Intersubband light absorption in double GaAs/AlGaAs quantum wells under lateral electric field

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Abstract. Spectra of variation of intersubband light absorption induced by lateral electric field and lattice temperature change were studied in the structure with double GaAs/AlGaAs quantum wells. The calculated positions of energy levels have been verified with interband photoluminescence measurements. The change in intersubband light absorption under lateral electric field was explained by the redistribution of hot charge carriers between the two lowest electronic states and by the subsequent emergence of space charge between quantum wells.

1. Introduction
Nowadays, investigation of intersubband light absorption in quantum wells attracts the scientific community’s attention. A lot of publications describe the influence of the electric field on the optical properties of the quantum wells, for example see Refs. [1–3]. The majority of papers are devoted to the analysis of transverse electric field effects. For example, Refs. [2–4] report the investigation of the effect of transverse electric field and temperature on intersubband light absorption in tunnel-coupled quantum wells. The electron redistribution between the size-quantization levels and a variation of the electron energy spectrum of quantum wells is stated as a cause of the observed absorption modulation. However, the effect of lateral electric field on the optical properties of tunnel-coupled quantum wells has not been adequately studied while it can heat electrons and, in turn, change intersubband absorption. The observed change in the intersubband absorption magnitude and spectra under strong heating lateral electric field in the single rectangular quantum wells was explained in Ref. [5, 6] by the real space transfer to the barrier and change of the electron exchange interaction due to their heating. The influence of nonparabolicity can also cause these changes. The electron heating effect on the photoluminescence spectrum was investigated in [7] under lateral electric field and intense optical pumping. However, the effect of lateral electric field on the optical properties of the double tunnel-coupled quantum well has not been extensively studied. This paper presents the original results on the stated phenomenon in double GaAs/AlGaAs tunnel-coupled quantum wells.

2. Sample and experiment
In order to estimate the electric field heating effect, the complex semiconductor structure was grown by molecular-beam epitaxy on a semi-insulating GaAs substrate. It contained 100 pairs of GaAs/Al_{0.38}Ga_{0.62}As tunnel-coupled quantum wells separated by 12 nm tunnel-nontransparent barriers. Each pair of tunnel-coupled quantum wells was formed by 5.6 nm and 4.0 nm GaAs layers separated by a 1.2 nm tunnel-transparent Al_{0.38}Ga_{0.62}As barrier (see figure 1). Quantum well layers were
uniformly doped with silicon up to the donor impurity concentration \( N = 5 \cdot 10^{17} \text{ cm}^{-3} \) (the surface impurity concentration in the quantum wells was \( N_d = 6 \cdot 10^{11} \text{ cm}^{-2} \)). Figure 1 schematically shows the potential profile of the conduction band of one period of tunnel-coupled GaAs/AlGaAs quantum wells at \( T = 77 \text{ K} \). During postgrowth processing, ohmic indium contacts were deposited on the sample. The contacts were made by annealing strips of indium deposited on the surface of the structure in nitrogen atmosphere. The sample was heated to the temperature \( T = 450 \, ^\circ \text{C} \) over a span of 2 minutes, and then cooled to room temperature. The facets of the sample were ground at 45° angle to create a multi-pass sample geometry. This sample geometry allows independent investigation of intersubband absorption of the light of two polarizations. The dimensions of the sample were chosen so that radiation passed 12 times through the quantum well layers. The total optical path length in the quantum-well layers was \( L = 11.5 \mu\text{m} \).

In order to perform the structure characterization and verification of the calculated energy level positions in quantum wells, the interband photoluminescence was studied. An automated monochromator Horiba Jobin Yvon FHR640 was used for photoluminescence studies. A liquid nitrogen cooled silicon CCD-camera served as a photodetector. A solid-state laser with a wavelength of 532 nm was used as a source of interband optical pumping. The sample was mounted into the liquid-nitrogen-cooled cryostat which allowed us to set the precise temperature in the range from 77 to 320 K. The input and output cryostat windows were made of fused silica due to its transparency in the near-infrared range.

The intersubband absorption spectra were studied using a Bruker Vertex 80v vacuum Fourier spectrometer. A built-in globar was used as a wideband infrared radiation source. A photovoltaic HgCdTe photodetector was chosen as a detector of radiation. The sample was mounted into the previously described liquid-nitrogen cryostat or into a Janis closed-cycle cryostat which allows the temperature to be maintained in the range of 4–320 K with an accuracy of 0.1°. The input and output cryostat windows made of ZnSe were selected because of ZnSe transparency in the mid-infrared range.

The absorption change under lateral electric field was measured in pulsed mode (electric field pulse duration was 250 ns with a duty cycle from 50 000 to 250 000). Since the signal of absorption change was rather small we used the averaged value derived from a large number of absorption spectra (30 - 100 counts). The results were obtained in two different ways. The necessity of secondary measurements will be discussed further in text. The first method of measurements consisted of acquiring the AC-coupled photodetector signal proportional to the transmission change for \( p \)-polarized light by an SR250 boxcar integrator synchronized with a pulse generator. The second used method involved measurements of time slices of DC-coupled photodetector signal proportional to the sample transmission. Change in transmission related to the electric field was obtained by subtraction of spectrum measured after the electric field pulse from the spectrum at the moment of the pulse. The transmission spectra were measured with a 25 ns time interval. The spectra measurements began 1.2
μs before and ended 25 μs after the 250 ns electric field pulse. This allowed us to estimate the contribution of lattice and electron heating. The main difference between the methods used is the signal sign sensitivity. For the first method, the transmission change signal can be of both signs. Application of the Fast Fourier Transform technique assumes the positivity of the resulting spectrum, therefore in our case the resulting signal change spectra do not contain absorption variation sign. Thus, the results require phase correction to discover the real modulation spectra. The procedure of phase correction is not a simple task and usually is uncertain. The second method is accurate in the sense of signal sign but is not so reliable in case of small signal values. Our implementation of both methods gave us the identical results and verified the phase correction procedure. The spectral resolution of the transmission spectra was about 3.5 meV in both measurement schemes.

Theoretical calculation of energy levels of electrons and holes and optical matrix elements of intersubband transitions in tunnel-coupled quantum wells was performed (see figure 1). The measured spectra of interband photoluminescence at $T = 300$ K and $T = 77$ K are presented in figure 2. At room temperature one can see the peaks associated with transitions between localized electron states and heavy hole and light hole states e1-hh, e2-hh2, e1-lh1. At liquid nitrogen temperature only one peak associated with transitions e1-hh1 can be observed due to the lack of electrons on the e2 level and holes on the lh1 level. The temperature shift of photoluminescence peaks is related to the bandgap change. The peak positions are in a good agreement with the results of energy spectra calculations for the structure with parameters stated above.

3. Results and discussions

According to the performed solution of the Schrödinger equation for electron energy levels at $T = 77$ K, the intersubband optical transitions e1-e3 and e2-e3 have energies of 187 meV and 135 meV, respectively. The transmission spectra of the structure were measured using multipass geometry for two different light polarizations ($p$ and $s$) at different lattice temperatures. According to the Bouguer–Lambert–Beer law, the intersubband absorption spectra were obtained as a ratio of transmission spectra of $p$- and $s$-polarized light. The absorption spectra for the different lattice temperatures are presented in figure 3. The calculated energies of intersubband transitions e1-e3 and e2-e3 at $T = 77$ K are shown with arrows. The temperature increase results in a slight red shift of these transition energies. A satisfactory agreement between calculations and experimental results is observed. At low lattice temperatures the charge carriers are mainly located at the ground subband thus only e1-e3 optical transitions can be observed in the measured spectra (the spectral position of optical transitions e1-e2 is located outside the photodetector sensitivity range). The electron concentration in the second electron subband e2 increases with increase in temperature which, in turn, causes optical transitions e2-e3. The observed shift of the intersubband absorption peaks to the longwavelength spectral region with temperature increase is connected with the change of the bandgap of the barrier and quantum well materials with the temperature and complies with calculations of the electron energy states. It should also be noted that the ground electron subband e1 is “genetically” connected with the wide quantum well while the second electron subband e2 is connected with the narrow quantum well. This fact can result in emergence of space charge and electric field between narrow and wide quantum wells which in turn can shift the peak positions.

The light transmission change under lateral electric field was obtained using two different experimental methods: as a spectrum of actual change of the signal, and as a difference of transmission spectra during the electric field pulse and without it. In the first case, transformation of the interferogram into the spectrum included the mandatory procedure of phase correction, because the standard Fourier spectroscopy method does not save information about a signal sign. The phase correction of the transmission change spectra is described more specifically in Refs. [3, 4, 8]. The measurements of the transmission spectra at the moments of the electric field pulse and without electric field were carried out mostly for confirmation of the phase correction results. The three-dimensional time and photon energy dependences of the $p$-polarized light intensity $I_p$ passed through the sample were obtained as a result of time-resolved step scan measurements. Time dependencies of
the intensity $I_p$ are presented in figure 4 for two certain photon energies $h\nu$ corresponding to the optical transitions $e_1$-$e_3$ ($h\nu = 187$ meV, curve 1) and $e_2$-$e_3$ ($h\nu = 135$ meV, curve 2), at the lattice temperature $T = 77$ K and electric field $E = 695$ V/cm. The first plot illustrates the fact that absorption associated with optical transitions $e_2$-$e_3$ increases, and absorption related to $e_1$-$e_3$ transitions decreases under electric field. A few microseconds after electric field pulse, the intensity $I_p$ returns to the equilibrium level which proves that lattice heating is negligible. Each transmission change spectrum was obtained as a difference between the spectrum under electric field in a moment of the maximum change in the transmitted light intensity $I_p$ ($t = 0.8 \mu$s in figure 4) and the spectrum without electric field. The 100 ns delay between the electric field pulse maximum and $I_p$ signal maximum can be associated with the response time of the photodetector used. The transmission change spectra of the structure under electric field obtained by both methods are identical which proves the feasibility of the chosen phase correction procedure.

Figure 2. Normalized interband photoluminescence spectra at temperatures 77 K (dashed curve) and 300 K (solid curve). Arrows mark the calculated energies of intersubband transitions $e_1$-$e_3$ and $e_2$-$e_3$ at $T = 300$ K.

Figure 3. Intersubband absorption spectra at different temperatures $T$. $L$ is optical path length. Arrows mark theoretically calculated transition energies at $T = 77$ K.

Figure 4. Time dependencies of light intensity passed through the sample at $T = 77$ K, $E = 695$ V/cm. Curve 1 and 2 were measured at quantum energies $h\nu = 187$ meV and $h\nu = 135$ meV which correspond to electron transitions $e_1$-$e_3$ and $e_2$-$e_3$, respectively.

Figure 5. Spectra of intersubband absorption change induced by different lateral electric fields at $T = 77$ K.
Figure 5 demonstrates the change in intersubband absorption spectra obtained at liquid nitrogen temperature at different lateral electric fields. The observed increase of absorption at the photon energy \( h\nu = 135 \text{ meV} \) is attributable to the heating of the first subband \( e_1 \) electrons by lateral electric field. As a result, nonequilibrium electrons occupy the upper electronic states and can populate the level \( e_2 \). An increase of the electron concentration in the second subband \( e_2 \) leads to an increase of intersubband absorption \( e_2-e_3 \) (\( h\nu = 135 \text{ meV} \)). The negative sign of modulation at the photon energy \( h\nu = 187 \text{ meV} \) can be attributed to the combined action of the absorption decrease and a shift of the \( e_1-e_3 \) absorption peak to longer wavelengths under lateral electric field. The observed modulation spectra correspond to the heating of the electron gas. Nonequilibrium hot electrons are being redistributed in the real space between two quantum wells. The consequent space charge variation leads to the change of energy level positions. Comparing the values of absorption variation \( \Delta\alpha_L \) induced by temperature change and \( \Delta\alpha_L \) induced by applied lateral electric field we were able to estimate the degree of electron heating: the electron temperature was \( T_e = 97 \text{ K} \) at \( E = 695 \text{ V/cm} \) and \( T_e = 103 \text{ K} \) at \( E = 1045 \text{ V/cm} \).

4. Conclusion

The intersubband light absorption in double tunnel-coupled GaAs/AlGaAs quantum wells in mid-infrared spectral range have been investigated under the conditions of applied lateral electric field. The temperature modification of the intersubband absorption spectra was studied as well. The redistribution of hot charge carriers between the two lowest electronic states under lateral electric field and subsequent emergence of space charge in the structure can cause the change in intersubband light absorption spectra. The electron temperature \( T_e \) was estimated. The value of the observed absorption variation suggests the application prospects of tunnel-coupled quantum wells as the basis for fast infrared light modulators.

Acknowledgments

The authors are grateful to A.N. Sofronov and V.Yu. Panevin for their help with the experiment preparation. This work was supported by the Russian Foundation for Basic Research (grants 14-02-00336, 14-02-31489) and the Ministry of Education and Science of the Russian Federation (state assignment).

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