Proceedings of the 14th International Symposium Ultrafast Phenomena in Semiconductors, Vilnius 2010

Enhancement of the Excitonic Photoluminescence in n^+/i-GaAs by Controlling the Thickness and Impurity Concentration of the n^+ Layer

A. Čerškus[a,b,*], V. Nargelienė[a], J. Kundrotas[a,c], A. Sužiedėlis[a,c], S. Ašmontas[a], J. Gradauskas[a,c], A. Johannessen[d] and E. Johannessen[d]

[a]Semiconductor Physics Institute, Center for Physical Sciences and Technology
A. Goštauto 11, LT-01108 Vilnius, Lithuania

[b]Department of General Physics, Vilnius Pedagogical University, Studentų 39, LT-08106 Vilnius, Lithuania

[c]Vilnius Gediminas Technical University, Saulėtekio 11, LT-10223 Vilnius, Lithuania

[d]Vestfold University College, Raveien 197, 3184 Borre, Norway

This communication presents the photoluminescence spectra of molecular beam epitaxially grown GaAs structures made from a 500 nm thick layer of intrinsic conductivity capped with a silicon doped layer with a film thickness ranging from 10 to 100 nm. Two different doping concentrations of the cap layer, $N_{\mathrm{Si}} = 10^{17}$ cm^{-3} and $N_{\mathrm{Si}} = 10^{18}$ cm^{-3}, was considered. The results showed the excitonic line of i-GaAs layer enhancement. The intensity of excitonic line was about 160 times higher for the homojunction compared to the intrinsic conductivity epitaxial layer at liquid helium temperature. Possible mechanisms of the observed intensity enhancement in the n^+/i-GaAs homojunction are discussed.

PACS: 78.55.−m, 71.35.−y, 71.55.Eq

1. Introduction

Current research in optical communication technologies aims to increase the operational bandwidth of emitters and detectors [1, 2]. The greatest achievements have been reported in the visible and near-infrared ranges, whereas the performance in the terahertz frequency range is still considered modest. Therefore, a new generation of emitters [3, 4] and detectors [5, 6], based on the construction of the n^+/n and n^+/i (or p^+/i) homojunction, have been proposed for operations in the terahertz range. Although they hold promising characteristics, these devices are still considered experimental in nature due to the underlying physics not being fully understood.

2. Samples and experimental technique

The n^+/i-GaAs homojunction samples were grown using molecular beam epitaxy. The GaAs layer of intrinsic conductivity with a thickness of 500 nm was grown on a semi-insulating GaAs substrate. Subsequently, a silicon doped GaAs cap layer with a thickness of 100 nm and donor concentration of either 10^{17} cm^{-3} or 10^{18} cm^{-3} was grown.

* corresponding author; e-mail: a_cerskus@yahoo.com

Chemical etching of GaAs structures in a H_3PO_4:H_2O_2:H_2O = 1:1:50 solution reduced the cap layer thickness below the initial 100 nm. The cap layer was removed entirely by the same process yielding the single i-GaAs layer samples that were investigated.

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

3. Experimental results and discussion

A series of PL spectra obtained at different temperatures from the n^+/i-GaAs homojunction at a laser excitation intensity of 0.16 W/cm^2 are depicted in Fig. 1a. One can clearly distinguish the detailed spectrum of the n^+/i-GaAs homojunction at a temperature of 3.6 K. The sharp line, entitled X_i, corresponds to the emission from i-GaAs layer, whereas the associated energy of 1.515 eV corresponds to the free exciton transition in a GaAs crystal of intrinsic conductivity [7]. The arrow

labeled $(e{-}A)_i$ indicates the free electron–neutral acceptor transitions, whereas the arrow $(D{-}A)_i$ denotes the donor–acceptors transitions in the n^+/i-GaAs layer. The arrows labeled $E_{\mathrm{g}}(n^+)$ and $E_{\mathrm{F}}(n^+)$ indicates the energy gap and Fermi level of the n^+-GaAs layer, respectively. The label (IB) marks the emission transitions related to the impurity band of the cap layer. Consequently, the PL spectrum of the n^+/i-GaAs consists of two parts:
(i) the base part constitutes the emission from the n^+-GaAs layer and dominates at higher temperatures;
(ii) the excitonic sharp line (X_i) corresponds to the emission from the intrinsic i-GaAs layer.

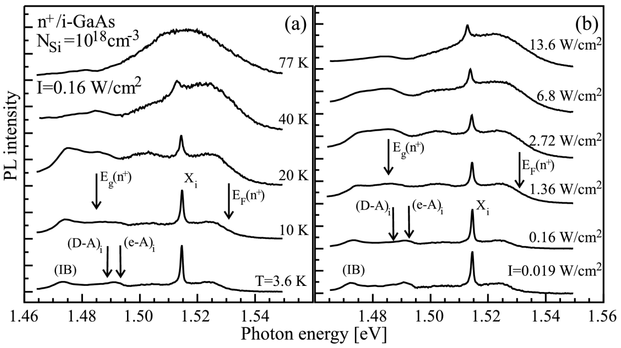

Fig. 1. The PL spectra of Si-doped ($N_{\mathrm{Si}} = 10^{18}$ cm^{-3}) n^+/i-GaAs homojunction obtained at various lattice temperatures (a) and different excitation intensities at a constant temperature $T = 3.6$ K (b).

The PL spectra measured at a constant temperature of 3.6 K in response to various laser excitation intensities, are shown in Fig. 1b. These results also support the dual constitution of the PL spectrum. Similar results of the PL spectra dependence on temperature and laser excitation intensity have previously been reported from the n^+/i-GaAs homojunction with $N_{\mathrm{Si}} = 10^{17}$ cm^{-3} [8].

Figure 2 shows the PL spectra of n^+/i-GaAs homojunction with different Si doped cap layer thickness and PL spectra of i-GaAs layer. The estimated full width at half maximum (FWHM) of the exciton peak for the n^+/i-GaAs homojunction is about 1–2 meV, while the FWHM for the single epitaxial i-GaAs layer is about 5–7 meV (see also [8]). We observe two phenomena: (i) excitonic line amplification, (ii) narrowing of the excitonic line in the n^+/i-GaAs homojunction.

The excitonic line intensity amplification coefficient k_{X_i} is introduced as the unit of measure of the excitonic line enhancement, and is described by: $k_{X_i} = I_{\mathrm{H}}(X_i)/I_i(X_i)$, where $I_{\mathrm{H}}(X_i)$ is the intensity of the excitonic line of the n^+/i-GaAs homojunction, and $I_i(X_i)$ is the excitonic line intensity of the epitaxial i-GaAs layer. The amplification coefficient k_{X_i} for various cap layer thicknesses d_n is indicated in Fig. 2.

The dependence of k_{X_i} on the thickness d_n of the heavily doped layer are shown in Fig. 3. The response from the sample with a cap layer doping of $N_{\mathrm{Si}} = 10^{18}$ cm^{-3} is indicated with solid circles whereas the response from the

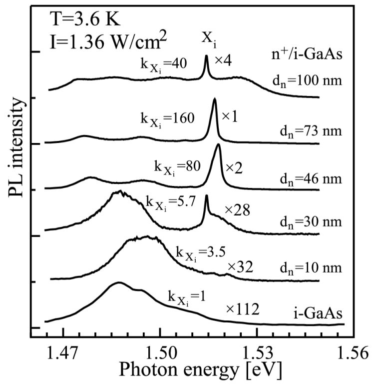

Fig. 2. The PL spectra of n^+/i-GaAs homojunction with different Si doped cap layer thickness at $T = 3.6$ K and $I = 1.36$ W/cm^2. Cap layer doping concentration was $N_{\mathrm{Si}} = 10^{18}$ cm^{-3}.

sample with a cap layer doping of $N_{\mathrm{Si}} = 10^{17}$ cm^{-3} [8] is indicated with solid triangles. The results show that the amplification of the excitonic line in the sample equipped with a cap layer doping of $N_{\mathrm{Si}} = 10^{18}$ cm^{-3} is higher than in the sample with a cap layer doping of $N_{\mathrm{Si}} = 10^{17}$ cm^{-3}. In contrast, when the thickness of the cap layer approaches 100 nm the coefficient of amplification is reduced with a doping of $N_{\mathrm{Si}} = 10^{18}$ cm^{-3}. This is due to a more intensive absorption of the excitonic radiation in the heavily doped cap layer.

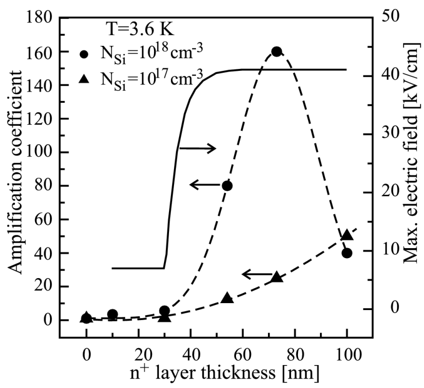

Fig. 3. The dependence of the excitonic line X_i amplification coefficient k_{X_i} on heavily doped layer thickness d_n: $N_{\mathrm{Si}} = 10^{18}$ cm^{-3} (solid circles) and $N_{\mathrm{Si}} = 10^{17}$ cm^{-3} (solid triangles). The dashed lines fitting serves for graphical interpretation. The solid line indicates calculated dependence of the maximum electric field on heavily doped layer thickness of the n^+/i-GaAs homojunction ($N_{\mathrm{Si}} = 10^{18}$ cm^{-3}).

Air or oxygen-exposed GaAs surfaces suffers from a large density of extrinsic states that tends to fix the location of the surface Fermi level near the midgap, which results in large surface recombination velocities [9, 10]. The surface properties can be controlled by chemical passivation, by introducing lattice-matched heterostructures, or using a highly doped surface cap layer [9–11]. The results presented in this paper as well as those in Ref. [10] suggest that the surface recombination is not as predominant in limiting the carrier lifetimes at low temperature as it is at room temperature. This paper presents an additional analysis that takes into account the surface potential.

Theoretical approximations have been adapted to interpret the PL spectrum composition of the n^+/i-GaAs homojunction [8] as the superposition of two separate spectra of n^+-GaAs and i-GaAs. The excitonic line in heavily donor doped GaAs samples is not observed due to a broadening of the excitonic emission until it becomes a wide band-to-band luminescence [12, 13]. The presence of a large concentration of dopant impurities triggers a significant reduction in the band gap in which the bound states of impurities broaden into a distinct impurity band [14, 15]. The metal–insulator Mott transition occurs when the impurity wave functions overlap [16], resulting in the conduction band edge moving downward when the impurity band merges with the conduction band. The result is a band gap narrowing as the doping impurity concentration increases. On the other hand, free carriers fill the conduction band extending the emission spectra towards higher energy up to the Fermi level. The edge of the conduction band energy $E_{\mathrm{g}}(n^+)$ and the Fermi energy $E_{\mathrm{F}}(n^+)$ of the heavily doped n^+-GaAs layer were depicted in Fig. 1.

The Poisson equation was solved in order to clarify the effect of amplification [17]. The energy band diagram, electron concentration and electric field strength in the n^+/i-GaAs homojunction was calculated by neglecting (Fig. 4a) or assuming (Fig. 4b) a surface potential Φ_{S}. The maximum built-in electric field in the homojunction equipped with a highly doped cap layer is nearly 40 kV/cm as follows from Fig. 4.

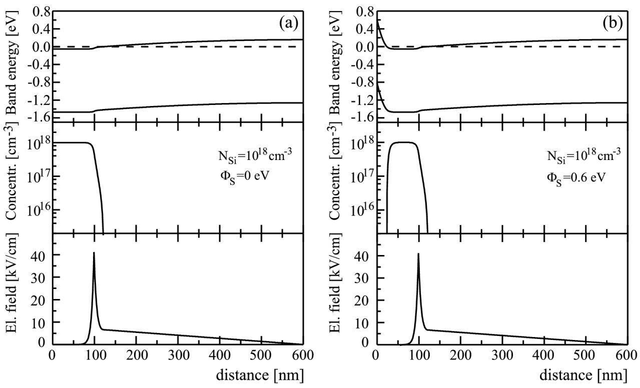

Fig. 4. Numerical calculations of the energy band diagram (top), electron concentration (middle) and built-in electric field (bottom) of the n^+/i-GaAs homojunction ($N_{\mathrm{Si}} = 10^{18}$ cm^{-3}) with no surface potential $\Phi_{\mathrm{S}} = 0$ eV (a) and assuming a surface potential of $\Phi_{\mathrm{S}} = 0.6$ eV (b). The thickness of the cap n^+-GaAs layer is 100 nm.

The built-in electric field of the n^+/i-GaAs homojunction ($N_{\mathrm{Si}} = 10^{18}$ cm^{-3}) considering a surface potential of 0.6 eV at various cap layer thicknesses was calculated. The results suggest a correlation between the calculated built-in electric field strength at various cap layer thicknesses, and the enhancement of the excitonic line intensity. This correlation is shown in Fig. 3.

The incident laser beam excites electrons down to a certain depth of light penetration. These photoexcited carriers can form excitons in the i-GaAs layer, which in turn may recombine back to emitting photons. However, the presence of a strong built-in electric field prevents exciton formation in the close proximity to the n^+/i interface region: holes are driven away from the interface while photoexcited electrons drift towards the interface. An electric field above 1 kV/cm has been shown to destroy excitons by tunneling [18]. An accumulation of free carriers increases the number of excitons in the flat band of i-GaAs layer. This can help explain the enhancement of excitonic line intensity in the n^+/i-GaAs homojunction [19]. The effect of a built-in electric field has previously been proposed to explain the origin of excitonic photoluminescence in modulation-doped GaAs/Al$_x$Ga$_{1-x}$As heterojunctions [20, 21].

The origin of the line narrowing phenomenon is not yet clear. On the one hand, it is known that excited electrons and holes in epitaxial layers stay mostly near residual donors, acceptors or other inhomogeneities that are randomly distributed in space. This interaction causes inhomogeneous broadening of the excitonic linewidth [22]. The FWHM of X_i line at low temperatures in n^+/i-GaAs structure is similar to the linewidth of a high quality GaAs crystal, suggesting that the interaction of excitons with crystal imperfections is changed in the n^+/i-GaAs homojunction. For example, light-induced narrowing of excitonic absorption lines in GaN was observed in Ref. [23].

4. Conclusion

The experimental results have showed that the PL spectrum of the n^+/i-GaAs homojunction consists of two parts: (i) the base of the spectrum from $E_{\mathrm{g}}(n^+)$ to $E_{\mathrm{F}}(n^+)$ is a result of the recombination in the heavily silicon doped layer, whereas (ii) the sharp peak X_i constitutes the free exciton luminescence in the layer of intrinsic conductivity. Comparison of the spectra of the homojunction and intrinsic conductivity epitaxial layer at a temperature of 3.6 K has shown an amplification of the excitonic line intensity of up to 160 times, concomitant with a line narrowing from about 5–7 meV to 1–2 meV of FWHM in the n^+/i-GaAs homojunction.

Acknowledgments

This work was supported by the Research Council of Lithuania under the contracts TAP-20/2010 and TAP-56/2010. The MBE grown structures were fabricated at Braun Submicron Research Center under contract No. HPRI-CT-2001-00114. The authors acknowledge Angelė

Steikūnienė and Gytis Steikūnas for the preparation of samples.

References

[1] L. Eldada, *Rev. Sci. Instrum.* **75**, 575 (2004).

[2] D. Dragoman, M. Dragoman, *Prog. Quantum Electron.* **28**, 1 (2004).

[3] H. Takeuchi, J. Yanagisawa, T. Hasegawa, M. Nakayama, *Appl. Phys. Lett.* **93**, 081916 (2008).

[4] A. Reklaitis, *J. Appl. Phys.* **101**, 116104 (2007).

[5] A.G.U. Perera, W.Z. Shen, H.C. Liu, M. Buchanan, M.O. Tanner, K.L. Wang, *Appl. Phys. Lett.* **72**, 2307 (1998).

[6] W.Z. Shen, A.G.U. Perera, H.C. Liu, M. Buchanan, W.J. Schaff, *Appl. Phys. Lett.* **71**, 2677 (1997).

[7] S.B. Nam, D.C. Reynolds, C.W. Litton, R.J. Almassy, T.C. Collins, C.M. Wolfe, *Phys. Rev. B* **13**, 761 (1976).

[8] V. Kazlauskaitė, A. Sužiedėlis, A. Čerškus, J. Gradauskas, S. Ašmontas, J. Kundrotas, *Lithuanian J. Phys.* **49**, 285 (2009).

[9] T.J. de Lyon, J.A. Kash, S. Tiwari, J.M. Woodall, D. Yan, F.H. Pollak, *Appl. Phys. Lett.* **56**, 2442 (1990).

[10] D.A. Harrison, R. Arès, S.P. Watkins, M.L.W. Thewalt, C.R. Bolognesi, D.J.S. Beckett, A.J. SpringThorpe, *Appl. Phys. Lett.* **70**, 3275 (1997).

[11] M.V. Lebedev, *Prog. Surf. Sci.* **70**, 153 (2002).

[12] J. De-Sheng, Y. Makita, K. Ploog, H.J. Queisser, *J. Appl. Phys.* **53**, 999 (1982).

[13] G. Borghs, K. Bhattacharyya, K. Deneffe, P. van Mieghem, R. Mertens, *J. Appl. Phys.* **66**, 4381 (1989).

[14] J. Serre, A. Ghazali, *Phys. Rev. B* **28**, 4704 (1983).

[15] V. Alex, B. Lux, A. Dargys, J. Kundrotas, A. Cėsna, *Lithuanian Phys. J.* **31**, 121 (1991).

[16] J. Kundrotas, A. Čerškus, G. Valušis, M. Lachab, S.P. Khanna, P. Harrison, E.H. Linfield, *J. Appl. Phys.* **103**, 123108 (2008).

[17] I.-H. Tan, G.L. Snider, L.D. Chang, E.L. Hu, *J. Appl. Phys.* **68**, 4071 (1990).

[18] L. Schultheis, K. Köhler, C.W. Tu, *Phys. Rev. B* **36**, 6609 (1987).

[19] T. Schmidt, K. Lischka, W. Zulehner, *Phys. Rev. B* **45**, 8989 (1992).

[20] J.X. Shen, R. Pittini, Y. Oka, *Phys. Rev. B* **64**, 195321 (2001).

[21] B.M. Ashkinadze, E. Linder, V. Umansky, *Phys. Rev. B* **62**, 10310 (2000).

[22] S. Rudin, T.L. Reinecke, B. Segall, *Phys. Rev. B* **42**, 11218 (1990).

[23] P. Trautman, K. Pakula, R. Bożek, J.M. Baranowski, *Appl. Phys. Lett.* **83**, 3510 (2003).