Optical properties of GaAs/AlGaAs double quantum wells in lateral electric field

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Abstract. The influence of the lateral electric field on the mid-infrared intersubband light absorption and near-infrared interband photoluminescence is experimentally investigated in tunnel-coupled GaAs/AlGaAs quantum wells. Absorption and emission modulation in lateral electric field are related to the electron heating and redistribution of hot electrons between the quantum well states resulting in variation of the space charge in the structure.

1. Introduction

Electric field influence on the optical properties of semiconductor nanostructures is investigated for a long time. Transverse electric field applied along the structure growth axis changes the energy spectrum of the structure (quantum confined Stark effect). Rather strongly optical properties are influenced by the transverse electric field in the structures with tunnel-coupled quantum wells (QW) [1 - 3]. Effects of lateral electric field in quantum wells are not studied thoroughly enough. In the structures with a single rectangular quantum well, the application of lateral electric field can lead to a slight change in carrier concentration on the quantum-size levels related to carrier heating [4]. More complicated band structure of tunnel-coupled quantum wells facilitates the observation of the influence of carrier heating on the QW optical properties. The present paper is devoted to the results of electro-optical investigations in tunnel-coupled QWs under the lateral electric field. Spectra of intersubband light absorption and interband photoluminescence affected by the electron heating and redistribution of hot electrons between the quantum well states were studied. Earlier, the influence of lateral electric field on the photoluminescence (PL) spectrum was investigated in [5]. In contrast to our work, the modulation of PL in [5] was not directly connected with electron heating. Carrier heating effect on the intersubband absorption in tunnel-coupled quantum wells was studied in [6] at a fixed radiation wavelength. Comparing the effect of an electric field and lattice heating on the spectra of intersubband absorption and interband PL, we were able to estimate the temperature of the hot electrons.

2. Sample and experiment

The sample was MBE-grown on a semi-insulating GaAs substrate. The investigated structure consisted of 100 pairs of GaAs/AlGaAs tunnel-coupled QWs. Tunnel-transparent barrier (12 Å wide) separated 56 and 40 Å wide quantum wells. The barrier between pairs of QWs had a width of 120 Å. The quantum well layers were uniformly doped with Si to the donor concentration $N_d = 6 \cdot 10^{11}$ cm^{-2}. The calculated energy of $e1 - e3$ and $e2 - e3$ transitions at $T = 77$ K are 187 and 135 meV, respectively

(see inset in figure 1). We used material parameters taken from the review paper [7]. In order to characterize the structure, interband photoluminescence spectra without electric field were measured with Horiba FHR-640 grating monochromator paired with a Symphony II CCD-camera and YAG laser as a source of interband optical pumping. Spectra of PL modulation in electric field were studied with another grating monochromator and Si detector.

The intersubband absorption was measured in a multi-pass sample geometry where two 45 degrees beveled facets and the substrate side of a sample were polished to allow multiple total internal reflections. Electric field was applied using indium contacts created on the surface of the sample. In order to avoid sample overheating, the lateral electric field was applied to the sample in pulsed mode (electric field pulse duration was 250 ns with a duty cycle from 50 000 to 250 000).

The absorption spectra were obtained using Bruker Vertex 80v vacuum Fourier transform infrared spectrometer. Globar was used as a source of broadband infrared radiation. A photovoltaic HgCdTe photodetector was chosen as a detector of radiation. Infrared absorption coefficient α was determined by taking the ratio of the transmission spectra T of TM and TE-polarized light: $\alpha L = - \ln(T_{TM}/T_{TE})$, were L is the optical path length. According to the polarization selection rules intersubband optical electron transitions can occur only upon exposure to the light with a polarization vector component directed along the structure growth axis, i.e., upon exposure to TM-polarized light. No significant absorption was observed in mid-infrared spectral range for TE-polarized light. The sample was placed in the closed cycle cryostat which allows the temperature to be maintained in the range of 4–320 K with an accuracy of 0.1°. Spectra of absorption modulation under lateral electric field were measured with Fourier transform spectrometer in step-scan mode.
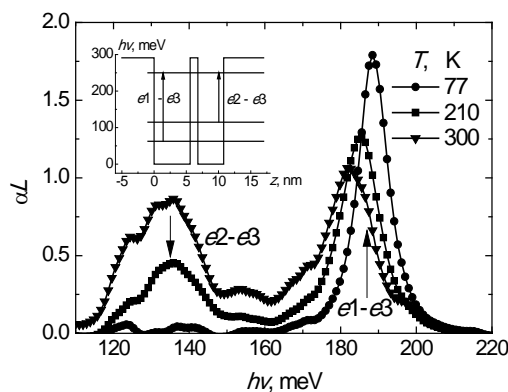

Figure 1. Intersubband absorption spectra at different lattice temperatures, L is the optical path length. The arrows indicate the calculated electron transition energies at $T = 77$ K. Inset shows the potential profile of one GaAs/AlGaAs QW pair at $T = 77$ K.
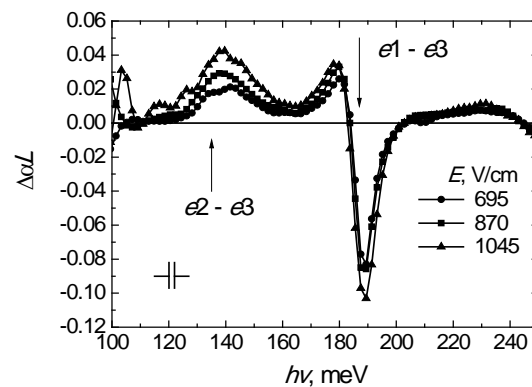
Figure 2. Spectra of intersubband absorption modulation under different lateral electric fields E at $T = 77$ K. The arrows indicate the calculated electron transition energies.

3. Results and discussions

The interband photoluminescence spectra without application of electric field were measured at different lattice temperatures. Spectral peaks demonstrate a temperature shift corresponding to the bandgap change. At room temperature, three peaks corresponding to the electron transitions $e1$-$hh1$, $e2$-$hh2$ and $e1$-$lh1$ were observed. At liquid nitrogen temperature only one peak associated with transitions $e1$-$hh1$ was registered due to the lack of electrons on the $e2$ level and holes on the $lh1$ and $hh2$ levels. The spectra are in a satisfactory agreement with the calculated energy spectrum.

The spectra of intersubband light absorption for different lattice temperatures without applied electric field are shown in figure 1. At low temperatures, there is only one peak associated with the

optical transitions $e1$-$e3$, which means that the carriers are localized mainly at the level $e1$. When the temperature rises, carriers begin to fill the overlying energy level. The observed longwavelength shift of the $e1$-$e3$ absorption peak with the temperature increase is primarily associated with temperature dependence of the conduction band potential profile of QWs. In addition, the space charge changes the structure potential due to the redistribution of carriers between QWs with the temperature increase.

The modulation of absorption under lateral electric field was measured at $T = 77$ K using two different experimental methods: i) direct measurement of only the transmission variation signal and ii) measurement of signals under lateral electric field and without it with subsequent comparison of these signals. 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 case of the first method the spectra of resulting signal change do not contain the information about the sign of absorption variation. Thus, this technique requires phase correction procedure to obtain the real modulation spectra. The procedure of phase correction is described more specifically in [1, 8]. The second method is accurate in the sense of signal sign but is not so reliable in case of small signal values. The three-dimensional time and photon energy dependences of the TM light transmission were obtained as a result of the second method implementation. 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. Modulation of intersubband absorption coefficient $\Delta\alpha$ in electric field was determined by taking the ratio of the TM light transmission spectra change measured under the electric field and in equilibrium conditions: $\Delta\alpha \cdot L = -\ln(\Delta T_{TM}(E) / T_{TM}(E=0) + 1)$. The absorption associated with optical transitions $e2$-$e3$ increases in electric field (see figure 2). This can be explained with the increase of the carrier concentration at the electron level $e2$. Absorption related to $e1$-$e3$ transitions changes due to the decrease of $e1$ concentration and due to the shift of the $e1$-$e3$ absorption peak to longer wavelengths under lateral electric field. Nonequilibrium hot electrons are being redistributed in the real space between the states of two quantum wells. Comparing the absorption variation $\Delta\alpha L$ induced by temperature change (see figure 1) and $\Delta\alpha L$ induced by lateral electric field (see figure 2) we were able to estimate the level of electron heating. The experimentally determined electron temperature was $T_e = 97$ K at $E = 695$ V/cm and $T_e = 103$ K at $E = 1045$ V/cm.
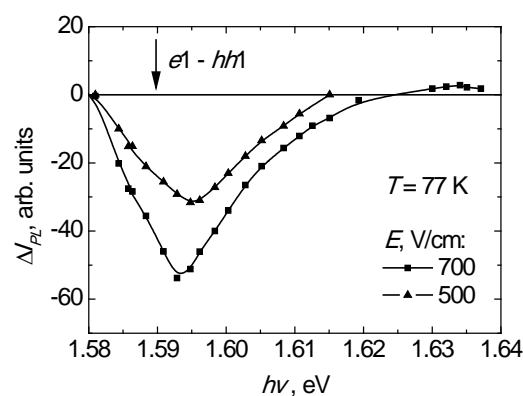

Figure 3. Modulation of interband photoluminescence at $T = 77$ K under lateral electric field E. Arrow shows the calculated energy of interband $e1$-$hh1$ transitions.

The interband photoluminescence variation spectra were measured at different lateral electric fields at $T = 77$ K. The hot carrier temperature was not high enough to significantly change the concentration of carriers at hole and electron levels $lh1$, $hh2$ and $e2$. Only modulation of interband photoluminescence associated with the $e1$-$hh1$ optical transitions was observed (see figure 3). It

should be noted that interband PL modulation was observed at high level of optical pumping. High nonequilibrium carrier concentration is created in such conditions, therefore we can consider the equality of electron and hole temperatures due to strong electron-hole scattering. The electron temperature T_e was estimated by means of the shortwave spectra shoulder analysis. To derive T_e value one should obtain the energy value $h\nu_0$ which corresponds to the zero photoluminescense modulation $\Delta I_{PL} = 0$ or, in other terms, $dI_{PL}/dT_e = 0$. Photoluminscense intensity I_{PL} is proportional to the number of spontaneous interband radiation quanta originating from elementary volume during elementary time period at the frequency range from ν to $\nu + \Delta\nu$. Therefore one can obtain nonequilibrium charge carrier temperature using Boltzmann distribution function: $T_e = (h\nu_0 - \varepsilon_g)/2k$, were k is Boltzmann constant, ε_g is effective band gap. The relative increase of electron temperature due to the heating was determined to be about 30 K. This temperature was close to the temperature obtained from the analysis of intersubband absorption modulation spectra.

4. Conclusion

The influence of the lateral electric field on the mid-infrared intersubband light absorption and near-infrared interband photoluminescence in tunnel-coupled GaAs/AlGaAs quantum wells is experimentally observed. The temperature modification of the intersubband absorption spectra was studied as well. Modulation of intersubband absorption and interband photoluminescence under lateral electric field is explained by redistribution of hot charge carriers between the two lowest electronic states belonging to different quantum wells off the pair and by subsequent variation of space charge in the structure. The electron temperature T_e was estimated from the comparison of equilibrium intersubband absorption spectra and modulation of absorption spectra under lateral electric field. The analysis of interband photoluminescence modulation spectra allowed us to derive electron temperature and compare it with temperature value obtained from the absorption spectra analysis. These temperature values were close. The value of the observed absorption variation suggests the application prospects of tunnel-coupled quantum wells as the basis for fast infrared light modulators.

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