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Terahertz and stimulated near-infrared photoluminescence in bulk *n*-GaAs layers

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Abstract. The work considers the methods for increasing the intensity of low temperature terahertz luminescence in semiconductor structures with bulk epitaxial *n*-GaAs layers doped with silicon donors under interband optical pumping. Such an increase can be realized due to the accelerated depopulation of the ground impurity level by stimulated near-infrared radiation, which is created in the same structure. Stimulated interband emission was induced by a total internal reflection optical resonator. Samples were investigated by measuring the near-infrared photoluminescence and terahertz photoluminescence at liquid helium temperature. Impurity-assisted near-infrared spontaneous and stimulated photoluminescence and their dependences on optical pumping power was demonstrated. Impurity-assisted generation of terahertz radiation was observed in further intention to investigate the influence of near-infrared stimulated emission on it. Obtained results can be used in the development of new semiconductor terahertz emitters.

Keywords: photoluminescence, terahertz emission, gallium arsenide, impurities, stimulated radiation

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Терагерцовая и стимулированная ближняя инфракрасная фотолюминесценция в объёмных слоях *n*-GaAs

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Аннотация. Работа посвящена исследованию возможности увеличения интенсивности низкотемпературной терагерцовой люминесценции в полупроводниковых структурах с объёмными эпитаксиальными слоями *n*-GaAs, легированными донорной примесью кремния, при межзонной оптической накачке. Такое увеличение может быть реализовано за счет ускоренного опустошения основного примесного уровня стимулированным излучением ближнего инфракрасного диапазона, которое создается в той же самой структуре. Для организации вынужденного межзонного излучения были изготовлены образцы в геометрии оптического резонатора полного внутреннего отражения. Исследовалась фотолюминесценция в ближнем инфракрасном и терагерцовом диапазонах при температуре жидкого гелия. Продемонстрирована спонтанная и стимулированная фотолюминесценция с участием примесных состояний в ближнем инфракрасном диапазоне, измерена эволюция спектров от мощности оптической накачки. Наличие в структуре излучения терагерцового диапазона с участием донорных состояний позволит в дальнейшем исследовать влияние на него стимулированного излучения ближнего инфракрасного диапазона. Полученные результаты могут быть использованы при разработке новых полупроводниковых источников терагерцового излучения.

Ключевые слова: фотолюминесценция, терагерцовая эмиссия, арсенид галлия, примеси, стимулированное излучение

Финансирование: Исследование влияния стимулированного излучения ближнего инфракрасного диапазона на терагерцовую люминесценцию в полупроводниковых микро- и наноструктурах, грант Российского научного фонда № 22-22-00105.

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Introduction

Creating compact and efficient sources of radiation in the terahertz (THz) range is one of the urgent tasks of modern optoelectronics. Terahertz radiation finds application in systems of chemical, medical diagnostics, and security systems [1–2]. Now, the only high-power semiconductor sources of THz radiation are quantum-cascade lasers [3]. However, the complexity of the production technology greatly limits the usage of such lasers and creates the necessity to search for alternative semiconductor sources of THz radiation. One of the approaches to the development of such sources is the use of optical transitions of nonequilibrium charge carriers with the participation of shallow impurity states in semiconductors.

For the first time, impurity-assisted THz radiation upon optical pumping was observed in bulk silicon layers doped with phosphorus [4]. Intraband pumping was performed using CO_2 laser, whose radiation excites charge carriers from the ground and lower impurity states to the higher excited or band states. Terahertz photoluminescence was also observed in bulk semiconductors doped with donors (*n*-GaAs) upon interband optical pumping [5].

The intensity of impurity-assisted THz emission depends on the population of the ground state. For the first time, depopulation of the ground state with stimulated near-infrared (NIR) radiation was used in diode structures with quantum dots to obtain mid-IR radiation [6]. Further studies of the effect of stimulated depopulation of the ground donor state on the intensity of terahertz radiation were carried out in structures with quantum wells (QWs) based on GaAs/AlGaAs under optical interband excitation [7–8].

The current work is devoted to further investigation of possibilities to increase the intensity of THz photoluminescence in doped semiconductor structures. The use of bulk *n*-GaAs epitaxial layers will make it possible to increase the radiation intensity due to the larger volume of the active region compared to QW structures.

Materials and Methods

The structure was grown by molecular beam epitaxy on a semi-insulating GaAs substrate. The active region contained a 0.52 μm thick GaAs layer doped with silicon to a concentration of 10^{16} cm^{-3} and embedded into the waveguide. Symmetric waveguide for the NIR radiation was formed by $Al_xGa_{1-x}As$ graded layers. Terahertz radiation was observed on samples 5×5 mm^2 in size. To obtain the stimulated NIR radiation, total internal reflection optical resonator was formed with dimensions of 0.6×0.6 mm^2. To study photoluminescence in the substrate, the epitaxial layers were removed from one of the samples.

For measurements, samples were mounted in a Janis PTCM-4-7 closed-cycle optical cryostat and cooled down to about 4.2 K. The optical pumping was performed by Nd:YAG pulsed laser ($\lambda = 532$ nm, pulse duration 250 ns, repetition rate 8 kHz). The pumping power was varied using an attenuator consisted of a half wave plate and a Glan-Taylor prism and measured by Thorlabs PM100D optical power and energy meter. The pumping laser radiation was directed and focused on the sample surface using a series of mirrors and converging lens. The diameter of the laser spot on the surface of the structure was about 0.9 mm, covering the whole area of a sample with a resonator.

The NIR interband photoluminescence spectra were measured by Horiba Jobin Yvon FHR 640 monochromator with 1200 groves/mm holographic grating and CCD detector. The THz photoluminescence spectra were measured by Bruker Vertex 80v vacuum Fourier transform spectrometer with Mylar beamsplitter operated in step-scan mode. The pumping laser radiation was modulated with optical chopper at 87 Hz. The luminescence collected from the sample passed through TPX windows and black polyethylene filter. The intensity of THz radiation was detected by liquid helium-cooled silicon bolometer. The detector photoresponse signal was measured by the SR830 lock-in amplifier synchronized in phase and frequency with the chopper.

Results and Discussion

Near-infrared photoluminescence spectra of structure and substrate at 4.2 K are presented in Fig. 1. At a low pumping power, the spectra of a sample without a resonator and a sample with a resonator are similar and are presented by black curve in Fig. 1. The energy of GaAs band gap is marked by E_g arrow at 1.519 eV. The binding energy of shallow donors in GaAs is 5.9 ± 0.1 meV [9], which corresponds to the distance between the *D-h* arrow (optical transition from the ground donor state to the valence band), and E_g value. The X arrow marks donor-bound exciton recombination energy. Residual acceptors may be contained in the substrate or introduced during epitaxial growth. Typical GaAs residual impurity is carbon (the binding energy is about 26 meV [10]). Acceptor assisted transition is marked by *e-A* arrow at 1.492 eV. The photoluminescence spectra of sample with a resonator at high pumping power demonstrated the same features, but also shown up the peak of stimulated emission (see red curve in Fig. 1). The blue curve in Fig. 1 shows the spectrum of the substrate. Impurity-assisted *e-A* peak and low-intensity exciton recombination peak are observed in the substrate spectrum.

The evolution of the NIR photoluminescence spectra of the sample with a resonator upon increasing pumping power is presented in Fig.2. Relatively narrow and intense emission line on the longwave side of the *D-h* donor peak marked by an arrow *Stimulated* in Fig. 1 and 2 is the line of stimulated emission. This stimulated luminescence line is presented in the spectrum at a pumping intensity above 320 W/cm^2, which is the near-infrared lasing *Threshold* (marked with an arrow in the inset to Fig.2). The inset in Fig. 2 shows the dependences of the integrated THz luminescence intensity on the pumping power. The intensity of the stimulated peak makes a

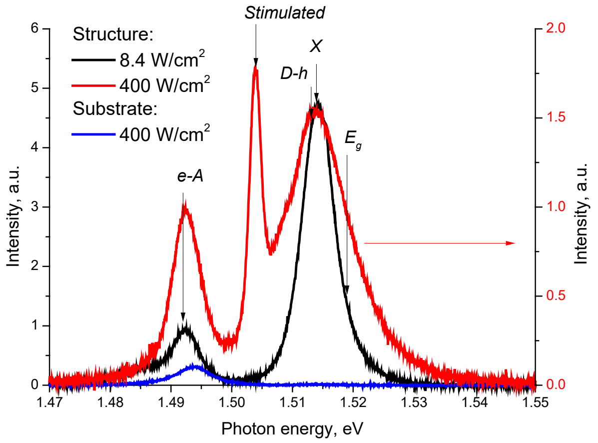

Fig. 1. Near-infrared photoluminescence spectra of the structure and substrate measured at the T = 4.2 K for different pumping levels. The spectral resolution is about 0.12 meV for structure spectra and 0.8 meV for substrate spectrum

significant contribution to the total intensity of the interband radiation of the sample (marked as *Sum*) at high pump power. At the level of threshold total intensity has an inflection point. The intensity of the spontaneous luminescence peak (marked as *D-h spontaneous*) saturates that is typical for semiconductor lasers.

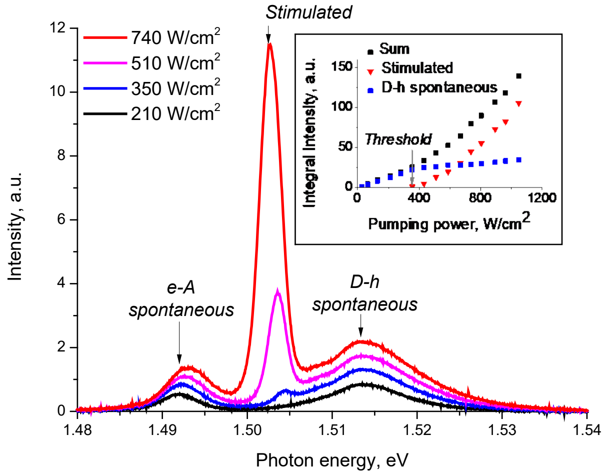

Fig. 2. Near-infrared photoluminescence spectra of the structure with a resonator measured at T = 4.2 K for different pumping levels. Spectral resolution is about 0.12 meV. The inset shows dependence of integrated near-infrared photoluminescence intensity on the optical pumping power

Fig. 3 shows the THz photoluminescence spectra at 4.2 K. The red curve shows the THz photoluminescence spectrum of sample without resonator. Binding energy of shallow silicon donors in GaAs is marked by *e-D* arrow at 5.9 meV [9]. The spectrum has a peak at a slightly higher photon energy (about 7.75 meV). This corresponds to the fact that the transition at exactly the photon energy equal to the binding energy is forbidden and to electron heating effects. The emission peak at 11 meV cannot correspond to electron transitions involving a silicon impurity. The same peak was observed in the measurements of THz photoluminescence in Ref. [5] where it was associated with residual extrinsic defects in GaAs. The emission band at energies of 15–28 meV replicates the photoluminescence spectrum of the substrate (see black curve in Fig. 3). Thus, residual acceptor-assisted radiative transitions both from the substrate and from the epitaxial layers may contribute to the THz luminescence. The THz emission band marked as *Substrate* is typical for such experiments and can either be observed [11] or not be observed [8] in similar samples, depending on the quality of the substrate and the grown structures. Based on this, we can conclude that the THz emission band in the range of 5–12 meV is associated precisely with the epitaxial layers, and not with the substrate.

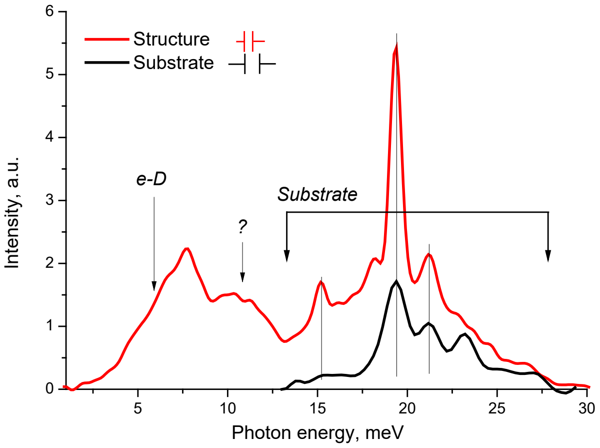

Fig. 3. Terahertz photoluminescence spectra of a structure without a resonator and of a substrate measured at T = 4.2 K

Conclusion

Impurity-assisted photoluminescence in the near-infrared and terahertz spectral ranges was demonstrated for the structure with bulk semiconductor *n*-GaAs epitaxial layers embedded in a waveguide. A narrow and intensive line of stimulated emission in the near-infrared range was observed for the samples with four cleaved facets resonator. The appearance of stimulated near-infrared radiation and spontaneous terahertz radiation makes it possible to study the effect of depopulation of the donor ground state on the characteristics of terahertz radiation in bulk *n*-GaAs layers.

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REFERENCES

1. **Gong, A., Qiu, Y., Chen, X., Zhao, Z., Xia, L., Shao, Y.,** Biomedical applications of terahertz technology. Applied Spectroscopy Reviews. 55(5) (2020) 418–438.
2. **Bogue R.,** Sensing with terahertz radiation: a review of recent progress. Sensor. 38 (2) (2018) 216.
3. **Belkin M.A., Capasso F.,** New frontiers in quantum cascade lasers: high performance room temperature terahertz sources. Physica Scripta. 90 (11) (2015) 118002.
4. **Pavlov S.G., Zhukavin R.Kh., Orlova E.E., Shastin V.N., Kirsanov A.V., Hübers H.W., Auen K., Riemann H.,** Stimulated Emission from Donor Transitions in Silicon. Physical Review Letters. 84 (2000) 5220.
5. **Zakhar'in A.O., Andrianov A.V., Egorov A.Yu., Zinov'ev N.N.,** Terahertz photoluminescence from GaAs doped with shallow donors at interband excitation. Applied physics letters. 96 (21) (2010) 211118.
6. **Vorob'ev L.E., Firsov D.A., Shalygin V.A., Tulupenko V.N., Shernyakov Yu.M., Ledentsov N.N., Ustinov V.M., Alferov Zh.I.,** Spontaneous far-IR emission accompanying transitions of charge carriers between levels of quantum dots. JETP Letters. 67(4) (1998) 275.
7. **Makhov I.S., Panevin V.Yu., Sofronov A.N., Firsov D.A., Vorobjev L.E., Vinnichenko M.Ya., Vasil'ev A.P., Maleev N.A.,** The effect of stimulated interband emission on the impurity-assisted far-infrared photoluminescence in GaAs/AlGaAs quantum wells. Superlattices and Microstructures. 112 (2017) 79–85.
8. **Makhov I.S., Panevin V.Yu., Firsov D.A., Vorobjev L.E., Vasil'ev A.P., Maleev N.A.,** Terahertz photoluminescence of the donor doped GaAs/AlGaAs quantum wells controlled by the near-infrared stimulated emission. Journal of Luminescence. 210 (2019) 352–357.
9. **Almassy R.J., Reynolds D.C., Litton C.W., Bajaj K.K., McCoy G.L.,** Observation of shallow residual donors in high purity epitaxial GaAs by means of photoluminescence spectroscopy. Solid State Communications. 38 (1981) 1053.
10. **Kisker D.W., Tews H., Rehm W.,** Luminescence study of C, Zn, Si, and Ge acceptors in GaAs. Journal of Applied Physics. 54 (1983) 1332.
11. **Vorobjev L.E., Firsov D.A., Panevin V.Yu., Sofronov A.N., Balagula R.M., Makhov I.S.,** Near- and far-infrared emission from GaAs/AlGaAs quantum wells under interband optical excitation. St. Petersburg State Polytechnical University Journal. Physics and Mathematics. 4(182-2) (2013) 109–114.

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