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Impurity-assisted terahertz luminescence in quantum well nanostructures under interband photoexcitation

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Abstract

The paper presents the results of an experimental study of impurity-assisted photoluminescence in the far- (terahertz) and near-infrared spectral ranges in *n*-GaAs/AlGaAs quantum well structures with different well widths under interband photoexcitation of electron–hole pairs. The optical electron transitions between the first electron subband and donor ground state as well as between excited and ground donor states were revealed in the far-infrared photoluminescence spectra. Observation of these optical electron transitions became possible because of the depopulation of the donor ground state in the quantum well due to the non-equilibrium charge carrier radiative transitions from the donor ground state to the first heavy hole subband. The opportunity to tune the terahertz radiation wavelength in structures with doped quantum wells by changing the quantum well width was demonstrated experimentally.

Keywords: Terahertz luminescence; Radiation; Quantum well; Spectrum; Nanostructure; Semiconductor.

Introduction

The task of developing effective semiconductor sources of terahertz radiation (the wavelength range of electromagnetic radiation is 30–300 μm) is rather important at present as these devices can be used in diverse areas of science and technology, such as medicine, environmental monitoring, security systems, and computer science (see, for example, Refs. [1–3]). One of the most promising mechanisms for generating terahertz radiation is based on optical transitions of nonequilibrium charge carriers involving impurity states in semiconductors and semiconductor nanostructures. This mechanism is an alternative to the quantum cascade laser [4], since fabricating the latter requires very sophisticated techniques of high-quality growth of semiconductor nanostructures.

There are currently several known mechanisms for generating terahertz radiation, based on impurity-assisted transitions of charge carriers in semiconductors and semiconductor nanostructures. For example, terahertz radiation was observed during optical transitions of nonequilibrium charge carriers involving

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impurity resonance states under impurity breakdown in electric field in mechanically strained *p*-Ge [5] and in GaAs/GaAsN:Be microstructures with built-in stresses [6]. Additionally, terahertz radiation was observed from bulk silicon doped with various impurities under intraband optical excitation of charge carriers [7]. Terahertz radiation under interband photoexcitation was observed in doped bulk semiconductors such as GaN [8], GaAs and Ge [9].

There are few studies examining terahertz radiation from nanostructures with doped quantum wells (QWs). For example, terahertz radiation in longitudinal electric fields was observed in GaAs/AlGaAs quantum wells doped with donor [10] and acceptor [11] impurities.

Terahertz radiation from nanostructures with doped QWs under interband optical pumping was first described in Ref. [11]. This type of pumping entails the generation of electron–hole pairs that are subsequently trapped in the QW. At low crystal lattice temperatures, donor impurities in the QWs are neutral. Electrons from donor ground states can recombine with nonequilibrium holes, which is usually accompanied by the emission of near-infrared photons. The impurity ground states depopulated as a result of this process can be filled with nonequilibrium electrons from the first subband of size quantization. This can occur with an emission of photons of the terahertz range.

This study continues our previous studies on the subject [11] and is dedicated to examining radiation of the terahertz and near-IR ranges in nanostructures with donor-doped QWs of different widths.

Samples and experimental procedure

Optical studies were carried out for three samples. Two of them were grown by molecular-beam epitaxy on a semi-insulating gallium arsenide substrate and contained doped GaAs/AlGaAs QWs of different widths. The first sample contained 226 periods of GaAs QW 16.1 nm in width, separated by 4.8-nm-thick $Al_{0.15}Ga_{0.85}As$ barriers. The second sample contained 50 periods of GaAs QWs 30 nm in width, separated by 7-nm-thick $Al_{0.30}Ga_{0.70}As$ barriers. Structures with narrow and wide QWs had GaAs cap layers 60 and 20 nm thick, respectively. The QWs in both structures were doped with silicon (acting as a donor) with a surface concentration $n_s = 3\cdot 10^{10}\,\mathrm{cm}^{-2}$. A semi-insulating GaAs substrate, similar to those on which the nanostructures with doped QWs were grown, was used as the third reference sample.

During optical measurements, the samples were mounted into a Janis PTCM-4-7 closed-cycle optical cryostat that allowed maintaining the sample's temperature in the range from 4 to 320 K. The optical excitation of nonequilibrium charge carriers in the structures was carried out through a fused-quartz window by a continuous wave radiation of a solid-state diode-pumped laser (with the wavelength of $\lambda = 532$ nm and the average output power of $P = 8$ mW).

The photoluminescence (PL) spectra in the terahertz spectral range were studied using a Bruker Vertex 80v vacuum Fourier transform infrared spectrometer operating in a step-scan mode. The output window of the optical cryostat was made of polymethylpentene, the entrance window of the spectrometer was made from polyethylene. These materials have a high degree of transparency in the terahertz spectral range. The PL radiation of the sample was collected by an off-axis parabolic mirror of the Fourier spectrometer through a black polyethylene filter that prevented the penetration of scattered pumping radiation into the measurement section of the experimental setup. A liquid helium cooled silicon bolometer, which had a vacuum contact with the spectrometer, was used as a detector of terahertz radiation. The signal of the bolometer photoresponse was measured by an SR830 lock-in amplifier which was synchronized with the pump laser. Laser radiation was modulated by a chopper at a frequency of 87 Hz with a duty cycle of 50%.

We used two configurations of the optical system of the Fourier spectrometer to obtain the terahertz PL spectra.

The first one consisted of a combination of a 0.5-mm-thick polyethylene filter at the entrance of the silicon bolometer and a 6-µm-thick multilayer Mylar beam splitter. This optical configuration allowed to perform measurements in the photon energy range from 4 to 40 meV.

The second configuration included a filter of crystalline quartz on the bolometer and a 25-µm-thick Mylar beam splitter; this configuration allowed to increase the optical transmission of the Fourier spectrometer in the photon energy range from 2 to 14 meV.

The PL spectra in the near infrared spectral range were measured by a Horiba Jobin Yvon FHR 640 grating monochromator with a 1200 groves/mm holographic grating. The fused silica exit window of the closed-cycle cryostat, was used for measuring the PL spectra in the near-IR range. The PL radiation passed through a red optical filter, transparent in the wavelength range 0.68–2.50 µm and stopping the scattered pump radiation, and was focused by a lens onto the entrance slit of the grating monochromator. The