparison, we extrapolated the experimental data obtained for 1.15 μm and calculated the conductance change value for power density of 0.065 W/cm^2. By comparing that value with the average value measured at the same power density for 3.39 μm, we obtained about 1 % higher conductance change. Although the photon energy of radiation at 3.39 μm coincides with the InAs bandgap, the obtained value for 1.15 μm is about 3 times higher than the value for 3.39 μm. This could be explained by the multiple electron-hole generation phenomenons observed in QDs [20].

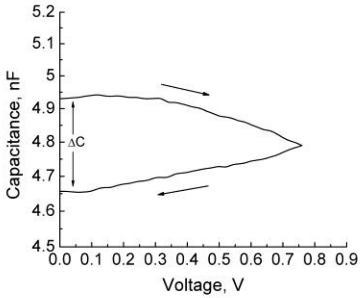

Fig. 3. Capacitance-voltage characteristic of the QD PCC at room temperature.

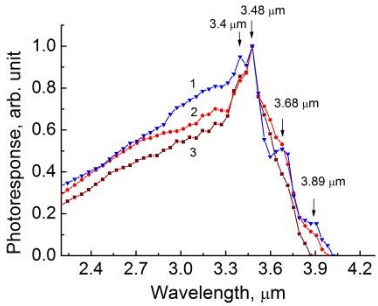

Fig. 4. Photoresponse spectrum of the QD PCC at different biases: 1 – 6 mV, 2 – 2 mV, 3 – 1 mV.

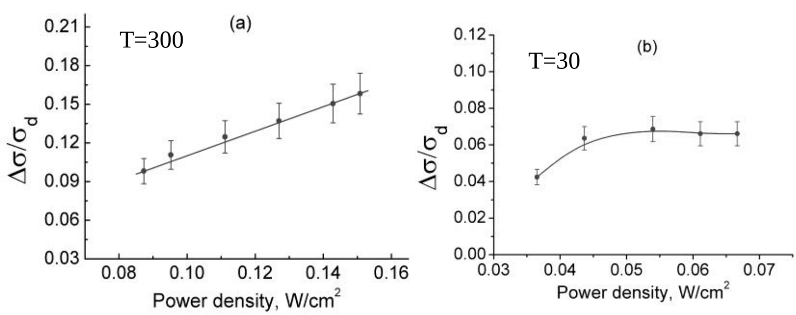

Fig. 5. Relative conductivity change ($\Delta\sigma/\sigma_d$) versus power density at (a) – 1.15 μm and (b) – 3.39 μm.

4. Conclusion

Thus, the results of investigations of InAsSbP quantum dot photoconductive cells are presented. The quantum dots are grown on an InAs(100) substrate by modified liquid phase epitaxy. During measurements, a capacitance hysteresis with remnant capacitance of 270 pF is revealed. The photoresponse spectrum of the photoconductive cell is in the range of 2.2 - 4 μm. The relative surface conductance change of up to 16 % is detected at room temperature.

Acknowledgments: This work was performed in the frame of the project № 15T-2J137 funded by the RA MES State Committee of Science, as well as in the frame of award № YSSP-13-08 funded by NFSAT, AYF and CRDF Global.

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