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Terahertz and infrared photoluminescence in a structure based on *n*-GaAs with a waveguide for the near-infrared range

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Abstract. The results of a study of near-infrared (IR) and terahertz photoluminescence in doped GaAs layers placed in a near-IR optical waveguide are presented. Terahertz radiation under optical interband pumping is associated with transitions of nonequilibrium electrons from the conduction band to impurity states. Stimulated interband near-IR emission involving impurity states was obtained. An accelerated increase in the integral intensity of terahertz radiation has been demonstrated at pump intensities exceeding the threshold for stimulated emission in the near-IR range. The increase in intensity is associated with the accelerated depopulation of the ground state of the impurity by stimulated emission.

Keywords: photoluminescence, terahertz radiation, impurity transition, epitaxial layer, bulk semiconductor, stimulated emission

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Терагерцовая и инфракрасная фотолюминесценция в структуре на основе *n*-GaAs с волноводом для ближнего ИК диапазона

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Аннотация. Приведены результаты исследования фотолюминесценции ближнего инфракрасного (ИК) и терагерцового диапазонов в легированных слоях GaAs, помещенных в оптический волновод ближнего ИК диапазона. Терагерцовое излучение при оптической межзонной накачке связывается с переходами неравновесных электронов из зоны проводимости на состояния примеси. Получено стимулированное излучение ближнего ИК диапазона с участием примесных состояний. Продемонстрирован ускоренный рост интегральной интенсивности терагерцового излучения при интенсивностях накачки, превышающих порог стимулированного излучения ближнего ИК диапазона. Рост интенсивности связан с ускоренным опустошением основного состояния примеси стимулированным излучением.

Ключевые слова: фотолюминесценция, терагерцовое излучение, примесный переход, эпитаксиальный слой, объемный полупроводник, стимулированное излучение

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Introduction

Despite significant advances in the development of quantum cascade lasers in the terahertz (THz) spectral range, consisting, for example, in the recent creation of such sources that do not require cooling with liquid gases [1], in recent years there has been continued interest in the development of effective low-cost solid-state sources of terahertz radiation. A good basis for creating such sources can be optical transitions of charge carriers involving impurity states in semiconductors and semiconductor nanostructures. Terahertz radiation upon optical interband excitation of nonequilibrium charge carriers has been observed in doped bulk semiconductors [2, 3] and structures with quantum wells [4]. The radiation arose due to optical transitions of nonequilibrium electrons from the conduction band or excited impurity states to the ground state of the donor impurity. The depopulation of the ground state of the impurity occurred due to the spontaneous recombination of electrons and nonequilibrium holes in the valence band. It was shown in [5], considering the radiation associated with intraband transitions of electrons between levels of quantum dots in diode laser structures, that stimulated laser radiation during interband transitions of electrons effectively depopulate the ground level of a quantum dot, which leads to an increase in the intensity of intraband (interlevel) optical transitions. This approach was implemented in [6] to increase the intensity of terahertz radiation during electron transitions from the conduction band to the ground state of the impurity. The radiation intensity increased due to the effective depopulation of the impurity state by stimulated interband radiation arising in the structure under study during optical interband pumping of structures with GaAs/AlGaAs quantum wells.

Near-IR laser lasing was realized in [7] through the ground donor state under interband optical pumping in a structure with a doped *n*-GaAs epitaxial layer and terahertz radiation associated with impurity transitions was detected. In this work, photoluminescence (PL) in the near-infrared and terahertz spectral ranges in doped GaAs epitaxial layers is studied in detail at various levels of optical pumping, including studies under conditions of generation of stimulated interband emission.

Materials and Methods

Donor-doped GaAs layers with a thickness of 0.52 μm were grown by molecular beam epitaxy. The donor concentration (Si) was $1.0 \cdot 10^{16}$ cm^{-3}. The epitaxial layer was enclosed in a waveguide, which was formed by layers of an $Al_xGa_{1-x}As$ solid solution with a composition gradient x. From the grown wafer, samples were formed by cleavage, representing a high Q-factor total internal reflection resonator with dimensions of 400×400 μm. The sample was soldered with indium to a copper holder of a Janis PTCM-4-7 closed-cycle optical cryostat;

studies were carried out at a temperature of 4.2 K. The surface of the sample was uniformly illuminated with radiation from a pulsed laser with a wavelength of 532 nm, a frequency of 8 kHz, and a pulse duration of 250 ns. The pump radiation was modulated by a mechanical chopper at 180 Hz to employ the synchronous detection technique. The photoluminescence signal in the near-IR range was recorded from the end of the sample using a Horiba Jobin Yvon FHR-640 grating monochromator. A silicon CCD matrix was used as a near-IR radiation detector. A photodetector made of gallium-doped germanium was used to record integral radiation in the terahertz spectral range arising under conditions of interband optical pumping due to transitions of nonequilibrium electrons involving impurity states. The Ge<Ga> crystal was located in close proximity to the sample on the same copper holder. Thus, the operating temperature of the detector was close to 4.2 K. The distance between the THz radiation detector and the sample was 12 mm. On all sides, except for the input face, the detector was shielded with metal foil to protect it from the background thermal terahertz radiation of the room. Filters made of black polyethylene and high-resistivity germanium were installed in front of the input face to prevent pump radiation from reaching the detector. Terahertz radiation was recorded from normal to the sample surface. The signal from the detector was fed to the SR-570 current preamplifier, and from there to the SR-830 lock-in amplifier, synchronized with the chopper frequency.

Results and Discussion

It was previously shown that, due to the presence of a waveguide and a total internal reflection resonator in the structure under study, stimulated emission in the near-IR range occurs at sufficiently high levels of optical interband excitation [7]. The near-IR photoluminescence spectra of the sample studied in the present work are shown in Fig. 1.

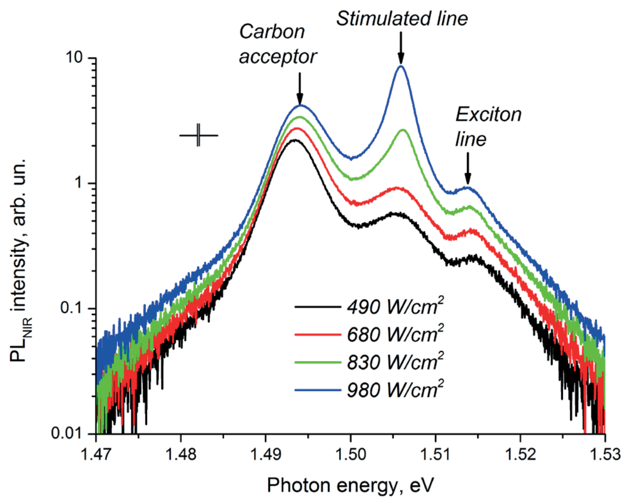

Fig. 1. Photoluminescence spectra in the near-IR range at different levels of optical pumping

From the obtained spectra, it is clear that stimulated emission occurs at photon energy of about 1.507 meV. This radiation in our sample is associated with the epitaxial layer and the silicon donor impurity [8]. The emission line designated "*Exciton line*" corresponds to the energy of a free exciton in GaAs [9]. The peak at an energy of 1.494 eV (designated "*Carbon acceptor*") corresponds to radiative electron transitions from the conduction band to acceptor states of an uncontrolled carbon acceptor impurity arising in the structure during growth.

Fig. 2 shows the dependence of the integrated intensity of photoluminescence in the near-IR spectral range on the level of optical interband pumping. The results obtained demonstrate the presence of a stimulated emission threshold. This dependence was obtained by integrating the photoluminescence spectra.

Previously, terahertz radiation associated with transitions of nonequilibrium electrons from the conduction band to the impurity level was discovered in similar samples, and its spectra

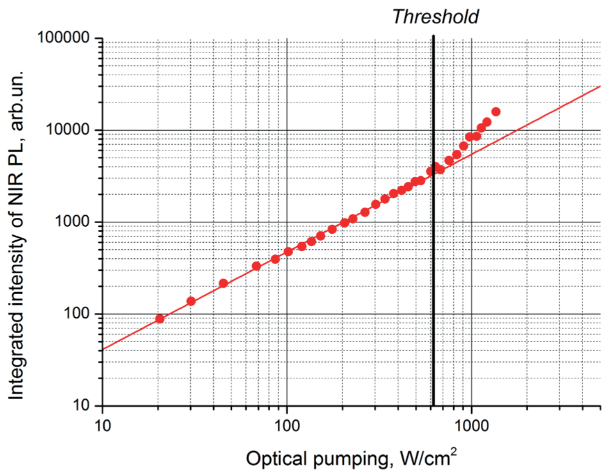

Fig. 2. Integral intensity of photoluminescence in the near-IR spectral range depending on the pump power

were obtained [8]. It was also demonstrated in [8] that the spectrum of terahertz radiation lies in the range of 6–30 meV. In order to clarify the influence of stimulated radiation, which should accelerate the depopulation of the ground impurity state, on the generation efficiency of terahertz radiation, in this work we studied the integral intensity of terahertz radiation using a Ge<Ga> detector, which has a spectral sensitivity that corresponds quite well to the radiation spectrum of the sample. The sensitivity spectrum of the photodetector, obtained using a Bruker Vertex v80 Fourier spectrometer, is shown in Fig. 3.

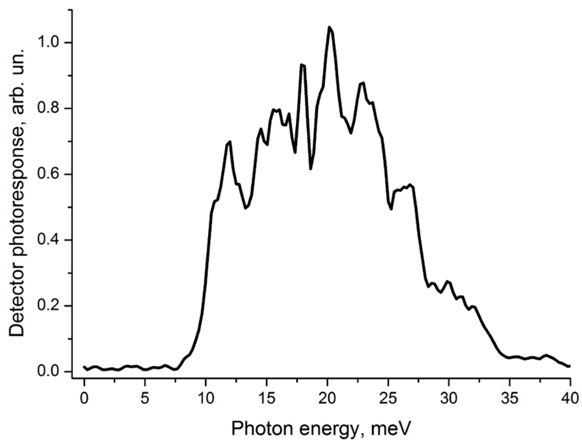

Fig. 3. Sensitivity spectrum of a gallium-doped germanium crystal, which was used as a THz radiation detector

Thus, the dependence of the integral intensity of terahertz photoluminescence on the intensity of optical pumping was obtained, shown in Fig. 4. The graph shows a significant increase in the growth rate of terahertz photoluminescence at optical pumping intensities exceeding 600 W/cm^2. This value corresponds to the pump level at which stimulated emission of the near-IR range occurs on electron transitions from the main impurity level to the valence band. The results obtained allow us to conclude that stimulated radiation in the near-IR range has a significant effect on the characteristics of terahertz radiation. The use of stimulated interband radiation for accelerated depopulation of the ground impurity state leads to an increase in the efficiency of the terahertz radiation source.

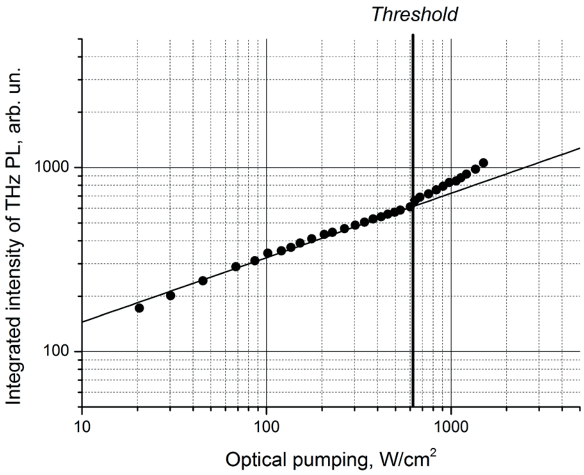

Fig. 4. Integral intensity of terahertz photoluminescence depending on the optical pump power

Conclusion

A semiconductor structure containing a doped GaAs epitaxial layer placed in an optical waveguide supporting near-IR radiation has been studied. Under conditions of optical interband pumping, stimulated emission was obtained related to electron transitions from the ground state of the impurity to the valence band. The structure under study is also a source of terahertz radiation, which occurs when nonequilibrium electrons are captured from the conduction band to impurity levels. At pump intensities exceeding the threshold of stimulated interband emission, the rate of growth of the integral intensity of terahertz radiation increases significantly with increasing optical excitation level. The observed effect is associated with accelerated depopulation of the main impurity level by stimulated interband emission and allows the development of a terahertz radiation source with increased efficiency.

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