Mid-infrared photoluminescence from structures with InAs/GaSb type II quantum wells

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Abstract. The results of experimental investigations of mid-infrared interband photoluminescence spectra from quantum well nanostructures based on InAs/GaSb/Al₀.₃₅Ga₀.₆₅As₀.₀₃Sb₀.₉₇ type II quantum wells in the wide temperature range from 10 K to the room temperature are presented. The photoluminescence line spectral positions are compared with the effective quantum well bandgap values obtained from the results of calculations of electron and hole energy states in quantum well. Analysis of the temperature dependence of the interband emission intensity allows to assume the presence of the traps near the middle of the effective energy gap. It is found that interband radiative recombination rate and nonradiative Shockley-Read-Hall rate are comparable.

1. Introduction

Type II heterojunctions have recently attracted considerable attention. The distinctive feature of these structures is the overlap of the one semiconductor valence band with conduction band of other one. The overlap of bands results in strong hybridization of states of one’s conduction band and valence band of other one. Type II heterojunctions can be formed by InAs/GaSb alternating layers. Quantum well (QW) for electrons would be formed in InAs layer and quantum well for holes would be formed in GaSb layer. Quantum wells and superlattices based on InAs/GaSb type II heterojunctions allow to create the photodetectors operating in mid-infrared spectral range [1-3], which are compete with HgCdTe-based devices. In the type II QWs, the spectral position of the interband absorption edge (or the luminescence line) is determined by the effective bandgap $E_{g\text{eff}}$ - energy gap between the ground electron and hole states, which are separated in the real space. Using the calculations of the electron and hole energy levels, one is able to design the necessary band profiles for devices operating in mid-infrared spectral range. Unfortunately, often the total error in $E_{g\text{eff}}$ corresponding to mid-infrared range could be the same order of magnitude as $E_{g\text{eff}}$ itself because of large dispersion of band structure parameters of the hetero-pair components in the reference data. In these conditions, the experimental investigation of the effective bandgap is very important task. In the present work, the effective bandgap value for InAs/GaSb type II QW is obtained from the study of the mid-infrared interband photoluminescence (PL) spectra at the different lattice temperatures. Additionally,
temperature dependence of the PL intensity allows one to obtain information about ratio between radiative and nonradiative lifetimes which define the performance of the many optical devices.

2. Samples and experimental setup

Sample for optical studies with type II QWs was MBE grown on GaSb substrate after a 500 nm GaSb buffer layer. Sample contains 20 periods GaSb/InAs/GaSb layers forming QWs for electrons and holes, separated with 20 nm Al0.35Ga0.65As0.03Sb0.97 lattice-matched barriers. Each period contains 4 nm InAs layer, forming QW for electrons. 25 nm GaSb layers are located on both sides of InAs layer forming QWs for holes. Finally, the structure covered by 25 nm undoped GaSb layer.

The potential profiles of the conduction band bottom and valence band top which determine the energy spectrum of electrons and holes in QWs along growth axis are shown in figure 1. The energy spectrum for our structure was calculated using the Schrödinger equation for the envelope function and transfer matrix method taking into account the mechanical stress in InAs layer. The values of material parameters were taken from paper [4], interpolation formula for parameters of alloys was taken from paper [5]. The calculated values of the band structure parameters for different crystal lattice temperatures \( T \) used in our energy spectrum calculations are shown in table 1. As it follows from table 1 the effective energy gap \( E_{g\text{eff}} \) for our structure decreases with the temperature increase. According to energy spectrum calculations only the one state for electrons (\( e1 \)) and one state for heavy holes (\( hh1 \)) are belong to our type II QW. These states are shown with the dashed lines on the figure 1.

For experimental studies the sample was mounted into the low vibration closed cycle cryostat based on the pulse tube thermodynamic cycle. Sample temperature can be varied from 10 K to 320 K. Interband optical excitation of the sample was attained through fused silica window by means the laser with \( \lambda = 1.064 \) µm, pulse duration 0.25 µs, repetition rate 8 kHz, maximum peak power about 30 W or by means the laser with \( \lambda = 532 \) nm, pulse duration 10 ns, repetition rate 10 Hz, peak power about 140 kW. The PL spectrum of the substrate was studied on a part of sample surface with the track from MBE holder leg. That part of the surface is left not covered by QW layers.
The mid-infrared photoluminescence spectra were studied using vacuum Fourier transform infrared spectrometer Bruker Vertex 80v operating in step scan mode. The photoluminescence intensity was measured by liquid nitrogen cooled HgCdTe-photodiode with cut-off wavelength about 12.5 µm equipped with the preamplifier. Spectrometer, cryostat and HgCdTe-photodiode were optically coupled using ZnSe windows. In order to block the pumping light, the high resistance Ge optical filter (transmittance of about 40% in the mid-infrared spectral range) was set in the front of the HgCdTe-photodiode. The photoresponse of HgCdTe-detector was measured by gated integrator SR250.

3. Experimental results and discussion

The photoluminescence spectra of the sample and its substrate studied in the spectral range 100-875 meV for the crystal lattice temperature \( T = 80 \) K (under optical excitation with wavelengths \( \lambda = 1.064 \) µm and \( \lambda = 532 \) nm) are shown in figure 2 (see the plot to recognize the curves). It should be noted that real emission spectra can slightly differ from spectra presented in our paper because of spectral dependency of photodetector sensitivity, windows, KBr-beamsplitter and Ge-filter transmission using in our experimental setup. In the sample PL spectrum under optical excitation with wavelength \( \lambda = 1.064 \) µm (please, see the bottom spectrum presented in figure 2) two peaks of radiation can be observed. The first peak shows a luminescence band lying in the spectral range from 180 - 260 meV near the effective bandgap calculated value (\( \Delta E_{\text{g eff}} \approx 217 \) meV for the 80 K). We associate above mentioned luminescence band with the \( e_1-hh_1 \) indirect in the real space radiative recombination of photoexcited electrons and holes in type II InAs/GaSb QWs. These optical transitions schematically shown on figure 1 with the red (online) arc arrows. The second peak with the photon energy about 700 meV could be connected with photoluminescence from bulk GaSb substrate. The high-energy part of this photoluminescence peak is determined by absorption in Ge-filter. Really, this peak does not observed on the PL spectrum for the sample under optical excitation with \( \lambda = 532 \) nm (please, see the middle curve on the figure 2). To understand that strong dependence of PL spectra from optical excitation wavelengths let us consider the sample design. The thickness of active layers containing QWs is 0.62 µm and about 70% of them consist of \( \text{Al}_{0.35}\text{Ga}_{0.65}\text{As}_{0.03}\text{Sb}_{0.97} \) barrier layers. The energy gap for this barrier layer at \( T = 77 \) K is 1.25 eV, so for the radiation with wavelength \( \lambda = 1.064 \) µm (\( \sim 1.16 \) eV) barrier layers are almost transparent (the absorption coefficient is very small). From the other side, for the radiation with \( \lambda = 532 \) nm (\( \sim 2.33 \) eV) the absorption coefficient in barrier is much greater. Thus radiation with \( \lambda = 532 \) nm doesn’t penetrate to the substrate and is absorbed in the nanostructure layers. When we excite with \( \lambda = 532 \) nm directly the substrate, the same luminescence band near 700 meV observing in the PL spectrum (please, see the top curve in figure 2).

The photoluminescence spectra of the sample under optical excitation with wavelength \( \lambda = 1.064 \) µm at different crystal lattice temperatures are presented in figure 3. The comparison of photoluminescence spectra for the different crystal lattice temperatures demonstrates the weak shift (within 40 meV) of the luminescence band to the lower photon energies region with the temperature increase from 10 K to 300 K. The shift of the luminescence band with temperature could be connected

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Table 1. Band offset parameter values for our structure at different crystal lattice temperatures.

| T, K | \( \Delta E_C \) (meV) | \( \Delta E_V \) (meV) | \( \Delta E_C \) (meV) | \( \Delta E_V \) (meV) | \( \Delta E_{g eff} \) (meV) |
|------|----------------|----------------|----------------|----------------|----------------|
| 10   | 967           | 561           | 246           | 204           | 226           |
| 77   | 967           | 561           | 246           | 204           | 217           |
| 300  | 945           | 561           | 246           | 204           | 160           |
with the change of the band offsets on the heterointerfaces of the QW with the temperature change. The spectral positions of PL peaks for different crystal lattice temperatures are in a good agreement with effective energy gap calculations for our type II QW structure presented in table 1. Corresponding to the different crystal lattice temperatures values of $E_{g}^{\text{eff}}$ are marked on figure 3 by arrows. Difference between the calculated effective energy gap values and the PL peak spectral positions can be explained by large dispersion of band structure parameters of the hetero-pair components for different temperatures in the reference data.

The temperature dependence of the integrated luminescence intensity for the interband transition $e_1$-$h_1$ in QW and its approximation (to recognize the curves see comments on the plot).

The temperature dependence of the integrated emission intensity $I^\nu$ related to $e_1$-$h_1$ optical transitions in QW under excitation with the wavelength $\lambda = 1.064 \, \mu$m is presented in figure 4 (points – the experimental data, line – approximation $I^\nu \sim T^{-m}$). The decrease of the interband luminescence intensity could be connected with the internal quantum efficiency decrease with the temperature increase. From fit line we can observe that spontaneous emission intensity $I^\nu$ varies as $I^\nu \sim T^{-m}$ (where $m \approx 0.7$). If $\tau_\nu$ – the charge carriers lifetime relative to nonradiative recombination, then $I^\nu = \frac{\Delta p}{\tau_\nu} = \frac{I_{\text{pump}} \cdot \tau_\nu}{\tau_\nu + \tau_{\text{SRH}}}$, where $I_{\text{pump}}$ – optical excitation intensity, $\Delta p$ – nonequilibrium charge carrier concentration, $\tau_{\text{SRH}}$ – nonradiative lifetime related to carrier capture on trap levels (Shockley-Reed-Hall lifetime (SRH) [6, 7, 8]), $\tau$ - charge carriers lifetime. If $\tau_\nu \ll \tau_{\text{SRH}}$ then $I^\nu$ doesn’t depend on temperature, and if $\tau_\nu \gg \tau_{\text{SRH}}$ then $I^\nu = \frac{I_{\text{pump}} \cdot \tau_{\text{SRH}}}{\tau_\nu}$. According to ref. [8] $\tau_\nu \sim T$ and $\tau_{\text{SRH}} \sim T^{-\frac{1}{2}}$ (when capture cross section $\sigma$ does not depend on temperature ($\tau_{\text{SRH}}^{-1} = \sigma \cdot M \cdot \sqrt{k_b \cdot T \sim T^{-\frac{1}{2}}}$, where $M$ – trap concentration, $k_b$ – Boltzmann constant)). $\tau_{\text{SRH}}$ varies like $T^{-\frac{1}{2}}$ if trap energy level for holes lies higher on energy than Fermi level for holes [6, 7, 8]. In this case $I^\nu \sim T^{-\frac{3}{2}}$. If $\tau_\nu$ and $\tau_{\text{SRH}}$ are comparable, then the dependence of the spontaneous emission intensity $I^\nu$ on temperature $T$ could be weaker and will better fit the experimental data, according to which $I^\nu \sim T^{-0.7}$.

Evaluation of the Fermi energy for the acceptor impurity concentration about $0.5 \cdot 10^{16}$ to $1 \cdot 10^{16}$ cm$^{-3}$, ionization energy $E_i \approx 0.03$ eV, hole effective mass about $m_h \approx 0.4 m_0$ (where $m_0$ – free electron mass
in vacuum) gives the trap energy level value about 0.1 eV. Thus, from the analysis of the temperature dependence of the spontaneous emission intensity it should be noted that lifetimes $\tau_{SRH}$ and $\tau_{n}$ are comparable, and traps are lying near middle of the effective energy gap $E_{geff}$.

Summary

In the present work, the interband photoluminescence spectra from quantum well nanostructures based on InAs/GaSb/Al$_{0.35}$Ga$_{0.65}$As$_{0.03}$Sb$_{0.97}$ type II QWs in mid-infrared spectral range and its temperature dependence were investigated. The quantum well nanostructure effective bandgap calculated value is in satisfactory agreement with the spectral position of interband photoluminescence line. The wavelength of emission line for the room temperature is about 180 meV (~ 6.8 µm). By means of the temperature dependence of the QW emission intensity analysis, the trap levels deepness and ratio between radiative and nonradiative (SRH) lifetimes were estimated. This work is partially supported by RFBR (Grant 13-02-12203) and the Ministry of Education and Science of Russian Federation.

References

[1] Haugan H J, Brown G J, Szmulowicz F, Grazulis L, Mitchell W C, Elhamri S, Mitchell W D 2005 Journal of Crystal Growth 278 198;
[2] Rehm R, Walther M, Schmitz J, Fleißner J, Fuchs F, Ziegler J, Cabanski W 2006 Opto-Electronics Review 14 19;
[3] Plis E A 2014 Advances in Electronics 2014 246769;
[4] Vurgaftman I, Meyer J R, Ram-Mohan L R 2001 Journal of Applied Physics 89 (11). 5815;
[5] Donati G P, Kaspi R, Malloy K J 2003 Interpolating Journal of Applied Physics 94(9) 5814;
[6] Shockley W., Reed W. T., Jr. 1952 Physical Review 87 835;
[7] Hall R. N. 1952 Physical Review 87 387;
[8] Vorobjev L. E., Danilov S. N., Zegrya G. G., Firsov D. A., Shalygin V. A., Yassievich I. N., Beregulin E. V. 2001 Photoelectric phenomena in semiconductors and dimensionally quantized structures ed. Il’in V. I. and Shik A. Ya. (Saint-Petersburg, Nauka) P. 236 (in russian).