Far- and near-infrared photoluminescence from n-GaAs/AlGaAs multiple quantum wells

L E Vorobjev¹, D A Firsov¹, V Yu Panevin¹, A N Sofronov¹, R M Balagula¹, I S Makhov¹ and A P Vasil’ev²

¹St. Petersburg State Polytechnical University, Politechnicheskaya str., 29, St. Petersburg, 195251, Russia
²Ioffe Physical Technical Institute, Politechnicheskaya str., 26, St. Petersburg, 194021, Russia

Email: makhoviv@gmail.com

The results of experimental investigations of impurity-assisted photoluminescence at low temperatures from n-GaAs/AlGaAs multiple quantum wells both in near- and far-infrared (terahertz) spectral ranges are presented. The optical electron transitions from impurity ground state to heavy hole subband in near-infrared spectral range are revealed. The depopulation of the donor ground state due to these transitions allowed us to observe photoluminescence in terahertz spectral range related to electron transitions from the first electron subband to donor ground state as well as to intracenter optical transitions. Experimental results in far- and near-infrared spectral ranges are in good agreement with the results on THz photoconductivity and energy spectrum calculation.

1. Introduction.

Binding energy of shallow impurities in semiconductors is about units or tens of meV [1]. Thus, the possible optical transitions between band and impurity can be observed in terahertz (THz) spectral range. Many papers are devoted to investigations of different principles of terahertz radiation emitting with assistant of impurity states. Amongst them - terahertz radiation emitting via resonant and localized impurity states under carrier heating in strong lateral electric field in uniaxially stressed bulk p-Ge [2], in GaAs/GaAsN:Be microstructures with internal strain [3], in n-doped GaAs/AlGaAs QWs [4]. In condition of powerful impurity-band optical pumping the terahertz radiation was achieved on band-impurity transitions in Si:Bi [5]. Recently, the interest to terahertz radiation emitting under interband optical pumping of bulk semiconductors is rising. The terahertz photoluminescence (PL), caused by electron radiative transitions from acceptor levels to valence band in bulk Ge [6] as well as by transitions from conduction band to ionized donor states in bulk GaAs [6,7] and in GaN epilayers [8] was recently observed under optical interband pumping. The depopulation of impurity ground states was achieved due to the impurity-assisted electron–hole recombination which was observed in the interband PL spectra in near infrared spectral range. The similar mechanism of terahertz radiation emitting via impurity state in QWs is not studied yet. At the same time, the binding energy of impurity states in QWs is increasing in comparison with bulk material allowing to easily tune the spectrum of emitting radiation with changing the QW parameters. That is why the present work is devoted to investigation of impurity related terahertz radiation in n-GaAs/AlGaAs QW structure under condition of interband optical pumping. We present spectra of both intraband terahertz (far-infrared) and
interband near-infrared emission where the impurity-assisted electron transitions in quantum wells are clearly observed.

2. Samples and experimental setups.

In this work we present results for sample with doped QWs in comparison with its substrate which has no any epitaxial layers. Sample was MBE grown on GaAs semi-insulating substrate on a 0.2 μm GaAs buffer layer and consisted of 50 layers of 30 nm GaAs quantum wells separated with 7 nm Al0.3Ga0.7As barriers. Quantum wells were doped in the 4 nm layer with surface donor (Si) concentration of 3·10^{10} cm^{-2}. Doped region was shifted on 6 nm from QW center. Samples had a 20 nm GaAs cap layer doped up to 5·10^{17} cm^{-3} with a silicon.

For optical study, the sample was mounted into the low vibration closed cycle Janis PTCM-4-7 cryostat based on the pulse tube thermodynamic cycle. Sample temperature can be varied from ~4 K to 320 K. QW sample was studied separately from substrate. Interband optical excitation of the sample was attained with solid state CW laser (λ = 532 nm, P = 8 mW). For directing the laser beam to the sample inside of the cryostat with an incidence angle of approximately 45° to growth axis, we used mirrors, lens and fused silica cryostat window. Far-IR emission was studied through the polymethylpentene (TPX) cryostat window, near-IR emission was studied through the fused silica cryostat window.

Far-IR photoluminescence spectra were studied with Fourier transform technique using vacuum Fourier transform infrared (FTIR) spectrometer Bruker Vertex 80v operating in step-scan mode. FTIR spectrometer had a polyethylene (PE) entrance window and a kit of exchangeable terahertz beamsplitters. There was a distance about 2 cm between cryostat TPX window and spectrometer PE window. Here we put ~100 μm black PE filter to block the pumping light. The intensity of the far-IR emission was measured with Si bolometer system (made by Infrared Laboratories, Inc.) cooled with liquid helium. Bolometer cryostat had a vacuum optical coupling with a FTIR spectrometer. Bolometer had a PE window and two internal interchangeable filters namely 0.5 mm thin PE filter and 1 mm thick crystalline quartz filter.

We have used two optical configurations of the far-infrared experimental setup with different spectral throughputs. The first configuration with the combination of 0.5 mm polyethylene bolometer filter with 6 μm multilayer Mylar beamsplitter was used to investigate the spectral range 4-40 meV. The second one is the combination of 25 μm Mylar beamsplitter with crystalline quartz bolometer filter. Second configuration considerably increased setup transmission in 2-14 meV spectral range but blocked higher frequencies.

Near-IR PL spectra were studied with grating monochromator Horiba Jobin Yvon FHR-640 operating in spectrograph mode with holographic grating with 1200 groves per mm and liquid nitrogen cooled CCD camera.

3. Experimental results and discussion.

The results of PL study in the far-IR spectral range for the sample, as well as for substrate are presented in figure 1 (please, see legend on the plot to recognize the curves). It should be noted that the real emission spectra can slightly differ from spectra presented in our paper because of spectral dependency of photodetector sensitivity, windows and beamsplitter transmission using in the first optical configuration of the setup. Anyway, comparing PL spectra for sample and substrate, one can distinguish wide emission band 14-30 meV inherent to both of them. This fact probably means, that in this spectral range we have deal with some impurity related emission from the bulk layers of the sample such as semi-insulated (probably compensated) substrate which as well could contain unintentional carbon impurity accompanying Czochralski grown process of bulk GaAs [9]. Really, the thickness of QW layers is not too high, so the exciting laser radiation can reach the substrate and produce impurity involved optical transitions in according to the mechanism described for bulk semiconductors in Ref.’s [6-8]. Slight difference of the QW sample and the substrate spectra in 13-30 meV range could be explained by the presence of additional impurities in QW sample “matrix”
(buffer, cap and probably barrier layers of the structure) which as well could contain unintentional impurities due to MBE growth process [11]. In the near-IR spectra of the sample and substrate shown, correspondingly, in figures 2 and 3, the bulk band-impurity interband radiative recombination is marked with label “Matrix”. Matrix luminescence in sample and substrate looks similar and lies, approximately, on 15-30 meV (at the level of the half of maximum) lower then GaAs interband transition energy (marked with arrow $E_{GaAs}$ in figure 3). That interband recombination depopulates impurity levels and allows nonequilibrium carrier capture from band to impurity, which could leads to terahertz photon emission. Intermid transition at the photon energy corresponding to energy gap of the bulk GaAs (1.519 eV [1]) is not clearly observed, due to exciton formation effects. Exciton binding energy for bulk GaAs is 4.2 meV [11] and emission line marked in figure 3 with arrow $Xe^{-hh1}$ could be connected with heavy free exciton. Also, the emission line marked with arrow $A-X$ lying on 2.9 meV lower in figure 3 could be connected with acceptor (carbon) bound exciton [12].

Returning to far-IR spectra presented in figure 1 one can see that the weaker emission band near 4-13 meV is a feature of QW spectrum only and is not observed on substrate spectrum. Using second optical configuration of experimental setup with improved throughput in 2-14 meV spectral range, we have studied the QW emission spectral feature more elaborately at two temperatures (see figure 4). It gives us broad spectra which overlap with photoconductivity spectra of the same QW structure, presented in Ref. [4] and cover both of the expected optical transitions of electrons: from ground QW subband to impurity ground state ($e_1-1s$) and intracenter transition $2p_{x,y}-1s$ (their energies are calculated in Ref. [4] and marked with arrows in figure 4). One should not wonder that in our spectra different impurity related transitions are broadening and cannot be resolved clearly. It is well known, that narrow impurity lines could be observed in pure samples only, with doping level significantly less then in our QW structure (see, for example Ref. [13]).

![Figure 1. THz PL spectra for the different samples](image1)

![Figure 2. Near-IR PL spectrum of the sample.](image2)

Results of PL investigations of the sample in the near-IR spectral range are shown in the figure 2. Accordingly to calculation of electron ($e$) and heavy hole ($hh$) energy states in our QW, we expected the interband transition $e_1-hh1$ at the photon energy of 1.526 eV, but due to exciton formation effects this transition is not clearly observed in our spectra. For such a wide QW as our one exciton binding energy is almost equal to bulk GaAs aforesaid value and emission line marked in figure 2 with arrow $Xe^{-hh1}$ could be connected with heavy free exciton for the first QW subband. Also, the emission line marked with arrow $Si-X$ in figure 2 could be connected with donor bound exciton. The emission line marked with arrow $Si_{1s}-hh1$ in figure 2 could be connected with electron-hole radiation recombination between ground donor state and first heavy hole subband with
the photon energy about 1.5183 eV. That recombination process forerun mentioned above $e1-1s$ and $2px,y-1s$ optical transitions observed in far-IR PL spectra. The energy separation between $e1-hh1$ and $Si_{1s}-hh1$ transitions in figure 2 is about 8 meV. This value corresponds with binding energy of silicon in our QW calculated in [4].

The observed in figure 4 temperature quenching of the terahertz PL can be explained with ionized donor capture probability decrease or with the increase of the carrier ejection from the neutral donor with temperature increase. Earlier, the similar temperature behavior of terahertz luminescence was observed in Ref. [5] in bulk doped semiconductor.

![Figure 3. Near-IR PL spectrum of the substrate.](image1)

![Figure 4. THz PL spectrum of the QWs sample at the different temperatures (see legend on the plot), measured in the second optical configuration suitable for 2-14 meV range.](image2)

**4. Summary.**

In the present work, the far- and near-infrared emission under optical interband excitation related to impurity states in silicon doped GaAs/AlGaAs quantum well structure was observed and investigated. In the near-infrared photoluminescence spectra of the QW the emission line associated with electron transitions from ground donor state to ground heavy hole subband is detected. Optical transitions from the ground electron subband $e1$ as well as from excited impurity state $2px,y$ to the getting free ground impurity state $1s$ becomes possible. Corresponding PL lines have been observed in far-IR spectra and their spectral positions are in good agreement with electron energy state calculations in QW including impurity states as well as with photoconductivity spectra for the same structure (see Ref. [4]).

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