PHOTOLUMINESCENCE OF THE GaAs SUPERLATTICES WITH QUASI-DELTA-DOPED LAYERS

B. N. Zvonkov[1], V. Ya. Aleshkin[2], S. V. Morozov[2], V. I. Gavrilenko[2], D. M. Gaponova[2], V. K. Kononenko[3], D. V. Ushakov[4]

[1] *Scientific-Research Physico-Technical Institute, N. Novgorod, Russia*
[2] *Institute for Physics of Microstructures RAS, N. Novgorod, Russia*
[3] *Stepanov Institute of Physics NASB, Fr. Scorina Pr., 70, Minsk, 220072, Belarus*
[4] *Belarussian State University, Minsk, Belarus*
E-mail: lavik@dragon.bas-net.by

INTRODUCTION

Doping superlattices, or *n–i–p–i* crystals, have advanced properties for the development of novel optoelectronic devices. The δ-doping technology extends possibilities of the superlattice design and allows improving the characteristics compared with homogeneously doped *n–i–p–i* structures. For the δ-doping, molecular-beam epitaxy is most widely applied [1]. The GaAs δ-doped superlattices were also grown by metal-organic vapor-phase epitaxy [2, 3]. For *n*- and *p*-type δ-doping, Si and C were used and tunable low-temperature photoluminescence (PL) was demonstrated.

In this work, the GaAs short-period superlattices have been grown for the first time by the metal-organic hydride epitaxy method using Se and C for quasi-δ-doping. Earlier, such a method was applied for making the photosensitive heterostructures with the GaInAs quantum-well spacer [4].

EXPERIMENTAL

The formed GaAs quasi-δ-doped superlattices have the 30-period *n–i–p–i* set of doped *n*- and *p*-type layers and undoped *i*-layers. The superlattice period *d* was 19 or 29 nm and *i*-layers were, accordingly, of the order of 7 or 11 nm. The structure thickness was 0.8 or 1.2 μm, including the 0.2-μm buffer layer and 0.1-μm top layer. The sheet concentrations of donors Se in the *n*-layers and of acceptors C in the *p*-layers made up $(1.5–1.6)\times10^{13}$ cm^{-2}.

The PL characteristics of the grown δ-doped superlattices were measured at CW excitation by the 488-nm radiation of an Ar^+-ion laser. At the structure temperature $T = 77$ K in the spectral region near 1.4 eV, a tunable PL band in dependence on power excitation is observed [5]. The PL spectrum for the longer-period structures is shifted to the long-wavelength region and its tuning bandwidth is larger as compared the shorter-period structures. Since the *i*-layers in the first structures is approximately in one and a half times thicker than for another structures, the superlattice effective energy band gap must be smaller for the first ones and it exhibits a greater tunability under optical excitation. In addition, it provides a narrower linewidth of the PL spectrum.

The PL spectra measured at 4.2 K (Fig. 1) display a structure shape with well-distinguished peaks which coincide with allowed optical transitions between quantizied levels of electrons and holes in the potential relief quantum wells. Such a behavior has been also observed for structures grown by gas-source molecular-beam epitaxy [6].

0-7803-7948-9/03/$17.00 ©2003 IEEE

THEORY

To describe the observed PL phenomena in quasi-δ-doped superlattices, we used the simulation procedure previously developed and successfully applied for the description of PL spectra of homogeneously and δ-doped superlattices as well [7, 8]. The theory taking into account existing tails of the density of states explains adequately experimental observations of the tuning and transformation of PL spectra and shows that at increasing the temperature the quantized character of the spectra is diminished.

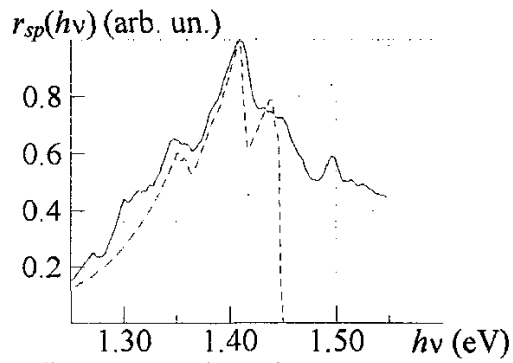

Figure 1 – The PL spectrum $r_{sp}(h\nu)$ of the quasi-δ-doped GaAs *n–i–p–i* structure at $T = 4.2$ K as compared a calculated spontaneous emission recombination spectrum (the dashed curve) at $\Delta F = 1.472$ eV.

As seen from Fig. 1, the best fitting between experimental and calculated PL spectra occurs where the superlattice design parameters are assumed such as $N_a = 5.17\times10^{19}$ cm^{-3}, $N_d = 1.5\times10^{20}$ cm^{-3}, $d_p = 2.9$ nm, $d_n = 1$ nm, $d_i = 5.55$ nm, $N_p = 10$, $m_c = 0.067m_e$, $m_{vh} = 0.34m_e$, $m_{vl} = 0.094m_e$, $m_{vh\perp} = 0.11m_e$, $m_{vl\perp} = 0.20m_e$ (for notations see [7, 8]). If a superlattice is excited up to the value of the quasi-Fermi level difference ΔF of ≈ 1.47 eV at $T = 4.2$ K, the effective energy gap E_g' equals ≈ 1.04 eV and the potential profile depth $2\Delta V \approx 0.45$ eV. In this case, distribution of quantized electron and hole levels in the periodic quantum wells is shown in Fig. 2.

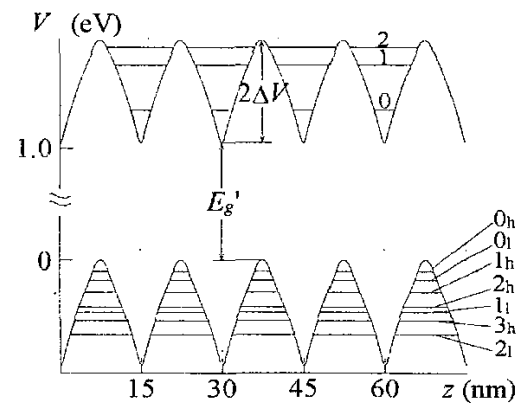

Figure 2 – Potential profile $V(z)$ of the modeling *n–i–p–i* structure and energy levels of electrons and heavy (*h*) and light (*l*) holes. Simulation parameters are listed in text. $T = 4.2$ K, $\Delta F = 1.472$ eV.

Obviously, the intensity and shape of the emission band of the structures is determined not only by the population of the excited subband states but also by the strength of overlapping the electron and hole envelope wave functions. Comparison of the observed PL spectrum and the numerical simulated shape of the recombination emission band shows that

more intensive transitions occur through the ground subband of electrons (the quantum number $n = 0$) and light hole states with quantum numbers $m = 0, 1$. At high enough excitation, significant value has transitions involving excited electron states ($n = 1$) and ground subbands of heavy and light holes ($m = 0$). For the optical transitions through the light hole subband, the squired overlap integral of the electron and hole envelope wave functions $|I_{nm}|^2$ has the highest value (see Table 1).

Table 1 – Energies of optical transitions $h\nu_{nm}$ between electron (E_{cn}) and heavy (h) or light (l) hole (E_{vm}) energy states with different quantum numbers n and m and the miniband wave vector $k_z = 0$, π/d and values of the squared overlap integral of the electron and hole envelop wave functions $|I_{nm}|^2$.

$h\nu_{nm}$ (eV)	(n, m, k_z)	E_{cn} (eV)	E_{vm} (eV)	$\lvert I_{nm}\rvert^2$
1.221	(0,0h,0)	0.134	0.047	0.011
1.258	(0,0l,0)	0.134	0.084	0.048
1.309	(0,1h,π/d)	0.135	0.134	0.038
1.379	(0,2h,0)	0.134	0.205	0.109
1.402	(0,1l,π/d)	0.135	0.227	0.245
1.407	(1,0h,π/d)	0.319	0.048	0.207
1.442	(0,3h,π/d)	0.135	0.267	0.216
1.443	(1,0l,π/d)	0.319	0.084	0.388

Character of a tunability of the PL band and transformation of its shape under excitation of the superlattice at different temperatures are shown in Fig. 3. Increasing the temperature results in a smooth of the PL band. The tuning bandwidth reaches up to 0.4 eV. However, it has to mention that at low levels of excitation the intensity of the tunable PL band markedly decreases and it is masked by a broad emission band in the range of 1 eV. The observed additional broad PL band can be attributed to deep levels of residual impurities or related complexes [5]. Available peaks at the short-wavelength edge of the tunable PL band are evidently related to carbon, exciton recombination, and direct band–band transitions.

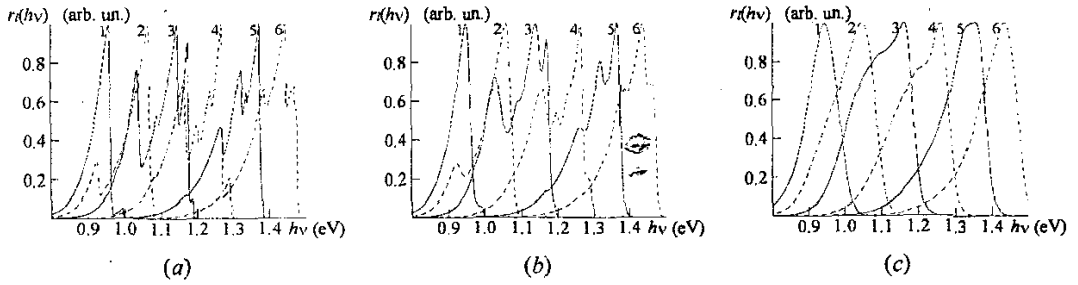

Figure 3 – Transformation of the PL spectrum $r_{sp}(h\nu)$ of the n–i–p–i structure at different temperatures (a) $T = 4.2$, (b) 20, and (c) 77 K versus the quasi-Fermi level difference (1) $\Delta F = 1.0$, (2) 1.1,. (3) 1.2, (4) 1.3, (5) 1.4, and (6) 1.5 eV. Simulation design parameters are listed in text.

ANALYTICAL APPROACH

Qualitative analysis can be provided in the frame of the sawtooth superlattice model [6, 9–11]. Analytical simulation of the redistribution of the energy subbands and, accordingly, of the optical transition quantum energies for a superlattice excited at low temperatures

approves and supports conclusions based on the above described more complex numerical calculations.

According to the effective impurity concentration approach the potential relief depth $2\Delta V$ of a quasi-δ-doped superlattice is described by the relation [7]

$$2\Delta V = 2\Delta V_0(1-r) = \frac{\pi e^2}{\varepsilon}\cdot\frac{N_\delta}{2}(d+2d_i)(1-r), \qquad (1)$$

where ε is the dielectric constant, $N_\delta = N_d d_n = N_d d_p$, $r = n/N_\delta$ is the excitation factor, n is the non-equilibrium concentration of electrons. The energy of quantizied levels depends also on the superlattice excitation power. For a sawtooth potential relief, the level energies can be calculated with the high enough accuracy using the effective mass approximation and transforming the Schrödinger equation into the Airy differential equation [9–11]. The Airy function asymptotic expansion approach [9] and variational calculations [6] provide almost the same results for the lowest several confined states. For the electron states E_{cn} we have analytically

$$E_{cn} = \left(\frac{3\pi}{4}\left(n+\frac{1}{2}\right)\right)^{2/3}\left(\frac{\pi e^2}{\varepsilon}\right)^{2/3}\left(\frac{2\hbar^2 N_\delta^2}{m_c}\right)^{1/3}(1-r)^{2/3} = E_{00}(2n+1)^{2/3}(1-r)^{2/3}, \qquad (2)$$

where the quantum number $n = 0, 1, 2, \ldots$, E_{00} is the ground electron state energy. Here, levels of the appeared minibands are not included, their width is assumed to be negligible small. Similar expressions are given for heavy and light hole states E_{vm}.

Thus, we obtain a simple expression for determining the energy $h\nu_{nm}$ of emitted quanta which are associated with transitions between electron states E_{cn} and hole states E_{vm}, i. e.,

$$h\nu_{nm} = E_g - 2\Delta V_0(1-r) + E_{00}(1-r)^{2/3}\left((2n+1)^{2/3} + \left(\frac{m_c}{m_{vi}}\right)^{1/3}(2m+1)^{2/3}\right), \qquad (3)$$

where E_g is the energy gap of the semiconductor, $i = h, l$ is the hole index. As seen, at increasing the superlattice excitation the quantum energy $h\nu_{nm}$ approaches E_g since the potential relief depth decreases, and the energies of various optical transitions become closer as a result of decreasing the energy levels which are involved in the transitions.

To find the relation between the quasi-Fermi levels F_e and F_h and to evaluate the excitation factor r, we use the electroneutrality equation for degenerate conditions which fulfillment at low temperatures, i. e.,

$$m_c\sum_n(F_e - E_{c0} - E_{cn}) = \sum_{m,i} m_{vi\perp}(E_{v0} - E_{vm} - F_h), \qquad (4)$$

where $E_{c0} - E_{v0} = E_g'$, $F_e - E_{c0} \geq E_{cn}$, $E_{v0} - F_h \geq E_{vm}$. In the parabolic band approximation, transverse components of effective hole masses are taken as $m_{vi\perp} = m_{vi}$. Calculations are carried out with the parameters such as $N_\delta = 1.5\times10^{13}$ cm^{-2}, $d = 19$ nm, $d_i = 6.8$ nm, $m_c = 0.067m_e$, $m_{vh} = 0.34m_e$, $m_{vl} = 0.094m_e$, $E_g = 1.519$ eV, $\varepsilon = 12.5$. In this case, the initial depth of the potential profile equals $2\Delta V_0 = 0.885$ eV.

At increasing the excitation of the superlattice, e. g., up to $r = 0.45$ and $\Delta F = 1.5$ eV, the relief depth becomes $2\Delta V = 0.487$ eV and current carriers occupy ground and excited

electron subbands and only ground heavy and light hole subbands. Therewith, the effective energy gap $E_g' = 1.032$ eV and a set of allowed optical transitions includes quantum energies 1.256, 1.300, 1.408, and 1.452 eV. The energies 1.256 and 1.300 eV are attributed to transitions between the ground electron ($n = 0$) and heavy and light hole ($m = 0$) subbands, and the energies 1.408 and 1.452 eV are associated with transitions from the excited electron states ($n = 1$) to the ground ($m = 0$) heavy and light hole subbands, respectively. It is in accordance with data [6] and numerical more precise self-consistent calculations (see Table 1).

CONCLUSION

Spectra of PL emission measured at 4.2 K display a structure shape with well-distinguished peaks which coincide with allowed optical transitions between quantizied levels of electrons and holes in the potential relief quantum wells. The developed theory with taking into account tails of the density of states explains experimental observations and shows that at increasing the temperature the quantized spectra behavior becomes less pronounced. The main attribute of doping superlattices, i.e., tunability of the emission spectrum in dependence on the excitation power is observed in a wide range 1.3 to 1.5 eV at the structure temperature up to 77 K. Tunable *n–i–p–i* structures can be attractive for integration with different optoelectronic devices, such as photoelectric detectors [12], quantum cascade lasers [13], or photonic crystal heterostructures [14].

The work was supported under joint Russian-Belarussian Fundamental Research Project No. 02-02-81036.

REFERENCES

1. E. F. Schubert, "Optical properties of δ-doped doping superlattices," *Surf. Sci.* 1990. Vol. 228, Nos. 1–3. P. 240–246.
2. G. Li, C. Jagadish, M. B. Johnston, M. Gal, "Growth of Si and C δ-doped *nipi* doping superlattices in GaAs by metal organic vapor phase epitaxy," *Appl. Phys. Lett.* 1996. Vol. 69, No. 27. P. 4218–4220.
3. M. B. Johnston, M. Gal, G. Li, C. Jagadish, "Photoluminescence study of the dynamical properties of GaAs sawtooth superlattices," *J. Appl.Phys.*1997.Vol.82,No.11.P. 5748–5752.
4. I. A. Karpovich, V. Ya. Aleshkin, A. V. Anshon, T. S. Babushkin, B. N. Zvonkov, I. G. Malkina, "Photoelectric properties of epitaxial GaAs/InGaAs quantum-well heterostructures," *Sov. Phys. Semicond.* 1990. Vol. 24, No. 12. P 1346–1348.
5. B. N. Zvonkov, V. Ya. Aleshkin, S. V. Morozov, V. I. Gavrilenko, D. M. Gaponova, V. K. Kononenko, V. N. Iodko, A. V. Mudryi, H. W. Kunert, D. Dale, "Optical characterizations of the GaAs quasi-delta-doped superlattices," *Materials IV Int. Sci.-Tech. Conf. on Quantum Electronics*. Minsk, 2002. P. 77-78.
6. E.F.Shubert,T.D.Harris,J.E.Cunningham,W.Jan, "Multisubband photoluminescence in sawtooth doping superlattices," *Phys. Rev. B.* 1989. Vol. 39, No. 15. P. 11011–11015.
7. V. K. Kononenko, I. S. Manak, D. V. Ushakov, "Optoelectronic properties and characteristics of doping superlattices," *Proc. SPIE.* 1998. Vol. 3580. P. 10–27.
8. D. V. Ushakov, V. K. Kononenko, I. S. Manak, "Effects of energy-spectrum broadening in alloyed semiconductor superlattices," *J. Appl. Spectrosc.* 1999. Vol. 66, No. 5. P. 820–825.

9. E. F. Shubert, B. Ulrich, T. D. Harris, J. E. Cunningham, "Quantum-confined interband absorption in GaAs sawtooth-doping superlattices," *Phys. Rev. B.* 1988. Vol. 38, No. 12. P. 8305–8308.
10. J. M. Ferreyra, C. R. Proetto, "Electronic band structure of GaAs sawtooth-doping superlattices," Phys. Rev. B. 1990. Vol. 42, No. 9. P. 5657–5664.
11. D. Ahn, "Intersubband transitions in a δ-doped semiconductor with an applied electric field: Exact solutions," Phys. Rev. B. 1993. Vol. 48, No.11 . P. 7981–7985.
12. B. Ulrich, C. Zhang, K. Klitzing, "Quantum-confined subband transitions of a GaAs sawtooth doping superlattice," *Appl. Phys. Lett.* 1989. Vol. 54, No. 12. P. 1133–1135.
13. J. Faist, A. Müller, M. Beck, D. Hofstetter, S. Blaser, U. Oesterle, M. Ilegems, "A quantum cascade laser based on an *n–i–p–i* superlattice," *IEEE Photon. Technol. Lett.* 2000. Vol. 12, No. 3. P. 263–265.
14. D. V. Ushakov, V. K. Kononenko, A. G. Smirnov, "Amplification in photonic crystal heterostructures with active media from doping superlattice layers," *Proc. 4th Int. Workshop LFNM 2002*. Kharkiv, 2002. P. 159–161.