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L.E. Vorobjev, D.A. Firsov, V.Yu. Panevin,
A.N. Sofronov, R.M. Balagula, I.S. Makhov

St. Petersburg State Polytechnical University,
29 Politechnicheskaya St., St. Petersburg, 195251, Russia

NEAR- AND FAR-INFRARED EMISSION FROM GaAs/AlGaAs QUANTUM WELLS UNDER INTERBAND OPTICAL EXCITATION

Л.Е. Воробьев, Д.А. Фирсов, В.Ю. Паневин,
А.Н. Софронов, Р.М. Балагула, И.С. Махов

ИЗЛУЧЕНИЕ БЛИЖНЕГО И ДАЛЬНЕГО ИНФРАКРАСНОГО ДИАПАЗОНА ИЗ КВАНТОВЫХ ЯМ GaAs/AlGaAs ПРИ МЕЖЗОННОМ ОПТИЧЕСКОМ ВОЗБУЖДЕНИИ

The results of experimental studies of low-temperature impurity-assisted photoluminescence of *n*-doped GaAs/AlGaAs quantum well structures both in near- and far-infrared (terahertz) spectral ranges under interband optical excitation are presented. In the near-infrared photoluminescence spectra the optical electron transitions from the donor ground state to the hole subband are revealed. The depopulation of the impurity ground states due to these transitions allowed us to observe photoluminescence in terahertz spectral range related to electron transitions from the first electron subband to the donor state as well as to intracenter optical transitions. Experimental results in near- and far-infrared spectral ranges are well-consistent with the results on terahertz photoconductivity and theoretical calculations.

IMPURITIES, QUANTUM WELLS, TERAHERTZ RADIATION, PHOTOLUMINESCENCE.

В настоящей работе представлены результаты экспериментальных исследований низкотемпературной примесной фотолюминесценции (ФЛ) из структур с квантовыми ямами (КЯ) GaAs/AlGaAs *n*-типа в ближней и дальней инфракрасной (ИК) областях спектра. В спектрах ФЛ в ближнем ИК диапазоне проявляются оптические переходы из основного состояния донора в КЯ в нижнюю подзону дырок в КЯ. Опустошение основного состояния донора благодаря этим переходам позволило нам наблюдать фотолюминесценцию в терагерцовом диапазоне, связанную с переходами электронов из первой электронной подзоны на состояния донора, а также с внутрицентровыми оптическими переходами. Результаты исследования ФЛ в ближнем и дальнем ИК диапазонах дополняют друг друга и хорошо согласуются с результатами исследования терагерцовой фотопроводимости и теоретическими расчетами.

ПРИМЕСИ, КВАНТОВЫЕ ЯМЫ, ТЕРАГЕРЦОВОЕ ИЗЛУЧЕНИЕ, ФОТОЛЮМИНЕСЦЕНЦИЯ.

I. Introduction

Development of effective emitters operating in terahertz (far-infrared) spectral range is considered as an important and urgent task because of the wide range of potential applications of various terahertz devices in information technologies, medicine, chemistry, physics, nanotechnology and other demanding areas [1]. The energies of intracenter carrier transitions in doped semiconductors and semiconductor nanostructures correspond to terahertz spectral ranges. Development of lasers using shallow impurity levels in the lasing scheme is a promising alternative to the well-known quantum cascade lasers [2] of a very complicated technology. That is why the optical studies of impurity related carrier transitions attract particular interest with respect to developing new types of terahertz radiation sources.

There are some mechanisms suggested for obtaining the impurity related terahertz emission. In Ref. [3] spontaneous emission in the THz range was observed from electrically pumped bulk silicon doped with phosphorus. Another way to create nonequilibrium carriers and to use intracenter carrier transitions can be realized with the impurity-band optical excitation by the radiation of CO_2 laser (see, for example, [4] where THz lasing was observed in bulk silicon doped with phosphorus).

Low-temperature interband photoluminescence in doped semiconductors can be used for the depopulation of the ground impurity states due to processes of impurity-band recombination. In Ref. [5] terahertz luminescence under the interband photoexcitation of bulk *n*-GaAs and *p*-Ge semiconductors at low temperatures was reported. The terahertz photoluminescence was caused by intraband radiative carrier transitions, which accompanied the capture of nonequilibrium carriers by impurity centers. The depopulation of impurity ground states was achieved due to the impurity-assisted electron-hole recombination.

In this work we present the investigation of impurity-related THz emission in nanostructures with quantum wells (QW). QW structures are of considerable interest because the energy differences between impurity levels can be changed easily with changing the QW structure parameters. Previously, terahertz emission in *n*-GaAs/AlGaAs quantum well structure was observed under impurity breakdown in strong electric field [6]. This emission was related mainly to electron intracenter optical transitions between resonant and bound donor states. In the present work we used optical interband excitation of nonequilibrium carriers in donor-doped GaAs/AlGaAs QW structures to initiate THz emission. After optical excitation, the electrons on the ground donor state radiatively recombine with nonequilibrium holes. Nonequilibrium electrons can be captured on the ground states of positively charged donors with the emission of terahertz photons. Nonequilibrium electrons can also be captured on excited states of donors and then fall on donor ground states with emission of photons.

In this work we present spectra of both intraband terahertz (far-infrared) radiation and interband near-infrared emission (photoluminescence). It is shown that the features in the measured spectra are related to impurity-assisted electron transitions in quantum wells.

II. Samples and Experimental Techniques

The samples for optical studies were MBE grown on GaAs semi-insulating substrate placed on a 0.2 μm GaAs buffer layer and they consisted of 50 layers of 30 nm GaAs quantum wells separated with 7 nm $Al_{0.3}Ga_{0.7}As$ barriers. Quantum wells were doped in the 4 nm layer with surface donor (Si) concentration of $3{\cdot}10^{10}$ cm^{-2}. Doped region was shifted by 6 nm from the QW center. The samples had a 20 nm GaAs cap layer doped up to the level of $5{\cdot}10^{17}$ cm^{-3} with a silicon.

The sample was mounted in a low vibration closed cycle cryostat Janis PTCM-4-7 based on the pulse tube thermodynamic cycle. Its temperature could be varied from ~4 to 320 K. Interband optical excitation of the sample was attained with solid state CW laser with diode pumping (λ = 532 nm, P = 8 mW). We used fused silica window, mirrors and lens to direct the laser beam to the sample inside the cryostat with an incidence angle of approximately 45 ° to the growth axis. Far-infrared (IR) emission as well as near-IR one was collected from the surface of the QW structure in the growth axis direction. Near-IR emission was studied through the fused silica cryostat window, far-IR emission was studied through the polymethylpentene (TPX) 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 the cryostat TPX window and the 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. The bolometer cryostat had a vacuum optical coupling with the 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. Pre-amplified and filtered bolometer photoresponse was measured by a lock-in amplifier SR-830 on a pump laser driven frequency (laser current was modulated with the frequency of 87 Hz, 50% duty cycle). Lock-in output signal was digitized by a 14-bit ADC. Bruker software OPUS triggered measurement cycle for each FTIR spectrometer mirror position and performed Fourier transform of the resulting interferogram.

We have used two optical configurations of the FTIR setup with different spectral throughputs. The combination of 6 μm multilayer Mylar beamsplitter with 0.5 mm PE bolometer filter allowed us to investigate as wide spectral range as 4 – 85 meV. The combination of 25 μm Mylar beamsplitter with a crystalline quartz bolometer filter significantly increased setup transmission in 2 – 14 meV spectral range but blocked higher frequencies.

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

III. Experimental Results and Discussion

In the conditions of low temperature (about 4 K) and interband optical excitation of *n*-doped QW nanostructures, the recombination of nonequilibrium holes and electrons initially localized at non-ionized donors can exist along with exciton recombination. That is why in the present work we had a pleasure to observe both near-IR emission and terahertz radiation. Near-IR emission was related to exciton recombination and electron transitions from donor states to the valence band. The terahertz radiation was related to electron transitions from the conduction band to donor states and probably to intracenter electron transitions accompanying the process of nonequilibrium electron capture by ionized donors.

The results of photoluminescence (PL) investigations in the *n*-doped QW nanostructure in the far-IR spectral range are shown in Fig. 1. PL spectrum of the substrate is also shown there. It should be noted that the real emission spectra can slightly differ from the spectra presented in our paper because of spectral dependency of photodetector sensitivity and windows and beamsplitter transmission. Anyway, Fig. 1 allows one to distinguish the difference in photoluminescence spectra of QW structure and its substrate. Really, the wide emission band 13 – 30 meV is presented in both spectra. This fact probably means, that in this spectral range we deal with some impurity related emission from the bulk layers of the sample such as semi-insulated (probably compensated) substrate and the cap or barrier layers. It is well known that the energies of intracenter hole transitions, for example, in Be-doped bulk GaAs, lie in this spectral range [7]. The thickness of QW layers is not too high, so the exciting laser radiation can reach the substrate and produce impurity involved optical transitions according to the mechanism described for donors in QW.

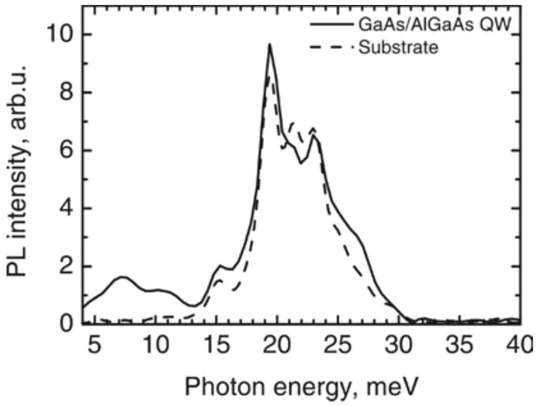

Fig. 1. Terahertz emission spectrum of optically excited GaAs/AlGaAs QW structure – solid line. Dashed line corresponds to substrate emission spectrum. $T = 4.4$ K

It should be noted that the weaker emission band near 4 – 13 meV is a feature of the QW spectrum only. Some changes of the optical path allow us to improve the throughput of our experimental setup in 2 – 14 meV spectral range and to study QW emission spectral features more elaborately at two temperatures (see Fig. 2). Beyond the above-mentioned spectral range, the throughput of the experimental setup is equal to zero.

In accordance with the results of electron energy spectrum calculations for our QW structure (see Ref. [6]), the energies of electron transitions between the first electron subband

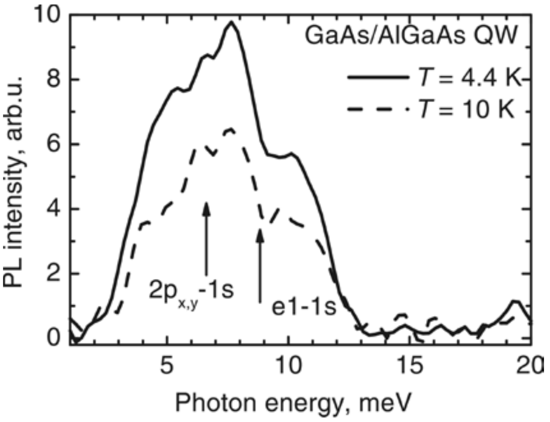

Fig. 2. Long wavelength part of QW emission spectrum measured at two temperatures.
Energies of some allowed electron optical transitions are shown with arrows

and the impurity ground state $e1\to 1s$, and between the excited and ground impurity states $2p_{x,y}\to 1s$ are 8.8 and 6.5 meV, respectively. Note, that these calculated values agree well with experimental photoconductivity spectra also presented in Ref. [6]. Energies of these transitions are shown by arrows in Fig. 2. One should not wonder that in our spectra different impurity related transitions are broadened and cannot be resolved clearly. It is well known that narrow impurity lines could only be observed in «pure» samples, with doping level significantly less then in our QW structure (see, for example, Ref. [7]). Thus, we can conclude that our 4 – 13 meV emission band can be connected exactly with band-impurity and intracenter transition in the QW. The observed decrease of photoluminescence intensity by 1.5 times with temperature increase from 4.4 K to 10 K can be explained with a variety of factors, such as ionized donor capture probability decrease or the increase of the carrier ejection from the neutral donor with temperature increase. Earlier, the similar temperature quenching of terahertz luminescence was observed in Ref. [5] in bulk semiconductors.

The results of photoluminescence investigations of the n-doped QW nanostructure, as well as of its substrate, in the near-IR spectral range are substantially supporting our conception pronounced above about the origin of the observed terahertz emission. As a rule, at low temperature, in the interband photoluminescence spectra of the doped semiconductor or nanostructures, one can observe series of emission lines associated with radiative recombination of the free heavy and light excitons (the latter can be observed in QW structures at higher temperatures), radiative recombination of the impurity-bound excitons and radiative electron-hole recombination via impurity states (see, for example, Ref. [8 – 10]).

The results of investigations of the interband excitonic and impurity assisted near-IR radiation under interband optical pumping in our QW structure are shown in Fig. 3.

According to the calculation of electron (e) and heavy hole (hh) energy states in our QW, we expect the interband energy separation between the first electron and hole QW levels $e1 - hh1$ to be of about 1.526 eV. Direct optical transitions between the electron and hole states are not observed in our spectra because of excitonic formation effects. The exciton binding energy in bulk GaAs is about 4.2 meV [11]. For such a wide QW as our one, the exciton binding energy value should not be significantly more. Thus, the emission line marked in Fig. 3 with the arrow Xe1-hh1 could be connected with free heavy exciton for the first QW subbands.

The emission line marked with the arrow Si-X in Fig. 3 could be connected with the donor bound exciton.

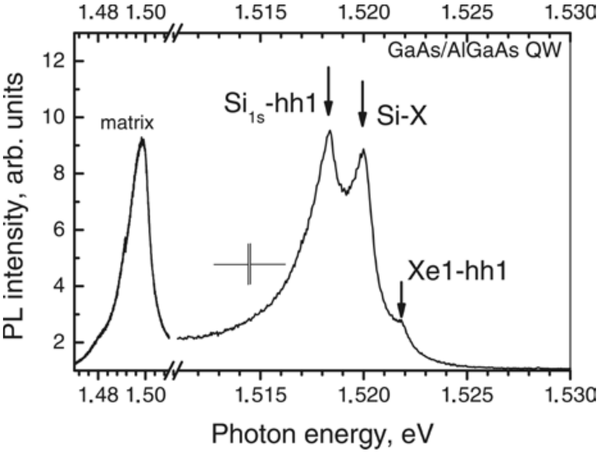

Fig. 3. Near-IR luminescence spectra
of the GaAs/AlGaAs QW structure under interband optical excitation; T = 4 K.
Arrows show the main emission lines (see discussion in the text). Spectral resolution is shown in the plot

Finally, as we expected for interband recombination via 1*s* donor state, we have observed optical transition marked as Si_{1s}-*hh*1 for the photon energy about 1.5183 eV.

As we have pointed above, that transition foregoes the *e*1 – 1*s* transition observed in far-IR PL spectra.

The low frequency part of near-IR spectrum with the main power concentrated between 1.49 eV and 1.50 eV (marked «matrix» in Fig. 3) lies at the distance of about 20 – 30 meV from GaAs energy gap (1.519 eV) and could be connected with some impurity transitions in the sample substrate which as well could give their impact on far-IR spectra described above.

IV. Summary

Finally, in the present paper, the emission of terahertz radiation related to band-impurity and intracenter optical transition under optical interband excitation in silicon-doped *n*-GaAs/AlGaAs quantum well structures has been observed and investigated.

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ВОРОБЬЕВ Леонид Евгеньевич – *доктор физико-математических наук, профессор кафедры физики полупроводников и наноэлектроники Санкт-Петербургского государственного политехнического университета.*

195251, Россия, Санкт-Петербург, Политехническая ул., 29
LVor@rphf.spbstu.ru

ФИРСОВ Дмитрий Анатольевич – *доктор физико-математических наук, профессор, заведующий кафедрой физики полупроводников и наноэлектроники Санкт-Петербургского государственного политехнического университета.*

195251, Россия, Санкт-Петербург, Политехническая ул., 29
DmFir@rphf.spbstu.ru

СОФРОНОВ Антон Николаевич – *кандидат физико-математических наук, доцент кафедры физики полупроводников и наноэлектроники Санкт-Петербургского государственного политехнического университета.*

195251, Россия, Санкт-Петербург, Политехническая ул., 29
Sofronov@rphf.spbstu.ru

ПАНЕВИН Вадим Юрьевич – *старший преподаватель кафедры физики полупроводников и наноэлектроники Санкт-Петербургского государственного политехнического университета.*

195251, Россия, Санкт-Петербург, Политехническая ул., 29
PVYu@rphf.spbstu.ru

БАЛАГУЛА Роман Михайлович – *аспирант кафедры физики полупроводников и наноэлектроники Санкт-Петербургского государственного политехнического университета.*

195251, Россия, Санкт-Петербург,. Политехническая ул., 29
RMBal@spbstu.ru

МАХОВ Иван Сергеевич – *студент Санкт-Петербургского государственного политехнического университета.*

195251, Россия, Санкт-Петербург,. Политехническая ул., 29
Makhoviv@gmail.com