Conference paper
UDC 535.3, 535.4
DOI: https://doi.org/10.18721/JPM.171.111

# Luminescence in nanostructures with compensated quantum wells under optical and electrical pumping

R.B. Adamov [1], G.A. Melentev [1], A.A. Podoskin [2], S.O. Slipchenko [2], I.V. Sedova [2], S.V. Sorokin [2], I.S. Makhov [3], D.A. Firsov [1], V.A. Shalygin [1]✉

[1] Peter the Great St. Petersburg Polytechnic University, St. Petersburg, Russia;
[2] Ioffe Institute, St. Petersburg, Russia;
[3] National Research University "Higher School of Economics", St. Petersburg, Russia
✉ shalygin@rphf.spbstu.ru

**Abstract.** Comprehensive studies of the luminescence of *p*–*i*–*n* structures with 10 compensated GaAs/AlGaAs quantum wells have been performed. The studies were carried out in the terahertz (THz) and near-infrared (NIR) spectral ranges with both optical and electrical pumping of nonequilibrium charge carriers. The THz photoluminescence spectra revealed an emission line caused by electron transitions from the first size-quantization subband *e*1 to the ground levels of donors *D*1*s*. The photo- and electroluminescence spectra in the NIR range revealed an emission line caused by electron transitions from the *D*1*s* levels to the first subband of heavy holes *hh*1. These transitions provide effective depletion of the *D*1*s* levels and are therefore relevant for creating a THz emitter operating at *e*1–*D*1*s* transitions. At high injection currents in the *p*–*i*–*n* diode, lasing occurs at the *D*1*s*–*hh*1 transitions, which increases the efficiency of depletion of the *D*1*s* levels. It is shown that for a given optical pump power or injection current density, the overall rate of the *D*1*s*–*hh*1 transitions in the *p*–*i*–*n* structure with 10 QWs is significantly higher than in similar structure with 50 QWs.

**Keywords:** quantum wells, *p*–*i*–*n*-structures, gallium arsenide, aluminum arsenide, impurities, photoluminescence, electroluminescence

**Funding:** The work of the authors R.B.A., G.A.M. and V.A.S. was supported by the Russian Science Foundation (Grant No. 22-22-00103, https://rscf.ru/project/22-22-00103/).

**Citation:** Adamov R.B., Melentev G.A., Podoskin A.A., Slipchenko S.O., Sedova I.V., Sorokin S.V., Makhov I.S., Firsov D.A., Shalygin V.A., Luminescence in nanostructures with compensated quantum wells under optical and electrical pumping, St. Petersburg State Polytechnical University Journal. Physics and Mathematics. 17 (1.1) (2024) 68–76. DOI: https://doi.org/10.18721/JPM.171.111



Материалы конференции
УДК 535.3, 535.4
DOI: https://doi.org/10.18721/JPM.171.111

# Люминесценция наноструктур с компенсированными квантовыми ямами при оптической и электрической накачке

Р.Б. Адамов [1], Г.А. Мелентьев [1], А.А. Подоскин [2], С.О. Слипченко [2], И.В. Седова [2], С.В. Сорокин [2], И.С. Махов [3], Д.А. Фирсов [1], В.А. Шалыгин [1]✉

[1] Санкт-Петербургский политехнический университет Петра Великого, Санкт-Петербург, Россия;
[2] Физико-технический институт им. А.Ф. Иоффе РАН, Санкт-Петербург, Россия;

[3] Национальный исследовательский университет «Высшая школа экономики», Санкт-Петербург, Россия
✉ shalygin@rphf.spbstu.ru

**Аннотация.** Проведены комплексные исследования люминесценции *p*—*i*—*n* структур с 10 компенсированными квантовыми ямами GaAs/AlGaAs. Исследования выполнены в терагерцовом (ТГц) и ближнем инфракрасном (БИК) спектральных диапазонах как при оптической, так и при электрической накачке неравновесных носителей заряда. На спектрах ТГц фотолюминесценции выявлена линия излучения, обусловленная переходами электронов из первой подзоны размерного квантования *e*1 на основные уровни доноров *D*1*s*. На спектрах фото- и электролюминесценции в БИК диапазоне выявлена линия излучения, обусловленная переходами электронов с уровней *D*1*s* в первую подзону размерного квантования тяжелых дырок *hh*1. Эти переходы обеспечивают эффективное опустошение уровней *D*1*s* и потому актуальны для создания ТГц эмиттера, работающего на переходах *e*1—*D*1*s*. При больших токах инжекции в *p*—*i*—*n* диоде возникает лазерная генерация на переходах *D*1*s*—*hh*1, что повышает эффективность опустошения уровней *D*1*s*. Показано, что при заданной мощности оптической накачки или плотности инжекционного тока общая скорость переходов *D*1*s*—*hh*1 в *p*—*i*—*n*-структуре с 10 КЯ значительно выше, чем в аналогичной структуре с 50 КЯ.

**Ключевые слова:** квантовые ямы, *p*—*i*—*n*-структуры, арсенид галлия, арсенид алюминия, примеси, фотолюминесценция, электролюминесценция

**Финансирование:** Работа авторов Р.Б.А., Г.А.М. и В.А.Ш. выполнена при финансовой поддержке Российского научного фонда (грант № 22-22-00103, https://rscf.ru/project/22-22-00103/).

**Ссылка при цитировании:** Адамов Р.Б., Мелентьев Г.А., Подоскин А.А., Слипченко С.О., Седова И.В., Сорокин С.В., Махов И.С., Фирсов Д.А., Шалыгин В.А. Люминесценция наноструктур с компенсированными квантовыми ямами при оптической и электрической накачке // Научно-технические ведомости СПбГПУ. Физико-математические науки. 2024. Т. 17. № 1.1. С. 68—76. DOI: https://doi.org/10.18721/ JPM.171.111



## Introduction

In recent decades, electrically pumped terahertz radiation sources are actively developed. One of the promising research directions in this field is related to impurity-assisted transitions of nonequilibrium charge carriers in semiconductors and semiconductor nanostructures. Terahertz radiation emission under current injection in *p*—*n* junctions fabricated from bulk silicon carbide and silicon has been experimentally observed in [1, 2]. Terahertz electroluminescence has been also studied in Be-doped GaAs/AlAs quantum wells sandwiched between two $p^+$-GaAs:Be layers [3].

Using *compensated* GaAs/AlGaAs quantum wells to create terahertz emitters with electrical pumping seems to be promising. It has already been shown experimentally that such nanostructures allow to obtain the emission of terahertz radiation under *optical pumping* [4, 5]. The experiments were performed on compensated quantum wells with different doping profiles. In some nanostructures, compensation was carried out directly in each quantum well by introducing donors and acceptors with the same concentration. In others, donors and compensating acceptors were spatially separated, namely, donors were located in quantum wells, while acceptors were embedded in barriers forming the quantum wells. Under interband optical pumping conditions, all studied structures exhibited terahertz radiation emission. The origin of the observed terahertz emission has been attributed to transitions of nonequilibrium electrons from the first size-quantization subband (*e*1) to the ground donor levels (*D*1*s*), as well as to intracenter electron transitions ($D2p_{xy}$—*D*1*s*). It has been found that the spatial separation of donors and acceptors provides an approximately twofold increase in the integral intensity of THz emission. This is directly related to the fact that the spatial separation of donors and acceptors in structures with compensated quantum wells increases the rate of radiative electronic transitions *D*1*s*—*hh*1 by a factor of 2.4—3.3 compared to the structure without the spatial separation, which has been confirmed by photoluminescence studies in the near-infrared (NIR) spectral range [5]. Indeed, the electron transitions *D*1*s*—*hh*1 provide dynamic depletion of *D*1*s* levels, which are the final states for terahertz radiative transitions *e*1—*D*1*s*; therefore, an increase in the rate of *D*1*s*—*hh*1 transitions is accompanied by an increase in the intensity of terahertz emission at *e*1—*D*1*s* transitions.

Luminescence in the NIR spectral range was studied in [6] in *p*—*i*—*n* structures with 50 compensated GaAs/AlGaAs quantum wells under conditions of *electrical pumping* of nonequilibrium charge carriers. At sufficiently high injection currents, stimulated emission at the *D*1*s*—*hh*1 transitions was observed in the electroluminescence spectra, associated with the generation of closed modes in the cavity formed due to total internal reflection by four cleaved edges of the *p*—*i*—*n* diode. It has been found that the structure with compensated quantum wells without spatial separation of donors and acceptors provides a fivefold increase in the integral intensity of stimulated NIR emission at the *D*1*s*—*hh*1 transitions compared to the structure with spatial separation of donors and acceptors (when donors are located in quantum wells, while acceptors are embedded in barriers). In this regard, to develop electrically-pumped terahertz emitters operating at the *e*1—*D*1*s* transitions under conditions of lasing at *D*1*s*—*hh*1 transitions, it is more expedient to use structures with the compensated GaAs/AlGaAs quantum wells without spatial separation of donors and acceptors.

Obviously, for a given injection current, it is possible to increase the concentrations of nonequilibrium electrons and holes in each quantum well if the total number of quantum wells in the structure is reduced. In this case, the choice of the optimal number of quantum wells must take into account the losses of electrons and holes injected from the emitters due to their recombination in the waveguide layers.

The present work is dedicated to the experimental study of these issues. The *p*—*i*—*n* structures with compensated GaAs/AlGaAs quantum wells have been grown without spatial separation of donors and acceptors, since, as noted above, such a doping profile provides high integral intensity of stimulated NIR emission at the *D*1*s*—*hh*1 transitions. To significantly increase the level of excitation of nonequilibrium electrons in each quantum well compared to [6], the number of quantum wells in the structure was reduced to 10 (i.e., it lowered by 5 times). We study NIR luminescence in these structures at a temperature of 10 K. The studies are carried out under both optical and electrical pumping. The main channels of radiative recombination are determined under various experimental conditions. In addition, the current-voltage characteristics (CVC) of *p*—*i*—*n* diodes made from these structures are studied. Terahertz luminescence in the *p*—*i*—*n* structures is investigated at optical pumping. The possibility of observing the emission of terahertz radiation from forward-biased *p*—*i*—*n* diodes under conditions of generation of stimulated emission in the NIR range is discussed.

## Experimental Technique

The *p*—*i*—*n* heterostructure with selectively doped GaAs/AlGaAs multiple quantum wells (MQWs) was grown by molecular beam epitaxy on epi-ready Si-doped $n^+$-GaAs (001) substrate at ~580 °C. The heterostructure contains the following layers (in the direction from the substrate to the surface): *n*-GaAs buffer layer with a thickness of ~ 0.5 μm ($n \sim 10^{18}$ cm$^{-3}$), bottom 1-μm thick *n*-$Al_{0.9}Ga_{0.1}As$ cladding layer ($n \sim 2\cdot10^{18}$ cm$^{-3}$), undoped 0.3-μm thick $Al_{0.3}Ga_{0.7}As$ waveguide layer, MQW region consisted of ten 6.9 nm thick GaAs QWs separated by 7.6 nm $Al_{0.3}Ga_{0.7}As$ barriers, undoped 0.3-μm thick $Al_{0.3}Ga_{0.7}As$ waveguide layer, top 1-μm thick *p*-$Al_{0.9}Ga_{0.1}As$ cladding layer ($p \sim 5\cdot10^{17}$ cm$^{-3}$), and 0.4-μm thick $p^{++}$-GaAs contact layer ($p \sim 10^{19}$ cm$^{-3}$). The MQW region was selectively doped, namely, the central part (about 2.6 nm) of each GaAs quantum well was doped simultaneously with Si and Be at a nearly equal concentration of ~ $1.2\cdot10^{17}$ cm$^{-3}$ (the surface density of both donors and acceptors is ~ $3\cdot10^{10}$ cm$^{-2}$), while the $Al_{0.3}Ga_{0.7}As$ barriers remained undoped.

Samples for luminescence studies were prepared by cleaving the heterostructure into square and rectangular pieces. Photoluminescence (PL) studies were carried out with the samples of 3×3 mm size. For electroluminescence (EL) studies, two-terminal sample devices with lateral sizes of 0.5×2 mm were fabricated. Au-Ge/Au contact was evaporated on the *n*-GaAs substrate and Ti/Pt/Au contact was made on the $p^{++}$-GaAs layer. Each device represents a *p*—*i*—*n* diode since MQWs have intrinsic conductivity due to compensation of donors by acceptors. The diodes were soldered *p*-side down to copper heatsinks.

The samples were mounted on cold finger of a closed cycle cryostat. The experiments were carried out at a temperature of 10 K. Optical pumping of the sample was provided by means of a continuous-wave solid-state laser at a wavelength of 532 nm. The laser beam was focused into a spot of 510 μm in diameter at the center of the sample. Photoexcitation power varied in the range of 0.1–100 mW.

Near-infrared photoluminescence studies were conducted by means of a grating monochromator Horiba Jobin Yvon FHR-640 with silicon CCD camera. Optical path between the sample and the monochromator contained a window and a lens fabricated from silica glass.

Experiments on terahertz photoluminescence were performed using a Fourier spectrometer Bruker Vertex 80v operating in step-scan mode. Terahertz radiation emitted from the sample was detected using a liquid helium-cooled silicon bolometer and a lock-in amplifier. Photoresponse was measured at the frequency of a chopper modulating the pumping laser beam (87 Hz). For more details see [5].

Electroluminescence studies were also conducted using the grating spectrometer (in NIR spectral range) and the Fourier spectrometer (in THz spectral range). The measurements were carried out under forward bias of the *p–i–n* diodes. At weak injection currents ($J$ < 10 mA), measurements were carried out in DC mode by using a Keithley 2601A System SourceMeter. Measurements at higher currents were carried out in pulsed mode (pulse duration of 1 μs, repetition frequency of 87 Hz) using self-made pulse generator. In parallel with the study of NIR electroluminescence, the current-voltage characteristics of the diodes were obtained. Oscillograms of current and voltage pulses were recorded using a Tektronix TDS2024B oscilloscope.

## Results and Discussion

Near-infrared photoluminescence spectra of the *p–i–n* structure with ten compensated QWs are presented in Fig. 1. The identification of the main spectral lines can be carried out using the results of our previous papers [5–7]. At a low pumping powers ($P$ = 0.1–1 mW), there are two PL lines in the spectra. The wide asymmetric line with the maximum at a photon energy of $\hbar\omega = E_M(p^{++}) \cong 1480$ meV is associated with the $p^{++}$-GaAs contact layer and can be attributed to radiative electron transitions from the conduction band to merged acceptor/valence band [6]. Other asymmetric line with maximum at 1536 meV (for $P$ = 0.1 mW), which undergoes a blue shift under increasing pumping power, can be attributed to the impurity-assisted electron transitions in the quantum wells. These are the radiative transitions from *e*1 subband to the ground acceptor state *A*1*s* which play negative role from the point of view of the THz radiation emission at *e*1–*D*1*s* transitions [5, 6]. But at pump power of 10 mW and higher, a hump due to the *D*1*s*–*hh*1 transitions emerges on the high-frequency side of the *e*1–*A*1*s* line. Let us emphasize once again that the *D*1*s*–*hh*1 transitions play a positive role from the point of view of the THz emission mechanism we are considering. At powers exceeding 30 mW, the line *D*1*s*–*hh*1 dominates over

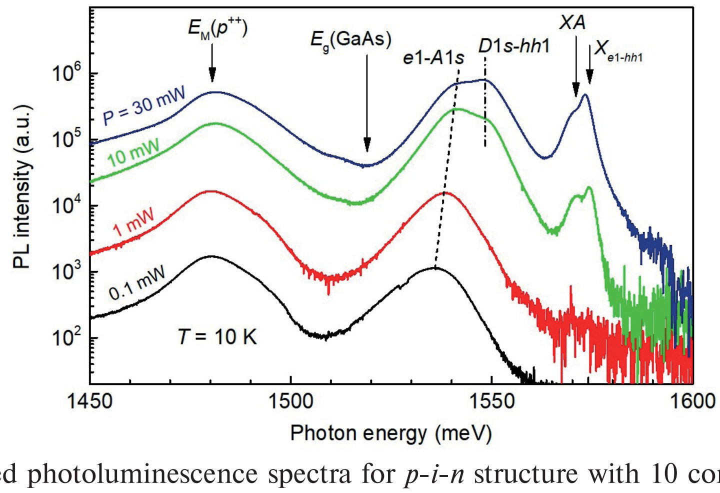


Fig. 1. Near-infrared photoluminescence spectra for *p-i-n* structure with 10 compensated QWs. Here $E_g$(GaAs) denotes the forbidden gap of GaAs. Dashed and dash-dotted lines point out the maximum positions of the impurity-assisted recombination lines for various pump powers

the line *e*1–*A*1*s*. It should be emphasized that the *p*–*i*–*n* structure with 10 quantum wells provides an advantage in the efficiency of optical excitation of the *D*1*s*–*hh*1 PL line in comparison with the 50-QW structure studied in [6]. Namely, the structure with 10 QWs, when it is pumped at power of 10 mW, provides the same magnitude of the *D*1*s*–*hh*1 line (per quantum well) that the structure with 50 QWs gives at pumping power of ~ 100 mW. As a result, at a given pumping power, the total rate of *D*1*s*–*hh*1 transitions in the structure with 10 QWs is twice as high as in the structure with 50 QWs.

Besides, one can also reveal two sharp PL peaks related to the radiative recombination of the acceptor-bound exciton *XA* (at $\hbar\omega$ = 1571 meV) and of free excitons formed from electrons of the *e*1 subband and holes of the *hh*1 subband, $X_{e1\text{-}hh1}$, at 1574.3 meV (see Fig. 1).

Before we move on to the analysis of the electroluminescence spectra, it is reasonable to discuss the current-voltage characteristics of the studied diodes. We measured CVC for the *p*–*i*–*n* diode with 10 compensated QWs at a temperature of 10 K and compared it with the experimental data for a similar diode of the same lateral sizes with 50 compensated QWs from [6], see Fig. 2. As can be seen from the figure, a fivefold reduction in the number of QWs drastically changes the behavior of CVC at forward bias. First, the region of negative differential conductivity disappears (in 50-QW diode the negative differential conductivity is observed in the voltage range of 5.0–8.5 V). Second, to provide the same electric current in the 10-QW diode it is necessary to apply significantly larger voltage compared to the 50-QW diode. The first factor can be considered as positive, but the second one is certainly negative. Experiments have shown that at forward voltage on the diode exceeding 15 V, when the electric field strength in the *i*-layer of the diode exceeds $1.5 \cdot 10^5$ V/cm, an electrical breakdown occurs in this layer, and the diode is destroyed. For this reason, 10-QW diodes cannot pass a current of more than *J* = 1.3 A (with a pulse duration of 1 μs or less), while 50-QW diodes could withstand pulse currents of up to *J* = 6 A. The above increase in the effective resistance of the *i*-layer is due to a 3-fold increase in the total thickness of the $Al_{0.3}Ga_{0.7}As$ waveguide layers (from 200 to 600 nm), which is required to provide a sufficient total width of the NIR waveguide layer (~ 730 nm).

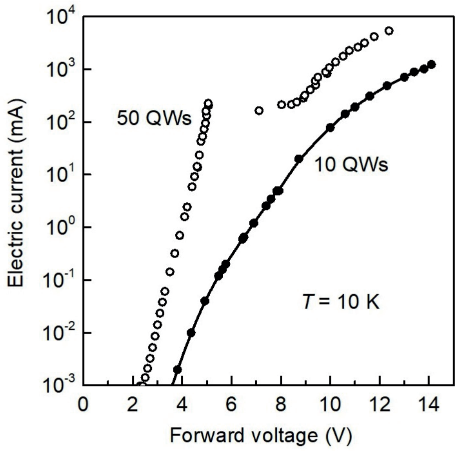


Fig. 2. Comparison of the current-voltage characteristics for *p-i-n* diodes of the same lateral sizes with 10 and 50 compensated QWs (solid and empty circles, respectively). Line is a guide for the eye

Near-infrared electroluminescence spectra of the *p*–*i*–*n* diode with ten compensated QWs at various injection currents are presented in Fig. 3. Note, that the EL line due to radiative recombination of the acceptor-bound exciton (*XA*) is significantly broaden. The broadening is caused by a rather high electric field in the *i*-layer of the diode even at the lowest injection current used in the EL experiment. Using the *i*-layer thickness of 730 nm and the CVC data from Fig. 2, one can estimate the electric field strength of about $5 \cdot 10^4$ V/cm. At injection current of 5 mA and less the position of the *XA* peak is almost unchanged (~ 1572 meV). As the current increases from 5 mA to 1230 mA, the exciton peak experiences a red shift of about 4 meV, which is caused by an increase in the voltage drop across the MQW layers. Microscopic mechanism of a red shift of the excitonic peak in electric field was considered in [8] and was called as the quantum-confined Stark effect.

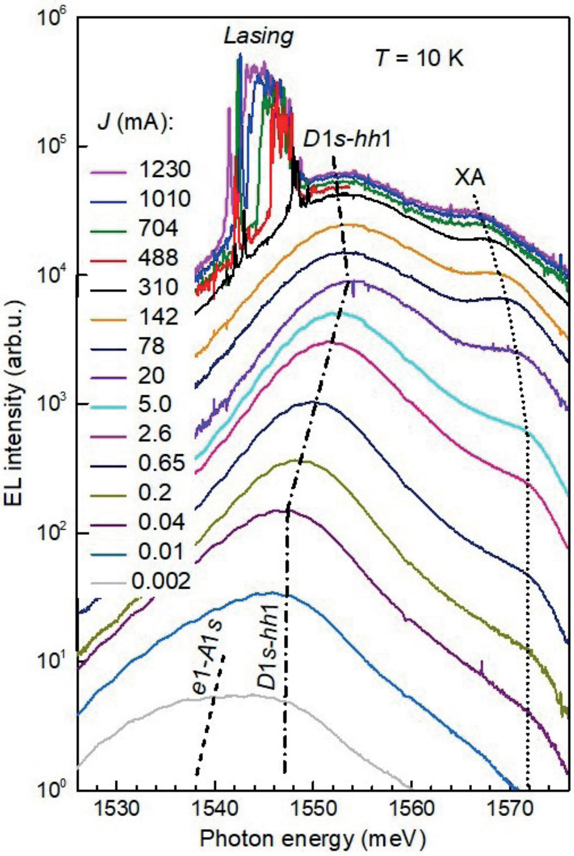


Fig. 3. Near-infrared electroluminescence spectra for *p-i-n* diode with 10 compensated QWs at various values of the injection current *J*. Dashed and dash-dotted lines point out the maximum positions of the impurity-assisted EL lines. Dotted line demonstrates the maximum positions of the acceptor-bound exciton line on the EL spectra

Let us consider the behavior of the donor-assisted recombination line *D*1*s*—*hh*1. As mentioned above, in the PL spectrum at a power of 30 mW, this line is slightly dominant over the acceptor-assisted recombination line *e*1—*A*1*s* (see Fig. 1). The same situation is observed in the EL spectra at the intermediate injection current between 0.002 and 0.01 mA (see Fig. 3). Under increase in the current up to 20 mA, the *D*1*s*—*hh*1 line begins to dominate significantly over the line *e*1—*A*1*s*, and superposition of these lines undergoes a blue shift of about +8 meV. With a further increase in the injection current to 1230 mA, a red shift of the *D*1*s*—*hh*1 line (of about −4 meV) is observed, which we associate with the quantum-confined Stark effect [9]. Previously, a similar transition from blue shift to red was also observed in *p*—*i*—*n* diodes with 50 compensated QWs [6]. A notable feature of the EL spectra at high injection currents (310—1230 mA) is the appearance of narrow emission lines on the low-frequency wing of the broad spontaneous EL line *D*1*s*—*hh*1, which merge into a single band several meV wide as the current increases. These lines represent high Q-factor closed modes of stimulated emission arising due to total internal reflection at the cleaved sample edges [10, 11].

The lasing threshold current for the 10-QW *p*—*i*—*n* diode is about 300 mA, which is 7 times less than the threshold current in the 50-QW diode [6]. This is an important advantage. Another advantage is that at a given injection current, the overall rate of *D*1*s*—*hh*1 transitions in the structure with 10 QWs is significantly higher than in the structure with 50 QWs. Indeed, comparing the spectral position of the *D*1*s*—*hh*1 line relative to the exciton peak of *XA* for *p*—*i*—*n* diodes with different numbers of quantum wells (see Fig. 3 here and Fig. 6 in [6]), one can, for example, notice that a current of 0.2 mA in the diode with 10 QWs provides the same level of nonequilibrium charge carrier excitation per QW as is achieved at a current of ~ 3 mA in the diode with 50 QWs. This means that increasing the current in the 10-QW diode by 5 times (up to 1 mA) one can achieve the same overall rate of *D*1*s*—*hh*1 transitions as in the 50-QW diode at 3 mA, and further increase in the current up to 3 mA will provide a threefold improvement compared to the 50-QW diode. Thus, we can conclude that 10-QW diodes are more promising for creating electrically pumped THz emitters based on $e1$-$D1s$ transitions in comparison with 50-QW diodes.

Then we studied THz luminescence. First, experiments were carried out under optical pumping. Spectra of the THz PL photoresponse are presented in Fig. 4. There are three pronounced peaks in the spectra. The low-frequency peak at $\hbar\omega$ = 18 meV can be attributed $e1-D1s$ transitions. In the limits of experimental accuracy its position corresponds to the $e1-D1s$ peak previously observed in similar MQW structure but without conducting cladding layers and $p^{++}$-GaAs top layer [5]. Two other peaks (centered at ~ 28 meV and ~ 38 meV) have not been observed in Ref. [5]. It is reasonable to associate them with highly doped $p^{++}$-GaAs layer. Both peaks can arise due to photorefractive effect in $p^{++}$-GaAs layer associated with the room-temperature background radiation and optical pumping. Note, that high-frequency peak at ~ 38 meV can be also associated with THz emission at the $A1s-hh1$ transitions (see Ref. [4]).

At the final stage of these investigations, we made an attempt to explore THz luminescence under electrical pumping. Since during optical pumping of the $p-i-n$ structures under study we have already observed the emission of THz radiation at the $e1-D1s$ transitions (see Fig. 4), and in diodes made from this structure we observed NIR lasing at the $e1-D1s$ transitions (see Fig. 3), we also expected to detect the emission of THz radiation from the $p-i-n$ diodes under NIR lasing conditions. Unfortunately, our expectations were not met. We did not observe measurable THz emission from the edges of the diodes.

Apparently, this is due to the fact that the area of the diode edge from which we tried to collect THz EL radiation is almost 3 orders of magnitude smaller than the surface area from which THz PL radiation was collected. A possible solution to this problem is to use metal grating as a semi-transparent electrical contact to the $p$-side of the diode, which will allow collecting THz EL radiation from a large area (even larger than in THz PL studies).

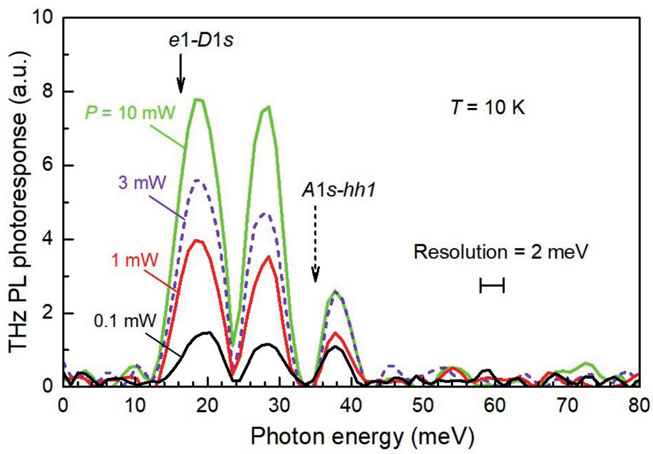


Fig. 4. Terahertz photoluminescence spectra for the $p-i-n$ structure with 10 compensated QWs at various pump power $P$. Solid arrow shows the peak position for the $e1-D1s$ transitions after [5]. Dashed arrow points out the peak position for the $A1s-hh1$ transitions after [4]

## Conclusion

The impurity-assisted NIR and THz photoluminescence have been studied in the $p-i-n$ structure with 10 compensated GaAs/AlGaAs quantum wells. The compensation was carried out directly in each quantum well by introducing donors and acceptors with the same concentration. In the $p-i-n$ diodes fabricated from the structure, the current-voltage characteristic and impurity-assisted NIR electroluminescence have been studied as well. Behavior of the $D1s-hh1$ emission line (which plays a positive role in the THz emission at the $e1-D1s$ transitions) has been analyzed in the NIR photo- and electroluminescence spectra. It has been shown, that at given power of optical pumping or density of injection current, the overall rate of $D1s-hh1$ transitions in the $p-i-n$ structure with 10 QWs is significantly higher than in the similar structure with 50 QWs.

NIR stimulated emission at the $D1s-hh1$ transitions has been observed in the electroluminescence spectra. It has been established that reducing the number of quantum wells from 50 to 10 leads to a 7-fold decrease in the lasing threshold current. THz emission line due to electron transitions $e1-D1s$ has been revealed in the THz photoluminescence spectra. To obtain THz radiation from forward-biased $p-i-n$ structures with compensated GaAs/AlGaAs quantum wells, it is proposed to use metal grating as a semi-transparent electrical contact to the $p-i-n$ diode.

## REFERENCES


1. **Andrianov A.V., Gupta J.P., Kolodzey J., Sankin V.I., Zakhar'in A.O., Vasil'ev Yu.B.,** Current injection induced terahertz emission from 4H-SiC *p-n* junctions, Applied Physics Letters. 103 (22) (2013) 221101.

2. **Zakhar'in A.O., Vasilyev Yu.B., Sobolev N.A., Zabrodskii V.V., Egorov S.V., Andrianov A.V.,** Injection-induced terahertz electroluminescence from silicon *p–n* structures, Semiconductors. 51 (5) (2017) 604–607.

3. **Li S.M., Zheng W.M., Wu A.L., Cong W.Y., Liu J., Chu N.N., Song Y.X.,** Terahertz electroluminescence from Be δ-doped GaAs/AlAs quantum well, Applied Physics Letters. 97 (2) (2010) 023507.

4. **Makhov I.S., Panevin V.Yu., Firsov D.A., Vorobjev L.E., Klimko G.V.,** Impurity-assisted terahertz photoluminescence in compensated quantum wells, Journal of Applied Physics. 126 (17) (2019) 175702.

5. **Adamov R.B., Melentev G.A., Sedova I.V., Sorokin S.V., Klimko G.V., Makhov I.S., Firsov D.A., Shalygin V.A.,** Terahertz photoluminescence in doped nanostructures with spatial separation of donors and acceptors, Journal of Luminescence. 266 (2024) 120302.

6. **Adamov R.B., Melentev G.A., Podoskin A.A., Kondratov M.I., Grishin A.E., Slipchenko S.O., Sedova I.V., Sorokin S.V., Klimko G.V., Makhov I.S., Firsov D.A., Shalygin V.A.,** Luminescence in *p-i-n* structures with compensated quantum wells, Semiconductors. 57 (8) (2023) 643–652.

7. **Adamov R.B., Petruk A.D., Melentev G.A., Sedova I.V., Sorokin S.V., Makhov I.S., Firsov D.A., Shalygin V.A.,** Near-infrared photoluminescence in n GaAs/AlGaAs quantum wells with different locations of compensating acceptor impurity, St. Petersburg Polytechnic University Journal: Physics and Mathematics. 15 (4) (2022) 32–43.

8. **Miller D.A.B., Chemla D.S., Damen T.C., Gossard A.C., Wiegmann W., Wood T.H., Burrus C.A.,** Electric field dependence of optical absorption near the band gap of quantum-well structures, Physical Review B. 32 (2) (1985) 1043–1060.

9. **Bastard G., Brum J.A., Ferreira R.,** Electronic States in Semiconductor Heterostructures, Solid State Physics. 44 (1991) 229–415.

10. **Podoskin A.A., Romanovich D.N., Shashkin I.S., Gavrina P.S., Sokolova Z.N., Slipchenko S.O., Pikhtin N.A.,** Specific Features of Closed-Mode Formation in Rectangular Resonators Based on InGaAs/AlGaAs/GaAs Heterostructures for High-Power Semiconductor Lasers, Semiconductors. 53 (6) (2019) 828–832.

11. **Podoskin A.A., Romanovich D.N., Shashkin I.S., Gavrina P.S., Sokolova Z.N., Slipchenko S.O., Pikhtin N.A.,** Switching Control Model of Closed-Mode Structures in Large Rectangular Cavities Based on AlGaAs/InGaAs/GaAs Laser Heterostructures, Semiconductors. 54 (5) (2020) 581–586.

## THE AUTHORS

**ADAMOV Roman B.**
roma.adamow@gmail.com
ORCID: 0000-0002-7731-349X

**MELENTEV Grigorii A.**
gamelen@spbstu.ru
ORCID: 0000-0002-1680-333X

**PODOSKIN Aleksandr A.**
podoskin@mail.ioffe.ru
ORCID: 0000-0002-8819-844X

**SLIPCHENKO Sergey O.**
serghpl@mail.ioffe.ru
ORCID: 0000-0003-4851-3641

**SEDOVA Irina V.**
irina@beam.ioffe.ru
ORCID: 0000-0002-9540-0933

**SOROKIN Sergey V.**
sorokin@beam.ioffe.ru
ORCID: 0000-0003-0320-2233

**MAKHOV Ivan S.**
imahov@hse.ru
ORCID: 0000-0003-4527-1958

**FIRSOV Dmitry A.**
dmfir@rphf.spbstu.ru
ORCID: 0000-0003-3947-4994

**SHALYGIN Vadim A.**
vadim_shalygin@mail.ru
ORCID: 0000-0001-6728-7286

*Received 05.12.2023. Approved after reviewing 07.12.2023. Accepted 12.12.2023.*