Impurity-assisted terahertz photoluminescence in quantum wells under conditions of interband stimulated emission

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Abstract. Terahertz and near-infrared photoluminescence under conditions of interband stimulated emission are studied in \textit{n-GaAs/AlGaAs} quantum well laser structure. The observed terahertz emission is related to the optical transitions of nonequilibrium electrons from the first electron subband and excited donor states to donor ground states in quantum wells. The opportunity to increase the intensity of impurity-assisted terahertz emission due to interband stimulated emission with the participation of impurity centres is demonstrated.

1. Introduction

In recent decades, the terahertz spectral range (0.1-10 THz) has attracted considerable interest because terahertz devices, particularly terahertz radiation sources, may find their application in various fields of science and technology. Thus, terahertz devices can be used in spectroscopy, medicine, monitoring of environment and food quality, wireless communications, etc.\cite{1}. The terahertz radiation mechanism based on optical transitions of nonequilibrium charge carriers with the participation of shallow impurity states in semiconductors is one of the promising for the creation of terahertz radiation sources.

Recently, spontaneous terahertz emission associated with the radiative transitions of nonequilibrium electrons from the first electron subband and donor excited states to donor ground states was observed in \textit{n-GaAs/AlGaAs} quantum wells (QWs) under interband optical excitation\cite{2,3}. The intensity of terahertz radiation in such systems is determined by the depopulation rate of the ground donor state in QW, which occurs due to the spontaneous radiative recombination of electrons from the donor ground state and holes from the first heavy hole subband. Thus, the increase in the depopulation rate for the donor ground state in QW should result in an increase of the terahertz radiation intensity. A possible way to increase the depopulation rate for the donor ground state is to realize stimulated emission between the donor ground state and the valence subband. A similar approach was used earlier in \textit{InGaAs/AlGaAs} quantum dots\cite{4}, where stimulated interband recombination led to an increase of mid-infrared radiation intensity associated with intraband interlevel optical transitions of charge carriers in quantum dots. In this work, we present the results of
the investigation of impurity-assisted terahertz photoluminescence (PL) under conditions of interband stimulated emission in doped QW laser structure.

2. Sample and experimental setups
The structure for optical studies was MBE grown on a semi-insulating GaAs substrate and contained 10 quantum wells formed with 7.6 nm thick GaAs layers and separated with 5 nm Al0.3Ga0.7As barrier layers. Quantum wells were doped with silicon (donor) in the 2.6 nm central region of each QW up to a surface impurity concentration of $5 \times 10^{19}$ cm$^{-2}$. In order to realize interband stimulated emission, QWs were embedded into a symmetric waveguide formed with 0.6 μm thick Al$_x$Ga$_{1-x}$As graded layers ($x$ varied from 0.4 to 0.6). The sample substrate was polished off to the thickness of about 120 μm. The four "as-cleaved" facets of the sample formed the total internal reflection optical cavity with dimensions of about 400×400 μm$^2$.

The sample was mounted in a closed cycle cryostat, which allowed to cool the sample down to about 5 K. The powerful interband optical excitation of the QW layers as well as the barrier and waveguide layers of the sample was attained with a frequency doubled Nd:YAG solid state pulsed laser ($\lambda = 532$ nm, 0.25 μs pulse duration, 8 kHz repetition rate). For the terahertz luminescence experiment, the laser beam was additionally chopped at 360 Hz with the aim to use a lock-in technique to measure the detector signal.

The terahertz PL spectra were studied in a step-scan mode of a vacuum FTIR spectrometer equipped with a 6 μm thick Mylar multilayer beamsplitter. The terahertz photoluminescence intensity was measured with a liquid helium cooled silicon bolometer. The bolometer photoresponse was measured by a lock-in amplifier SR510 on a pump laser chopper frequency. Near-infrared photoluminescence spectra were measured from the facet of the sample using a monochromator with a holographic grating with 1200 groves per mm and a liquid nitrogen cooled silicon CCD camera.

In order to reveal the influence of interband stimulated emission on impurity-related terahertz emission in QWs, the integrated terahertz photoluminescence intensity and near-infrared photoluminescence spectra were measured simultaneously. A terahertz sensitive Ge:Ga photodetector was mounted opposite the surface of the sample at a distance of about 12 mm, in this way integrated terahertz emission was measured in “face to face” mode, when the excited sample and the detector were mounted in a cryostat at the same cold finger. The surface of the Ge:Ga detector was covered with two cold filters: 1 mm thick high resistivity compensated Ge (Sb, Au) and a layer of black polyethylene (about 100 μm thick) with the aim to block pumping laser radiation scattered from the surface of the sample, as well as near-infrared radiation of the sample. After being pre-amplified and filtered by a current preamplifier SR-570, the detector photoresponse was measured by a lock-in amplifier SR-510 on a pump laser chopper frequency.

3. Experimental results and discussion
Spectral measurements of the terahertz PL intensity in our sample with doped QWs at a low optical pumping power (about 7 W/cm$^2$) show that terahertz photoluminescence spectrum contains two broad emission bands with maxima at the photon energies $h\nu$ of about 10 and 20 meV. Note that a terahertz photoluminescence signal from the GaAs semi-insulating substrate (without QW layers) was not detected. Thus, according to the results of theoretical calculations of the energy spectrum of donor states in QWs from the Ref. [5], the binding energy of a donor impurity in the 7.6 nm wide QW is about 15 meV and the photoluminescence band near the photon energy 20 meV is associated with the capture of nonequilibrium electrons from the first electron subband $e1$ to the ground impurity state $1s$. The terahertz emission band near a photon energy of about 10 meV could be associated with electron transitions from the excited donor state $2p_{3/2}$ to the ground donor state $1s$ in QW. These terahertz optical transitions are marked with the arrows $h\nu_{THz}$ in the optical transitions scheme presented in figure 1.

Investigations of near-infrared photoluminescence spectra at different levels of interband optical excitation show broad emission bands associated with radiative recombination of free and bound
excitons, radiative recombination of electrons and heavy holes via ground and excited donor states (1s-hh1 and 2p_{x,y}-hh1 optical transitions shown in figure 1), as well as via impurity states of residual acceptor [6] (the e_{1}-A optical transition shown in figure 1) in QWs. At relatively high optical pumping levels three narrow stimulated emission lines associated with radiative recombination of electron-hole pairs via excited and ground donor states and ground acceptor states in QWs arise (these stimulated optical transitions are shown in figure 1 with the arrows $h\nu_{\text{NIR}}$). The threshold value of the optical pumping power for interband lasing is approximately the same for all stimulated emission lines and is about 370 W/cm².

The dependence of the integrated terahertz emission intensity on the optical pumping power is presented in figure 2 by dots. At low levels of optical pumping, the intensity of terahertz radiation increases with the optical pumping increase by the square root law. This dependence is in good agreement with results of the experimental studies for terahertz photoluminescence in bulk GaAs doped with donor impurities [7]. We do not expect any difference in such dependence due to 2D-quantization phenomena. At relatively high optical pumping intensities exceeding 2 kW/cm², this dependence changes its behavior to linear (the corresponding pumping power is shown with the arrow labeled "terahertz intensity increase" in figure 2). We connect this change in the dependence of the integrated terahertz intensity on the optical pumping power with the beginning of more effective depopulation of the ground donor state 1s in QW due to stimulated interband emission related to radiative recombination of electrons from the ground donor state 1s and holes from the valence subband hh1.

In accordance with the mentioned above mechanism of terahertz radiation in QWs in conditions of interband stimulated emission, we expected to find the increase of terahertz integrated intensity at the optical pumping power corresponding to the interband lasing threshold value (this value is marked with the arrow labeled "interband lasing threshold" in figure 2) for the 1s-hh1 optical transitions. But as it was mentioned earlier, the stimulated emission lines associated with the 2p_{x,y}-hh1 and e_{1}-A optical transitions were also revealed in the near-infrared emission spectra, simultaneously with the...
1s-\textit{hh}1 one. This fact means that all of our states e1, 1s and 2p_{x,y} are well enough depopulated due to interband stimulated transitions, and there are no reasons to observe the expected increase of the terahertz integrated intensity. However, the intensity of the 1s-\textit{hh}1 and 2p_{x,y}-\textit{hh}1 stimulated emission lines is much higher than the intensity of the e1-A stimulated emission line within the all studied pumping power range, and their comparative intensities depend on the pumping power.

The dependence of the ratio of the integrated intensities of the 1s-\textit{hh}1 to the 2p_{x,y}-\textit{hh}1 stimulated emission lines on the optical pumping power is presented in figure 3. From this dependence, one can see that the ratio between the integrated intensities of the 1s-\textit{hh}1 and 2p_{x,y}-\textit{hh}1 stimulated optical transitions is constant up to the optical pumping power of about 2.5 kW/cm² and at higher values of the optical pumping power this ratio begins to increase linearly. This ratio increase is connected with the fact that the integrated intensity of the 2p_{x,y}-\textit{hh}1 stimulated optical transitions begins to saturate, while it continues to increase for the 1s-\textit{hh}1 transitions. We recall that at the optical pumping power just of about 2.5 kW/cm², the terahertz intensity starts to increase more quickly (this pumping power value is shown with the arrows labeled ”terahertz intensity increase” in both figures 2 and 3). Thus, the more intensive increase of terahertz intensity observed at the optical pumping power exceeding 2.5 kW/cm² (see figure 3) can be connected with more effective depopulation of the ground donor states in QWs under interband lasing conditions.

Conclusion
Luminescence of terahertz and near-infrared spectral ranges in GaAs/AlGaAs QWs doped with donor impurities under interband photoexcitation is studied under conditions of interband stimulated emission. Terahertz photoluminescence from doped QWs is connected with the optical transitions of nonequilibrium electrons with the participation of donor states in QWs. The increase of the impurity-assisted terahertz luminescence intensity in doped QWs due to fast depopulation of impurity states under conditions of impurity-assisted interband lasing is shown.

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