Influence of neutron irradiation on optoelectronic properties of structures with the InAs/GaAs quantum dots

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Abstract. The effect of neutron irradiation on the photosensitivity of the InAs/GaAs quantum dots has been investigated. It was shown that after neutron irradiation with a fluence of 1.5×10^15 cm^2 the photosensitivity at the room temperature has been decreased at 3 times, whereas the shape of the photosensitivity’s temperature dependence didn’t reveal any visible changes, despite an appearance of defects in quantum dot layer. The effect was explained by the difficulty of a motion of photoexcited carriers in quantum dot layer to the recombination centres arisen after irradiation.

1. Introduction
The possibilities of using semiconductor devices based on quantum confined structures are determined, among other factors, by radiation durability in conditions of increased radiation exposure [1]. Thus, it is necessary to study the influence of various types of ionizing radiation on the physical properties of such structures. In this paper photoelectric spectroscopy [2] was used in order to investigate the influence of defect formation induced by the gamma-neutron irradiation on photoelectric properties of the InAs/GaAs quantum dot (QD) structure.

2. Experiment details
The structure was grown by Metal Organic Vapour Phase Epitaxy at the atmospheric pressure of hydrogen [3]. Initially, a 300 nm thick n-GaAs buffer layer with the electron density of ~ 10^16 cm^-3 on (100) n-GaAs substrate was formed at 650°C. Subsequently, an InAs QDs layer and a 30 nm thick GaAs cap layer were deposited at 520°C.

The heterostructure was irradiated with neutrons with an average energy of 1.89 MeV and a fluence of 1.5×10^15 cm^-2. The exposure dose of the accompanying γ-ray irradiation was 3×10^5 R. For a comparison, another InAs QDs sample with defects created by anodic oxidation was investigated. The oxidation was carried out at 10 VDC in the electrolyte consisted from 0.5 M solution of ammonium pentaborate and ethylene glycol in the ratio 1:1. Ohmic contact to the buffer layer and the substrate was formed by burning of the tin foil using electric sparks.

In order to characterise the defect influence’s degree on QDs optoelectronic properties the spectral dependences of the photovoltage at surface barrier was studied in the wide temperature range of 77 - 350 K. The measurements were carried out by the "soft-contact" technique [4]. The Acton SpectraPro-500i monochromator equipped with a 250 W tungsten halogen lamp and a grating of...
600g mm\(^{-1}\) was used as a monochromatic light source. The measurements were performed on an alternating signal, using a mechanical optical chopper (Stanford Research Systems SR540) operating at the 130 Hz frequency. Detection of the alternating electrical signal was carried out according to the standard lock-in technique using the Stanford Research Systems SR810 DSP lock-in amplifier. The spectral dependence of the relative photosensitivity \(S_{\text{ph}}(h\nu) = V_{\text{ph}}(h\nu)/L(h\nu)\) was plotted, where \(V_{\text{ph}}(h\nu)\) stands for a photovoltage, and \(L(h\nu)\) stands for the light intensity (in arbitrary units).

A photoelectric signal in the spectral region of the interband optical absorption of QDs appears as a result of the escape of photoexcited electrons and holes from quantum confined levels into the semiconductor matrix and is determined by the ratio of the escape and recombination effective lifetimes. The method based on the analysis of the temperature dependences of the photosensitivity was found to be more informative in the study of defect formation. The photoelectric signal was found to be more sensitive to a defect formation, when the recombination lifetime was approximately equal to the escape lifetime of photoexcited charge carriers in QDs. In this case, the escape efficiency \(\eta\), was roughly estimated as 50\%. The generation of defects into the structure substantially affects the recombination lifetime of charge carriers, whereas the temperature influences the escape lifetime. Therefore, the equality of these lifetimes at different defect concentrations is bound to be attained at different temperatures; consequently, it is expected that the corresponding temperature dependences will be shifted with respect to each other. Previously, this method was successfully applied in the study of defects originating from the cobalt deposition on the surface of the QD structure [5].

3. Results and discussion

The photosensitivity spectra of the QDs structure at 300 K before and after neutron irradiation are shown on the Fig. 1a. The peaks at 0.94 eV and 1.01 eV are related to optical transitions between holes’ and electrons’ discrete ground states and the first excited states in QDs, respectively. After the irradiation the photosensitivity \(S_{\text{ph}}\) at 300 K related to the interband QDs optical absorption was uniformly decreased at 3 times over the whole spectrum. This result is explained by the fact that defects, formed in the QD layer increased the effective carrier recombination rate.

The Fig. 1b shows the temperature dependence of photosensitivity of the InAs QDs ground state transition of the sample before and after irradiation. The shape of the photosensitivity temperature dependence is determined by the ratio between the recombination and escape lifetimes of carriers in the QD. The rapid drop of photosensitivity with temperature occurring under 220 K is associated with decreasing of the electron’s escape rate from the QD ground state to the semiconductor matrix. It is worth to mention the fact that the shape of the temperature dependence of the photosensitivity in the region of the ground state transition in QDs after irradiation kept the same.

![Figure 1](image-url). The influence of neutron irradiation on the photosensitivity spectrum from the QDs (a) and on the temperature dependence of photosensitivity in the region of the ground state transition in QDs \((h\nu \approx 0.94\ \text{eV at 300 K})\) (b). 1 – before irradiation, 2 - after irradiation.
The effect of defect formation at anodic oxidation on the QD optoelectronic characteristics was found to be substantially different. The influence of anodic oxidation on photosensitivity spectra (300 K) for the similar nanostructure with the QDs layer is displayed on the Fig. 2a. After an oxidation the photosensitivity of QDs ground state transition was decreased, which also associated with defects formation as well as in the case of neutron irradiation. The red shift of QD photosensitivity spectrum (60 meV) is related with elastic strain relaxation due to the decreasing of the GaAs cap layer thickness. A strong shift in the temperature dependence of the photosensitivity to the region of high temperatures took place (Fig. 2b). In this case, shift in the temperature dependence of photosensitivity and therefore the escape efficiency can be due both to a decrease in the recombination carrier lifetime in QD due to a defect formation, and to an increase in the height of the escape barrier in QD due to a change in the QD energy spectrum due to an elastic strain relaxation. Calculations using the theory [6] show that if the escape barriers for electrons and holes increase by 30 meV with an unchanged recombination lifetime, the temperature dependence of QD photosensitivity shifts by no more than 25 K, which is significantly less than the 60 K shift observed in this work. We note that after application of other methods of surface defect formation in such structures (ion beam implantation [7], deposition of a chemically active metal [5]) the same shift of the temperature dependence of the photosensitivity was observed without any changes in QD ground state transition energy.

![Figure 2](image)

**Figure 2.** The influence of anodic oxidation on the photosensitivity spectrum from the QDs (a) and on the temperature dependence of photosensitivity in the region of the ground state transition in QDs (b). 1 – before oxidation, 2 - after oxidation.

This difference in features of defect influence is caused by a different nature of the defect formation. At low energy treatment, such as anodic oxidation, ion beam implantation [7], chemically active metal deposition [5], defects distribute uniformly over the area of the structure. In the case of neutrons, highly defective regions with a defect concentration of ~ 10^{20} cm^{-3} [8] are formed in the structure, but they are compact (the radius of the region is about 20 nm [8]) and are located at a considerable distance from each other. These disordered defective regions can’t suppress the photosensitivity from the entire array of QDs. The photosignal completely disappears (even at 300 K) only from those QDs that directly located into these highly defective regions. In the remaining QDs the conditions for recombination stay the same as before irradiation, since there is spatial limitation of the lateral motion of carriers in the QD layer.

4. Conclusion

It was shown that after neutron irradiation the behavior of the temperature dependence of InAs/GaAs QDs photosensitivity does not change, despite the fact that defect formation is present in the QD layer.
The effect is explained by the difficulty in moving the photoexcited carriers in the quantum dot layer to the recombination centres that arise during irradiation.

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