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ACTUAL PROBLEMS OF RADIOPHYSICS

Proceedings of the VI International Conference "APR-2015"

October, 5–10, 2015, Tomsk, Russia

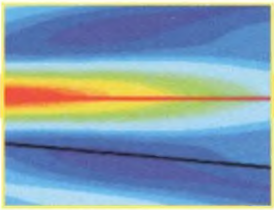

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Table of Contents

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INVESTIGATION OF Si/Ge p-i-n STRUCTURES WITH Ge QUANTUM DOTS BY ADMITTANCE SPECTROSCOPY METHODS

A.A. Pishchagin[1], K.A. Lozovoy[1], V.Yu. Serokhvostov[1], A.P. Kokhanenko[1], A.V. Voitsekhovskii[1], A.I. Nikiforov[2]

[1]National Research Tomsk State University, Tomsk, Russia
[2]Rzanov Institute of Semiconductor Physics SB RAS, Novosibirsk, Russia

Correspondence to:
A. A. Pishchagin
Post Address: Tomsk State University, 36 Lenin Ave., Tomsk, Russia, 634050
E-mail: apisch@gmail.com

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Abstract. The experimental results on synthesis of Si/Ge p-i-n structures with Ge quantum dots in the *i*-region and their investigation by the method of admittance spectroscopy are presented. The activation energies of the emission process from localized states are calculated for two types of structures. Current-voltage characteristics without illumination and under illumination are measured.

Keywords: quantum dots, silicon, germanium, p-i-n structure, admittance spectroscopy.

Currently optoelectronics is experiencing rapid development, and the main objects of research are complex heterostructures with nanoscale inclusions. Creating semiconductor structures with new physical properties is the primary goal of nanotechnology, which has the aim of expanding the limits of applicability of semiconductor materials. In recent years the interest in photoelectric properties of Ge/Si heterostructures (primarily in the spectral range of 1.3–1.55 μm) has increased. New types of photodetectors based on silicon-germanium low-dimensional heterostructures using intrasubband and intersubband transitions are intensively being developed. Such devices may be used in optoelectronic communication systems and remote monitoring [1, 2].

In this paper we present the experimental results on synthesis of Si/Ge

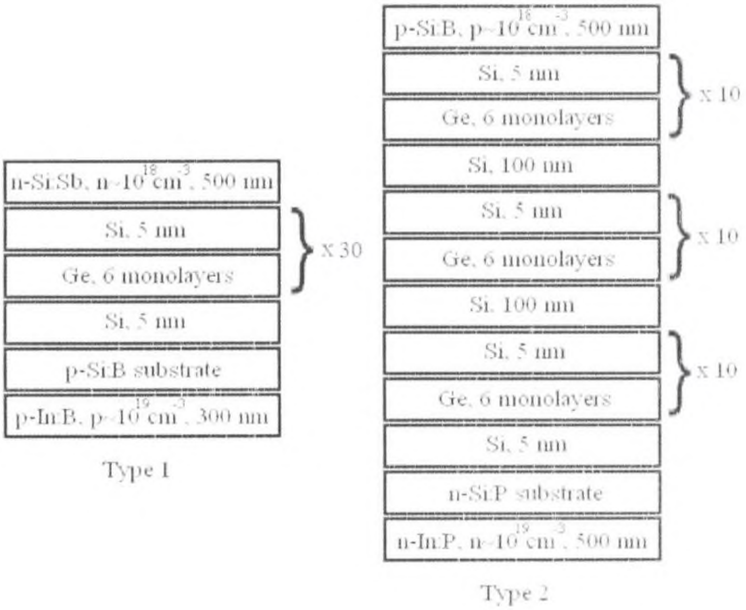
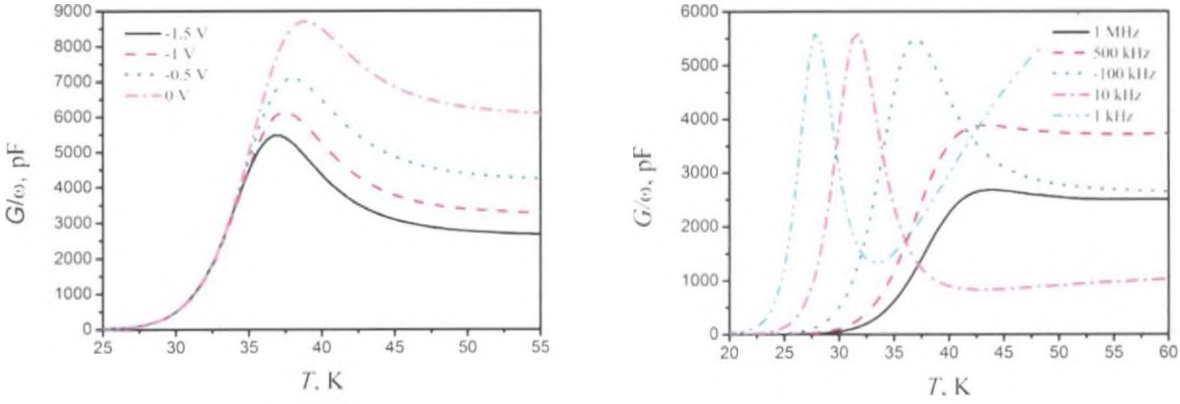


Fig 1. – Schematic representation of the structures studied.



a b

Fig. 2. – Temperature dependence of conductance for type 1 sample measured at various bias voltages at the test signal frequency of 100 kHz (a) and at various frequencies of the test signal and the applied bias voltage of –1.5 V (b).

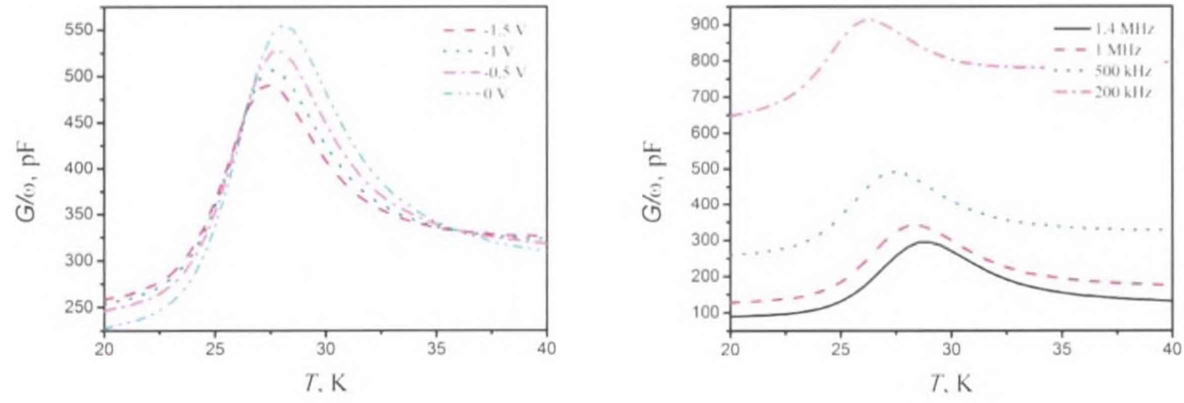


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Fig. 3. – Temperature dependence of conductance for type 2 sample measured at various bias voltages at the test signal frequency of 100 kHz (a) and at various frequencies of the test signal and the applied bias voltage of –1.5 V (b)

p-i-n structures with Ge quantum dots in the *i*-region and their investigation by the method of admittance spectroscopy.

The samples were fabricated by molecular beam epitaxy in an ultra-high vacuum installation "Katun-C". Evaporation of silicon and germanium was carried out by electron beam evaporators, the dopants (Sb and B) were evaporated from effusion cells. The analytical part of the epitaxy chamber consists of a quadrupole mass spectrometer, a quartz thickness meter, and reflection high energy electron diffractometer (RHEED). The growth of Ge quantum dots was carried out on Si(100) substrates with misorientation less than 0.5°. Array of Ge hut-clusters with height 1.5–3 nm, lateral size 10–40 nm, and surface density ~10^{11} cm $^{-2}$ was formed on Si surface.

The samples with quantum dots, studied in this paper, were fabricated in Institute of Semiconductor Physics. Multiple layers with Ge quantum dots separated by thin 5 nm silicon layers are included in the intrinsic region of the samples. The *i*-region of type 1 samples contained 30 layers of 6 monolayer Ge quantum dots separated by 5 nm silicon layers. The *i*-region of type 2 samples contained 30 layers of 6 monolayer Ge quantum dots separated by 5 nm silicon layers, and every 10 layers of Ge quantum dots were additionally separated by 100 nm of Si (Figure 1).

Measurements were performed on an automated admittance spectroscopy installation [3]. The principle of admittance spectroscopy of structures with quantum dots is based on measuring the complex conductivity of the system that occurs when discrete energy levels recharge due to emission of charge carriers and their capture by localized states.

The temperature spectra of conductance (G-T) at different frequencies of the test signal and various bias voltages were measured for examined structures (Figures 2, 3). In the temperature dependence of conductance of type 1 samples a maximum was observed at low temperatures of 25–40 K. The observed maximum of conductance corresponds to a discrete energy level. The position of this peak is shifted on the temperature scale as the frequency of the applied signal changes (Figure 2, *b*). With fixed bias voltage V_b recharging of the level occurs. The charge carrier emission rate from this level decreases at lower temperatures, so with a decrease in the frequency of the test signal the condition of maximum conductance is achieved at lower temperatures. Conductance peak position for the sample remains constant with changes in the applied bias voltage (Figure 2, *a*).

Similar results were obtained in studies of type 2 sample. Figure 3 shows the temperature conductance spectra measured at different voltages and at different frequencies.

Processing temperature spectra leads to a typical family of Arrhenius plots for finding activation energies of the emission process. The GT/ω value has a maximum at $\omega = e_p$, where ω is the angular frequency of the test signal, e_p is the charge carrier emission rate from a discrete level. By plotting maxima T_{max} in coordinates $\omega = f(1/T)$ the activation energy characterizing the position of the energy levels is determined. For each frequency a point with coordinates $\ln(e_p/T^2)$, $1/T_{max}$ is plotted and the approximating straight line is built. From the slope of this line the activation energy is calculated. The observed maximum of conductance corresponds to a discrete energy level.

In a further study of type 2 sample a conductance peak at low positive bias was also detected (peak 2 in Figure 4). This maximum is observed only at positive bias at higher temperatures and is most pronounced at low frequencies, while the first maximum is also observed at negative bias.

For both samples activation energies were calculated. For the first peak of conductance calculated activation energies of type 1 and type 2 samples do not depend on the applied bias voltage and are equal to 38±5 meV and 46±4 meV respectively. For the second peak the calculated activation energy at a bias voltage of 1 V is 65±10 meV, at a bias voltage of 2 V it is 165±30 meV. This peak is broadened and probably corresponds not to a single discrete level but to a system of closely lying levels, due to the inhomogeneity of such parameters of quantum dots as their lateral size, height, shape and density in the array.

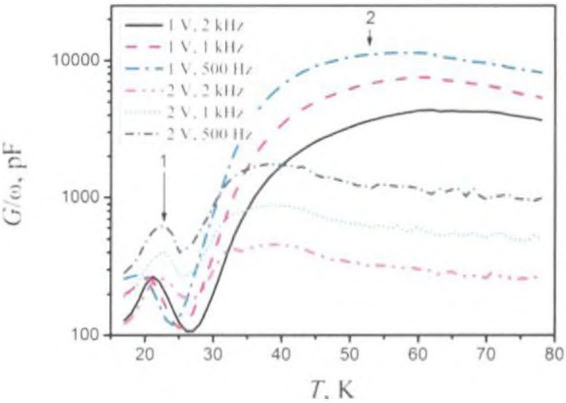

Fig. 4. – Temperature spectra of conductance of type 2 sample, measured at the voltages of +1 V and +2 V at different frequencies.

The first peak on the temperature dependence of conductance may be associated with the impurity level in Si. The second peak is explained by the presence of spatial quantization levels in the system associated with Ge quantum dots. Appearance and modification of peaks can be explained by the fact that with a change in the applied voltage the electrochemical potential occasionally crosses the discrete energy levels, producing oscillations in the charge density distribution. The reason for this is the thermionic emission of charge carriers from a discrete level. Discrete level gives partial charge density increment. This increment of charge leads to an increase in the external circuit current measured as a change in conductance of a sample.

Also, current-voltage characteristics without illumination and under illumination by incandescent lamp and halogen lamp were measured in the temperature range 10–300 k. Processing current-voltage characteristics revealed that energy conversion efficiency and fill-factor of structures increase with decreasing temperature and reach their maximum in the temperature range of 20–30 к. Maximum of short-circuit current is observed in the same temperature range and match the maximum of temperature spectra of conductance at low frequency.

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