Photoinduced absorption and photoconductivity of Ge/Si quantum dots in mid-infrared range under interband excitation

R M Balagula¹, A N Sofronov¹, V Yu Panevin¹, D A Firsov¹, L E Vorobjev¹, A A Tonkikh²,³ and P Werner²

¹St.Petersburg State Polytechnical University, Polytechnicheskaya str., 29, St. Petersburg, Russia.
²Max Planck Institute of Microstructure Physics, Weinberg 2, 06120 Halle (Saale), Germany
³Institute for Physics of Microstructures RAS, 603950, Nizhny Novgorod

E-mail: rmbal@spbstu.ru

Abstract. Photoinduced absorption and lateral photoconductivity of Ge/Si quantum dots with different doping levels are studied under interband optical excitation. The obtained spectra of absorption and photoconductivity are in good agreement. Observed photoconductivity is attributed to hole escape from ground and excited states while interlevel transitions do not impact the photoconductivity signal. Temperature dependence of photoinduced photoconductivity was measured. The decrease of photoresponse with the temperature increase is attributed to the hole recapture into the quantum dots.

1. Introduction
Ge/Si quantum dots (QD) can be used to develop near-IR and mid-IR radiation detectors, and a possibility of integration into existing Si technology is their advantage. A lot of research groups in the world are engaged in research of optical and photoelectrical phenomena in these structures, and their results tend to be useful and applicable for device development [1, 2]. At the same time details of these phenomena in Ge/Si quantum dots are not clear enough now. Studies of optical and photoelectrical properties of Ge/Si QD structures under the external photoexcitation of charge carriers may improve this situation since it is possible to observe the contribution of excited states occupied with nonequilibrium photoexcited carriers. In this paper, we present the results of both photoinduced mid-infrared photoconductivity and photoinduced absorption studies in Ge/Si quantum dots with different levels of boron doping. Photoexcitation with interband light allowed us to vary the number of holes per QD.

2. Samples and methods
Samples containing self-assembled Ge/Si quantum dots were studied. They were grown by molecular beam epitaxy on both-sides-polished Si (100) substrates with a resistivity of 1 kΩ·cm. Growth temperature was 600°C. The structures consisted of a 100 nm silicon buffer layer, on which ten layers of Ge QDs separated by 15 nm Si interlayers were grown. Seven Ge monolayers (MLs) were
deposited at a rate of 0.14 ML/s in order to form QDs. A 100 nm Si cover layer was deposited to complete the structure fabrication process. The average content of germanium in the QD material was about 60–65%. A surfactant (Sb) was used during the growth process in order to increase the density of the QD array. The structure was locally doped with boron. Doping was performed out of the Ge dot layer at 5 nm distance from it. We had at our disposal undoped structures and structures with boron doping levels of $4 \times 10^{11}$ and $8 \times 10^{11}$ cm$^{-2}$. The form and dimensions of QDs were found using transmission electron microscopy. Average height of QDs was 2.7 nm, and average size of QD base was 14 nm. Results of atomic force microscopy of specially grown samples with one QD level and no surface silicon layer showed that QD density was $2 \times 10^{11}$ cm$^{-2}$.

The undoped structure was used in the photoinduced absorption studies. Doped structures were used in the photoconductivity measurements.

Samples were mechanically processed in order to create multipass geometry. Sample sides were polished at 45˚ angle, and radiation lighted normally on these sides. This allowed light to pass the structure multiple times due to internal reflection in the sample. This also made polarization dependent studies possible.

The electrical contacts made of thin gold stripes were formed on the sample surface to measure photoconductivity.

Fourier transform IR vacuum spectrometer Bruker Vertex 80v with globar as a source of broadband mid-infrared radiation was used for spectral measurements. Samples were mounted into the liquid nitrogen-cooled cryostat with ZnSe windows. In both photoconductivity and absorption measurements the non-equilibrium charge carriers were generated by solid-state YAG:Nd laser with frequency doubling. Liquid nitrogen-cooled MCT detector was used in the absorption measurements. ZnSe metal grid polarizer was used to study photoresponse for two different light polarizations. Photoconductivity signal was amplified with low-noise current preamplifier SR570, which was also used to bias a sample and compensate the change of DC signal with excitation level. Amplified signal was then registered by lock-in amplifier SR830. In the photoconductivity studies we had to modulate globar radiation instead of exciting laser radiation (as in the photoinduced absorption measurements) because in the latter case giant interband photoconductivity signal would make it impossible to detect intraband photoconductivity.

3. Experimental results

Photoinduced absorption spectra were measured for two light polarizations and different pumping levels at 77 K. Spectrum for the highest excitation level is shown in figure 1.

![Figure 1](image-url)
The absorption spectrum for s-polarized light (curve I) demonstrates one low-energy peak 1, which we attribute to the hole transitions from ground to excited localized state. The absorption spectrum for p-polarized light (curve II) demonstrates two peaks corresponding to transitions of holes from ground state (peak 2) and from excited state (peak 3) to continuum. Curves III show Gaussian fit of the absorption coefficient of the observed peaks.

Inhomogeneous broadening of the absorption peaks can be attributed to the variation of QD geometry.

The peak positions correlate well with previously obtained data for the equilibrium light absorption in the doped structures [3], and with the theoretical estimates of energy spectrum [4]. But in the described experiments nonequilibrium charge carrier concentration pumped by the external photoexcitation exceeded the values of equilibrium hole concentration existing due to the original doping. Thus one can see the absorption peak corresponding to the previously unoccupied excited states.

Photoinduced photoconductivity spectra were measured in Ge/Si quantum dots at liquid nitrogen temperature (figure 2). Again, external photoexcitation allowed us to create nonequilibrium population of QD states. Both doped samples demonstrate a peak in photoconductivity spectra for z-polarized light. Peak position correlates well with absorption measurements considering that absorption of z-polarized light leads to escape of holes from QDs. This fact is also proved by previously obtained data for equilibrium photoconductivity and absorption in Ge/Si QDs with higher doping level [5].

The nature of the observed absorption peaks is confirmed by the photoconductivity specifics. As such only the peak at the energy of about 300 meV is observed at the photoconductivity spectra, because the absorption of radiation at this energy results in the appearance of free charge carriers in the Si matrix. The intersubband absorption (at approximately 100 meV) doesn’t have an influence on the photoconductivity spectra because the involved holes are still localized inside the QD.

![Figure 2. Photoconductivity spectra for z-polarized light for two samples under different excitation levels (shown in the plot) at 79 K.](image)

For the sample with lower doping level photoconductivity signal increases with excitation level and peak position remains the same, while for the sample with higher doping level the signal increase is not so fast and the observed peak broadens to the lower energy range. This broadening with an excitation can be attributed to the contribution of hole transitions from previously unoccupied QD excited states.

The obtained temperature dependence of photoconductivity signal is shown in figure 3. Measurements of a photocurrent at different temperatures show that photoconductivity signal diminishes with the temperature increase. Temperature suppression of photoconductivity can be related to the increase of recapture rate of free holes to the quantum dots at the presence of a potential...
barrier for holes at the heterointerface. The band bending can occur in silicon around the QD as a result of redistribution of mechanical strain [6] and due to the influence of selective doping.

The presence of a barrier for holes at the Ge/Si interface can also qualitatively explain a slight blue shift of photoconductivity compared to the absorption peak (2) in figure 1. Light with low photon energy transfers holes from QD ground state to the states under the QD at the top of silicon valence band. To contribute to the photocurrent holes must overpass the barrier while nothing prevents them from falling back into the quantum dot (transition I on figure 4). Light with higher photon energy transfers holes to the higher states above the barrier so they can easily contribute to the photoconductivity (transition II on figure 4).

**Figure 3.** Temperature dependence of photocurrent spectra for z-polarized light for the sample with doping level of $4 \times 10^{11}$ cm$^{-2}$ (excitation level is shown on the plot). $T = 77, 85, 95, 105, 115$ K.

**Figure 4.** Schematics of excitation processes in the QD structure.

4. Conclusion
In conclusion, in this work the lateral photoconductivity and absorption spectra were studied under the conditions of interband optical excitation. Absorption spectra reveal contribution of hole transitions from ground and excited states under their nonequilibrium occupancy. Spectrum of the photocurrent is in good agreement with the absorption spectrum. The absence of the low energy peak related to hole interlevel transitions corroborates the fact that only holes escaping from quantum dots may contribute to the photoconductivity.
Acknowledgments
This work has been supported by the Russian Foundation for Basic Research (Project №13-02-12203).

References
[1] Yakimov A I, Timofeev V A, Boshkin A A, Kirienko V V, Nikiforov A I, Dvurechenskii A V 2012 J. Appl. Phys. 112 034511
[2] Schilling J, Talalaev V, Tonkikh A, Fuhrmann B, Heyroth F, Otto M 2013 Appl. Phys. Lett. 103 161106
[3] Vorobjev L E, Firsov D A, Shalygin V A, Panevin V Yu, Sofronov A N, Yakimov A I, Dvurechenskii A V, Tonkikh A A, Werner P 2012 Semiconductors 46 1529
[4] Anikeeva M S, Vinnichenko M Ya, Firsov D A, Vorobjev L E, Tonkikh A A 2012 St. Petersburg State Polytechnical University Journal. Physics and Mathematics 158 9
[5] Panevin V Yu, Sofronov A N, Vorobjev L E, Firsov D A, Shalygin V A., Vinnichenko M Ya, Balagula R M, Tonkikh A A, Werner P, Fuhrman B, Schmidt G 2013 Semiconductors 47 1574
[6] Yakimov A I, Dvurechenskii A V, Nikiforov A I, Boshkin A A, Nenashev A V, Volodin V A 2001 Phys. Rev. B 73 115333