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ENHANCEMENT OF EXCITONIC PHOTOLUMINESCENCE IN SILICON-DOPED n^+/i-GaAs STRUCTURES

V. Kazlauskaitė, A. Sužiedėlis, A. Čerškus, J. Gradauskas, S. Ašmontas, and J. Kundrotas

Semiconductor Physics Institute, A. Goštauto 11, LT-01108 Vilnius, Lithuania
E-mail: vika@pfi.lt

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We present photoluminescence spectra of a molecular beam epitaxy grown GaAs structure consisting of the layer of intrinsic conductivity having 500 nm thickness and capped with silicon-doped 100 nm thick layer. The spectra were measured in the range of 3.6–77 K crystal lattice temperatures and at various laser excitation energies. Possible mechanisms of experimentally observed excitonic line narrowing and intensity enhancement in n^+/i-GaAs homojunction are discussed.

Keywords: GaAs homojunction, photoliuminescence, exciton

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1. Introduction

Rapid development of technologies for optical communication is directed towards broadening the operation bandwidth of emitters and detectors. The greatest achievements are made in visible and near-infrared ranges. However, the results in terahertz frequency range are quite modest. Recently new emitters [1, 2] and detectors [3] on the base of n^+/n and n^+/i GaAs homojunctions have been proposed. Nevertheless, despite all the theoretical and experimental research done, the physics of these devices is still under consideration.

We investigate photoluminescence (PL) properties of n^+/i-GaAs homojunction and homogeneous i-GaAs at low temperatures. We briefly discuss the possible model of excitonic photoluminescence enhancement in a n^+/i homojunction in comparison to a homogeneous layer. The influence of the internal electric field and various mechanisms of recombination are also considered.

2. Samples

n^+/i-GaAs homojunction samples were grown using the molecular beam epitaxy. Undoped GaAs buffer layer of 500 nm thickness was grown on semi-insulating GaAs substrate and, subsequently, silicon-doped GaAs layer with thickness of 100 nm and donor concentration of 10^{17} cm^{-3} was grown.

For the formation of n^+/i-GaAs samples having thinner doped layer or for the formation of single i-GaAs layer, a chemical etching using H_3PO_4:H_2O_2: H_2O = 1:1:50 was performed from the top of the GaAs structure.

3. Experimental technique

Argon ion laser operating in the continuous wave mode was used for the sample excitation with photon energy of 2.4–2.7 eV. The PL signal was dispersed by a monochromator and detected by a thermoelectrically cooled GaAs *Hamamatsu* photomultiplier operating in photon counting regime. The PL spectra of the structures were measured using various intensities of excitation in the range from 0.019 to 13.6 W/cm^2. Closed cycle helium cryostat enabled us to achieve temperatures from 77 down to 3.6 K.

4. Experimental results

A series of PL spectra of n^+/i-GaAs homojunction obtained at different temperatures from 3.6 up to 77 K at laser excitation intensity of 1.36 W/cm^2 are depicted in Fig. 1. PL intensity is given in arbitrary units and spectra are shifted along vertical axis for better visualization and comparison. One can distinguish the detailed spectrum of n^+/i-GaAs homojunction at 3.6 K

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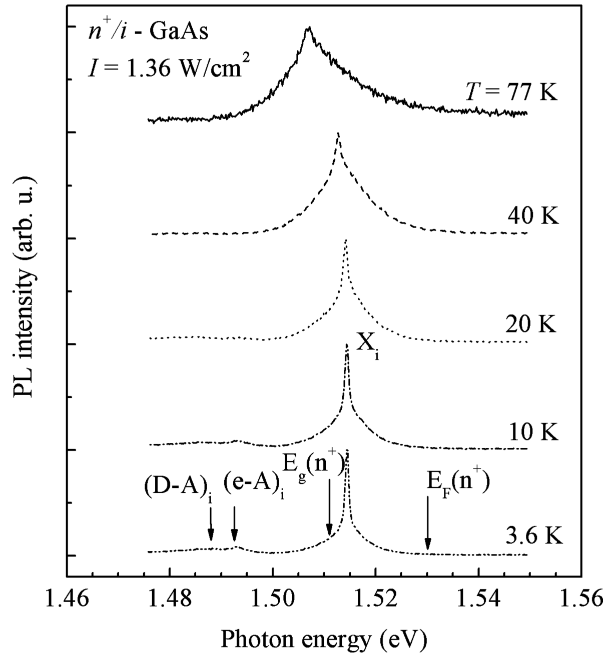

Fig. 1. PL spectra of Si-doped n^+/i-GaAs homojunction at various lattice temperatures.

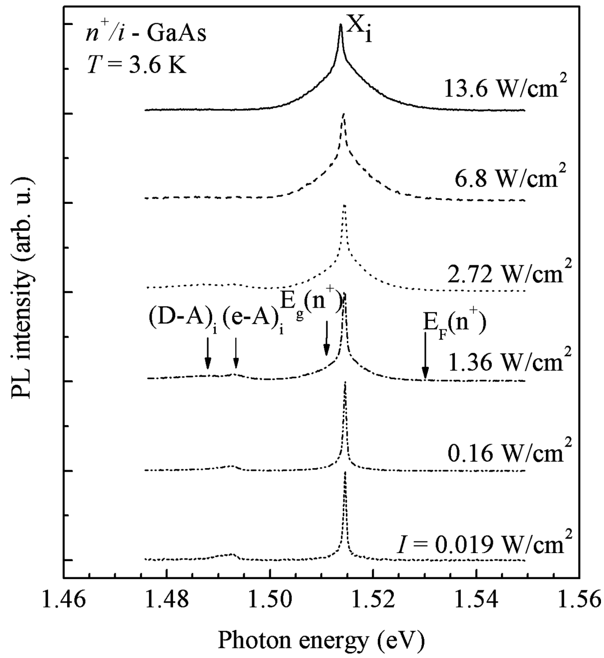

Fig. 2. PL spectra of Si-doped n^+/i-GaAs homojunction at T = 3.6 K and at different laser excitation intensities.

temperature. The sharp line, entitled X_i, corresponds to the emission from i-GaAs layer and has the energy of 1.515 eV, which corresponds to free exciton transition in GaAs crystal of intrinsic conductivity [4]. $(e–A)_i$ indicates free electron–neutral acceptor transitions, and $(D–A)_i$ denotes donor–acceptor transitions in i-GaAs layer. Arrows labelled $E_g(n^+)$ and $E_F(n^+)$ indicate the energy gap and Fermi level in n^+-GaAs layer, respectively. Consequently, the PL spectrum of n^+/i-GaAs consists of two parts: the base part is the emission from n^+-GaAs layer and dominates at higher temperatures, and the sharp line, named X_i, is the emission from i-GaAs layer.

PL spectra measured at 3.6 K temperature using various laser excitation intensities are shown in Fig. 2. These results also evidence dual constitution of PL spectrum. Domination of PL of n^+-GaAs layer prevails at higher intensities of laser excitation. The narrow line X_i shape and position independent of the laser intensity show that this emission is related to free exciton transition.

PL spectrum of single epitaxial i-GaAs layer in comparison with the PL spectrum of the homojunction was measured. Both spectra obtained at 3.6 K temperature are shown in Fig. 3. The spectrum of i-GaAs is enlarged 50 times, as the excitonic line in n^+/i-GaAs structure is about 50 times more intensive than in the i-GaAs layer. Label $(D–A, e–A)_{1LO}$ indicates the first longitudinal optical (LO) phonon replica of $(D–A)_i$ and $(e–A)_i$ transitions in the i-GaAs layer. The energy of LO phonon is indicated as a horizontal bar $\hbar\omega_{LO} = 36.75$ meV.

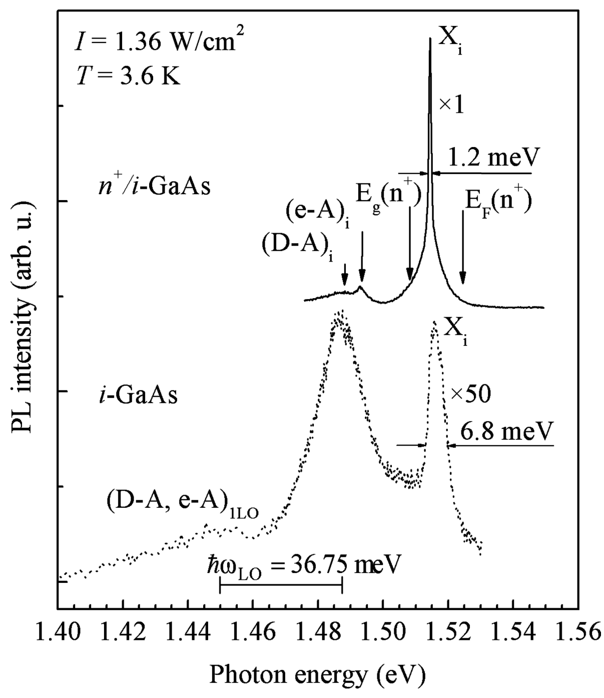

Fig. 3. PL spectra of Si-doped n^+/i-GaAs homojunction (top) and i-GaAs layer (bottom) at 3.6 K temperature and laser excitation intensity of 1.36 W/cm^2.

We introduce the excitonic line intensity amplifica-

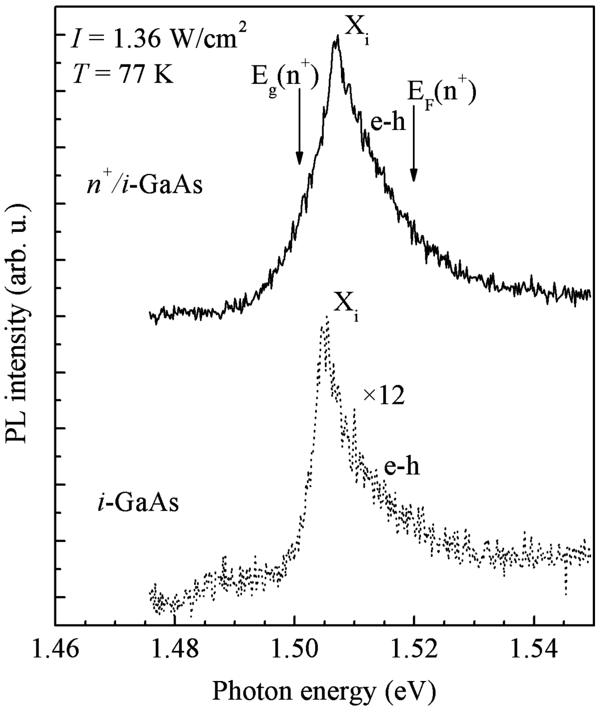

Fig. 4. PL spectra of Si-doped n^+/i-GaAs homojunction (top) and i-GaAs layer (bottom) at liquid nitrogen (77 K) temperature and laser excitation intensity of 1.36 W/cm^2.

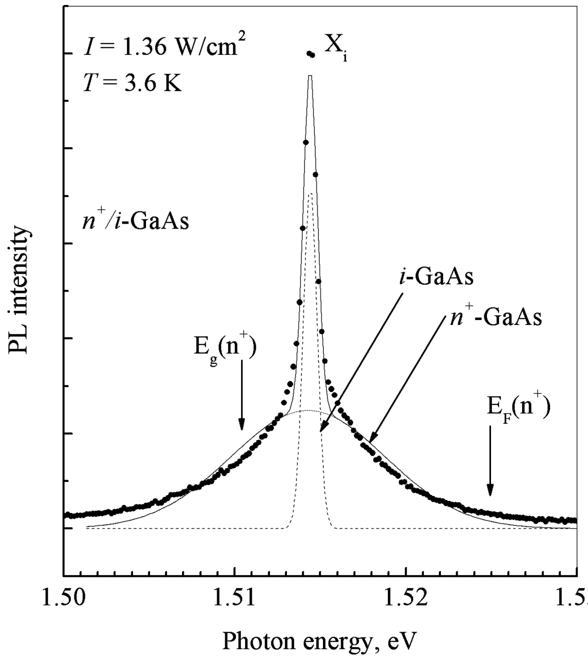

Fig. 5. Experimental PL spectrum of Si-doped n^+/i-GaAs homojunction at 3.6 K temperature (dots) and theoretical approximation with Gaussian functions of PL of i-GaAs layer (dashed line) and of PL of n^+-GaAs layer (dotted line). Solid line is the resultant numerical approximation.

tion (k_{X_i}) as the unit of measure of the excitonic line enhancement:

$$k_{X_i} = \frac{I_{\mathrm{H}}(X_i)}{I_i(X_i)}\,, \tag{1}$$

where $I_{\mathrm{H}}(X_i)$ is the intensity of excitonic line of n^+/i-GaAs homojunction and $I_i(X_i)$ is the excitonic line intensity of epitaxial i-GaAs layer.

Estimated full width at half maximum (FWHM) of exciton peak for n^+/i-GaAs homojunction is 1.2 meV, while FWHM for i-GaAs layer is 6.8 meV. Thus, in Fig. 3 we observe two phenomena associated with (i) excitonic line amplification with $k_{X_i} = 50$ and (ii) narrowing of the excitonic line in the n^+/i-GaAs homojunction.

PL spectra of n^+/i-GaAs homojunction and i-GaAs layer at 77 K temperature are depicted in Fig. 4. At liquid nitrogen temperature the biggest part of the spectrum is the base part due to emission from n^+-GaAs layer. *e–h* indicates free electron and hole band-to-band recombination. However, amplification of excitonic line intensity with $k_{X_i} = 12$ is observed at higher temperatures as well.

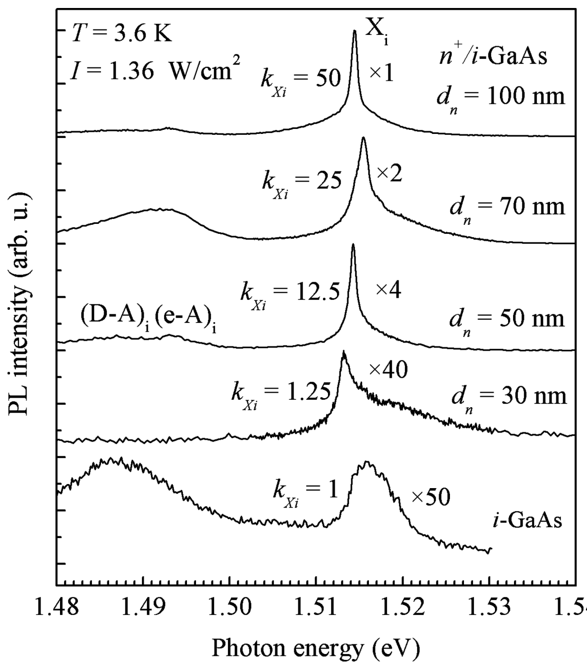

Fig. 6. PL spectra of n^+/i-GaAs homojunction with different silicon-doped layer thickness at 3.6 K tempereature and laser excitation of 1.36 W/cm^2. The bottom graph is the PL spectrum of i-GaAs layer.

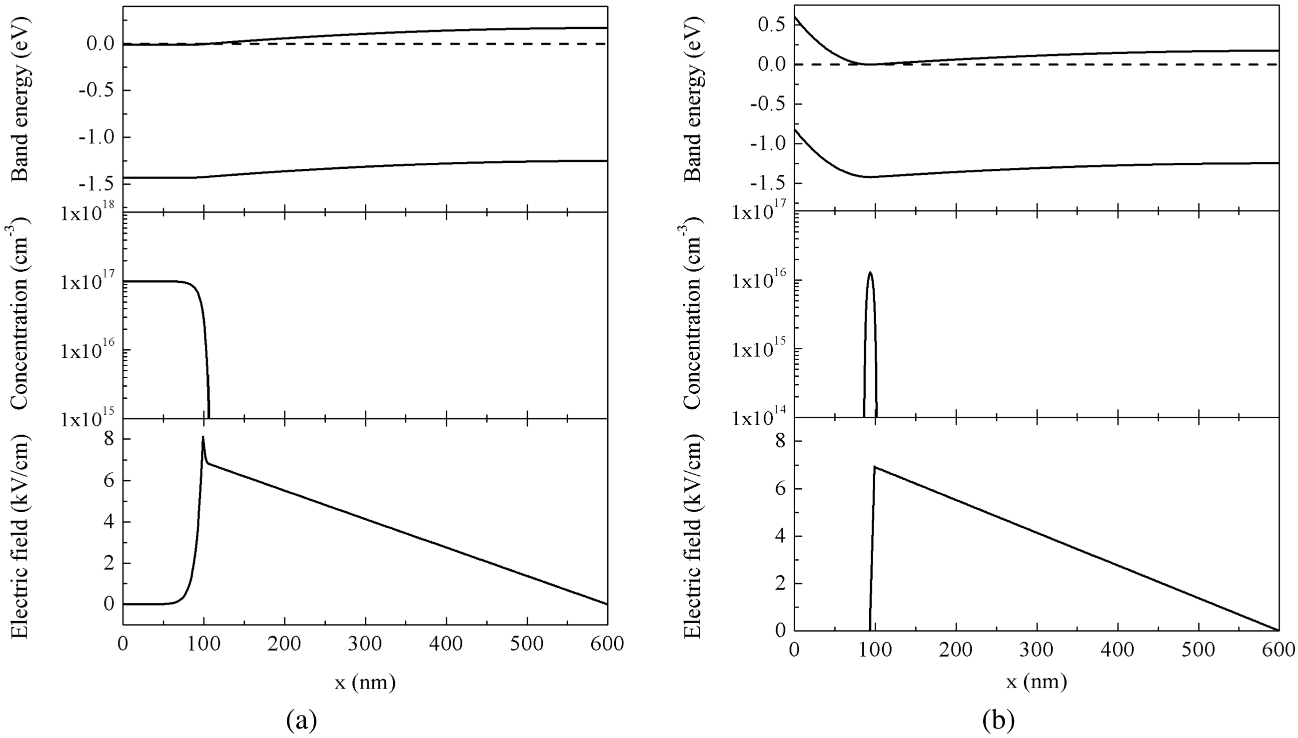

Fig. 7. Numerical calculation of energy band diagram (top), electron concentration (middle), and internal electric field (bottom) of n^+/i-GaAs homojunction (a) with no surface potential and (b) assuming surface potential of 0.6 eV.

5. Discussion

To clarify the composition of PL spectrum of n^+/i-GaAs homojunction, theoretical approximation was made. The PL spectrum was interpreted as the superposition of two separate spectra of n^+-GaAs and i-GaAs (see Fig. 5). Excitonic line in heavily donor-doped GaAs samples is not observed, because heavy doping broadens the excitonic emission until it becomes a wide band-to-band luminescence [5, 6]. The presence of a large concentration of dopant impurities also causes significant reduction of a band gap. At high doping levels the bound states of impurities broaden into a distinct impurity band because of the overlap of impurity wave functions, and Mott transition metal–insulator occurs [7]. The impurity band merges with the conduction band and the conduction band edge moves downward. Hence, we can observe the band gap narrowing as the doping impurity concentration increases.

On the other hand, free carriers fill the bottom of the conduction band thus extending the emission spectra towards higher energy up to a Fermi level. The edge of conduction band energy $E_{\mathrm{g}}(n^+)$ and Fermi energy $E_{\mathrm{F}}(n^+)$ for heavily doped n^+-GaAs layer are depicted in Figs. 1–5.

The emission spectra of n^+-GaAs layer is approximated with Gaussian function and is shown as dotted line (see Fig. 5) [8]. Narrowed and amplified excitonic line X_i of i-GaAs layer is also approximated with Gaussian function and is shown as dashed line [9]. Solid line shows the resultant spectrum of separate n^+-GaAs and i-GaAs layers. This line well coincides with the experimental spectrum of n^+/i-GaAs homojunction.

Discussing the physical origin of the observed phenomena we make an assumption that both narrowing and amplification of the excitonic line originate from penetration of free carrier from n^+-GaAs to i-GaAs layer. A part of free carriers is captured by surface states. Therefore the thinning of n^+-GaAs layer should reduce the concentration of carriers, thus changing the amplification k_{X_i} of the excitonic line intensity. Figure 6 shows spectra of n^+/i-GaAs having various thicknesses of the silicon-doped layer. The results show that k_{X_i} decreases as the doped layer is thinned down.

To clarify the effect of amplification we solve the Poisson equation [10] and calculate energy band diagram, electron concentration, and electric field strength in n^+/i-GaAs homojunction. These calculations are made neglecting (in (a) case) and assuming (in (b)) the surface potential and are shown in Fig. 7. The presence of surface potential is obviously crucial for free carrier concentration and their distribution near the surface, while interface electric field is influenced insignificantly and has a value of 7 kV/cm.

During the experiment, the laser excites electrons in a certain depth of light penetration. In i-GaAs layer the photoexcited carriers can form excitons, which in turn can recombine emitting photons. However, the presence of strong internal electric field has a crucial influence on exciton formation in the close to interface region: holes are driven away from the interface while photoexcited electrons drift towards the interface. Electric field stronger than 1 kV/cm is sufficient to destroy excitons by tunnelling [11]. The most favourable conditions for the exciton formation are in the flat band region of i-GaAs. Accumulation of free carriers increases the number of excitons in i-GaAs layer. This can explain the amplification of excitonic line intensity in n^+/i-GaAs homojunction [12].

However, the origin of the line narrowing phenomenon is not clear yet. On the one hand, excited electrons and holes in epitaxial layer stay mostly near residual donors, acceptors, or other inhomogenities that are randomly distributed in space. This interaction causes an inhomogeneous broadening of excitonic linewidth [13]. The FWHM of X_i line at low temperatures in n^+/i-GaAs structure is similar to the linewidth of a very high quality GaAs crystal, showing that the interaction of excitons with crystal imperfections is changed in n^+/i-GaAs homojunction. On the other hand, the excitonic line narrowing shows that the system possesses a macroscopic coherence. Such spontaneous appearance of coherence indicates that the exciton system in n^+/i-GaAs homojunction has a possibility of the macroscopic occupation of a narrow mode spectrum. This phenomenon may be also related to a collective interaction of excitons in n^+/i-GaAs homojunctions [14].

6. Conclusion

Experimental results showed that the PL spectrum of a n^+/i-GaAs homojunction consists of two parts: base of the spectrum from $E_g(n^+)$ to $E_F(n^+)$ is recombination in heavily silicon-doped layer, and the sharp peak X_i is free exciton luminescence in the layer of intrinsic conductivity. Comparison of the spectra of a homojunction and an epitaxial layer at 3.6 K temperature has shown the amplification of excitonic line intensity up to 50 times and its narrowing from about 7 to 1 meV of FWHM in the homojunction.

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EKSITONINĖS FOTOLIUMINESCENCIJOS SUSTIPRĖJIMAS n^+/i-GaAs DARINIUOSE SU SILICIO PRIEMAIŠA

V. Kazlauskaitė, A. Sužiedėlis, A. Čerškus, J. Gradauskas, S. Ašmontas, J. Kundrotas

Puslaidininkių fizikos institutas, Vilnius, Lietuva

Santrauka

Ištirta n^+/i-GaAs vienalyčių sandūrų fotoliuminescencija plačiame temperatūros ruože – nuo 3,6 iki 77 K, esant įvairiems žadinančios lazerio šviesos intensyvumams. Gauti rezultatai palyginti su i-GaAs sluoksnio fotoliuminescencijos tyrimų rezultatais. Aptiktas eksitoninės spinduliuotės iš savojo laidumo (i) sluoksnio sustiprėjimas ir linijos susiaurėjimas vienalytėje sandūroje lyginant su epitaksiniu sluoksniu. Nustatyta, kad eksitoninės linijos sustiprėjimas priklauso nuo viršutinio elektroninio laidumo (n^+) sluoksnio storio, tuo pačiu ir nuo elektronų tankio šiame sluoksnyje. Eksperimentiniai rezultatai ir teorinis vidinio elektrinio lauko įvertinimas leido daryti prielaidą, jog eksitoninės linijos sustiprėjimas susijęs su didelio tankio eksitonų susidarymu savojo laidumo sluoksnyje dėl krūvininkų dreifo vidiniame elektriniame lauke ir jų akumuliacijos siauroje šio sluoksnio srityje. Eksitoninės linijos susiaurėjimas gali būti susijęs su krūvininkų sąveikos su kristalo nehomogeniškumais pakitimu ir kolektyvine eksitonų sąveika.