Intersubband absorption modulation in the GaAs/AlGaAs double tunnel-coupled quantum wells

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Abstract. Structures with multiple doped double tunnel-coupled GaAs/AlGaAs quantum wells were grown and formed in mesa configuration. Positions of the energy levels have been verified with interband photoluminescence measurements. Temperature modulation of the intersubband absorption spectra was registered. Intersubband absorption modulation under transverse electric field was detected and explained.

1. Introduction

Recently, the fast frequency modulation of the radiation of quantum cascade lasers (QQL) was suggested for the use in communication [1]. Such modulation type increases the signal / noise ratio at heterodyne reception as compared with amplitude modulation [2] and allows the weatherproof optical communication over long distances. Frequency modulation of laser radiation can be realized if we embed system of tunnel-coupled quantum wells in QQL waveguide. Transverse (vertical) electric field applied in the growth direction changes the absorption coefficient of light polarized along the growth axis of the structure [3], and simultaneously changes the dielectric constant of the layer [4-7]. The change of layer refraction index leads to the change of radiation frequency. The change of intersubband light absorption in vertical electric field can be associated with two factors. The first one is the Stark shift of energy levels. In stepped and tunnel-coupled QWs the Stark shift can be rather strong (see theoretical works [8, 9]). Besides, transverse electric field can redistribute electrons between energy levels resulting in additional absorption modulation.

This work is devoted to the investigation of intersubband absorption modulation in double tunnel-coupled QWs GaAs / AlGaAs induced by the application of transverse electric field.

2. Sample and experiment

The structure was MBE grown on semi-insulating GaAs substrate and contained 100 pairs of double tunnel-coupled GaAs/AlGaAs QWs. The width of the quantum wells and alloy composition of the barriers were chosen in order to have three levels of dimensional quantization in the QWs system. The narrow and wide quantum wells have widths of 4.5 and 6.6 nm, respectively; the barrier $Al_{0,25}Ga_{0,75}As$ is 3 nm thick. The energy gap between the electronic levels e1 and e2 is about 30 meV. The energy of the e1-e3 transition is about 125 meV, energy of e2-e3 transitions is about 95 meV. Doping with silicon was performed in the central part of the wide quantum well (~2.5 nm) resulting in surface electron concentration of about $4 \cdot 10^{11}$ cm^{-2}. The highly doped (10^{18} cm^{-3}) GaAs layers were created above and under the QW layers in order to ensure effective electric field application. The thicknesses of these layers are 1.5 and 0.5 μm, respectively. Mesa was etched on the surface of structure at the stage of post-growth processing to ensure access to the lower contact layer. AlGaAs stop-layer above the lower doped layer was used to stop the selective etching of the structure.

It is well known that the normal incidence geometry of the experiment is not suitable for the intersubband absorption investigation due to selection rules. So, Brewster's or multipass geometry configuration should be used. Preliminary studies of intersubband absorption at Brewster's angle incidence showed the low level of absorption and presence of interference of *s*-polarized light on thin film. Therefore, the multipass geometry of experiment was chosen. Two opposite edges of the sample were ground away at a 45 degrees angle (see figure 1). It resulted in an increase of the optical path length and an improvement of the measurements accuracy.

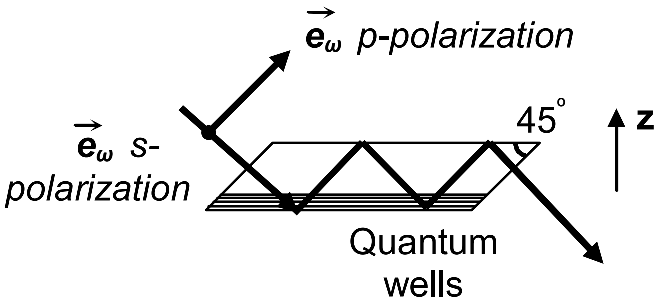

Figure 1. Multipass geometry scheme.

The samples were characterized by the investigation of the interband photoluminescence (PL) with a Horiba Jobin Yvon FHR640 monochromator. A CCD-camera Symphony II was used as a detector. A solid-state YAG laser with 532 nm radiation wavelength was used for pumping. The samples were placed in a liquid nitrogen bath cryostat. It allowed operating in the temperature range from 77 to 300 K.

The spectra of intersubband absorption were obtained with a vacuum Fourier transform spectrometer Bruker Vertex 80v paired with different photodetectors (MCT, pyroelectric, silicon bolometer). A globar was used as a source of infrared radiation. The sample was placed into a closed cycle cryostat Janis PT407RM with operational temperature range of 4–320 K and a temperature setting accuracy of 0.1 degrees.

3. Results and discussions

The interband photoluminescence spectra were measured in order to determine the real electron energy spectrum of the structure. The investigations were carried out at different temperatures and different optical pumping levels for the structure as-grown (curve 1, figure 2) and for the structure with a removed doped surface layer (curve 2, figure 2). It was found that the heavily doped surface GaAs layer significantly changes the PL spectrum. The obtained positions of the PL peaks of the structure without the top conductive layer are in a good agreement with the theoretical calculation of electron transition energies at room temperature: e1-hh1 = 1,486 eV and e2-hh2 = 1,525 eV.

The photoluminescence spectra of the structure without doped GaAs layer were then measured for various lattice temperatures (77-300 K) and different levels of optical pumping. Figure 3 shows the PL spectra for optical pump power about 550 mW. The photoluminescence spectrum shift to longer wavelengths with increasing temperature is associated with a decrease of the bandgap. Also, the temperature increase causes the changes of the carrier distribution function. It results in the increase of the electron concentration at the second electron level, therefore, transitions e2-hh2 become possible (see figures 2 and 3).

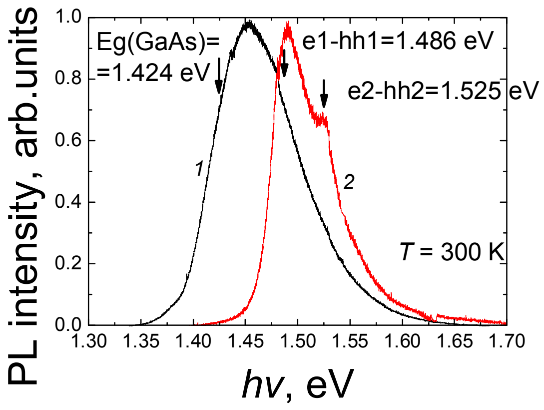

Figure 2. Normalized photoluminescence spectra of structures with tunnel-coupled GaAs/AlGaAs QWs at room temperature: structure with top doped layer (curve 1); structure without doped surface layer (curve 2). The arrows show the calculated energies of corresponding carrier transitions and the bandgap of GaAs. Optical pumping power was about 200 mW.

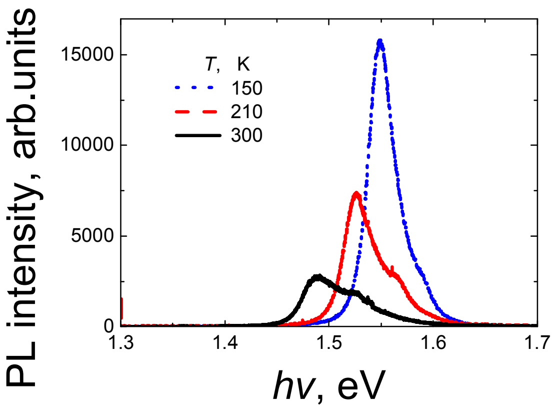

Figure 3. The photoluminescence spectra of tunnel-coupled QWs GaAs/AlGaAs without top doped GaAs layer at different temperatures. Spectral resolution was less than 1 meV.

The intersubband absorption spectra were studied for two light polarizations (*s* and *p*) in multipass geometry (see figure 1) for the temperature range of 4 to 300 K. According to the intersubband transitions selection rules, only *p*-polarized light (which has the polarization component along the structure growth axis) can be absorbed by QW layers. The typical transmission spectra for two light polarizations at 4 K is presented in figure 4. The absorption peak for *p*-polarized light (~130 meV) corresponds to the electron transitions from the ground subband e1 to the third subband e3. Its position is in a good agreement with the theoretical calculation of e1-e3 transition energies.

The spectrum of *p*-polarized light transmission (I_p) was normalized to the spectrum for *s*-polarized light (I_s) in order to estimate the intersubband absorption of quantum wells only (α_{QW}). According to the Beer–Lambert–Bouguer law,

$$\ln(\frac{I_p}{I_s}) = \ln(\exp((\alpha_p - \alpha_s)L)) = (\alpha_p - \alpha_s)L = \alpha_{QW} L\,, \qquad (1)$$

where L is optical length. Figure 5 shows the intersubband absorption spectra at different temperatures.

The absorption peak at approximately 135 meV (see figure 5) corresponds to e1-e3 electron transitions. Absorption related to these transitions decreases with the temperature. Simultaneously temperature increase leads to an increase of the absorption intensity at the wavelength corresponding to e2-e3 transitions but we were not able to study light absorption in this spectral range. We associate variation of absorption with redistribution of electrons between electron levels e1 and e2. Slight broadening of the e1-e3 peak with increasing temperature can be attributed to the thermal broadening of the electron levels. Thus, the influence of the change of lattice temperature on the light absorption is similar to the influence of the vertical electric field.

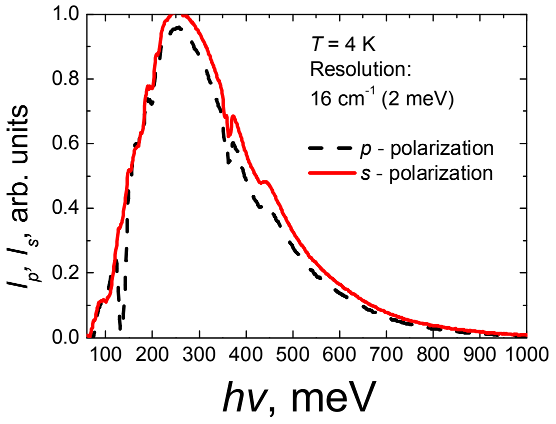

Figure 4. Transmission spectra of tunnel-coupled GaAs/AlGaAs QWs for *p*- and *s*-polarized light (dashed and solid line) at 4 K. Spectral resolution was about 2 meV.

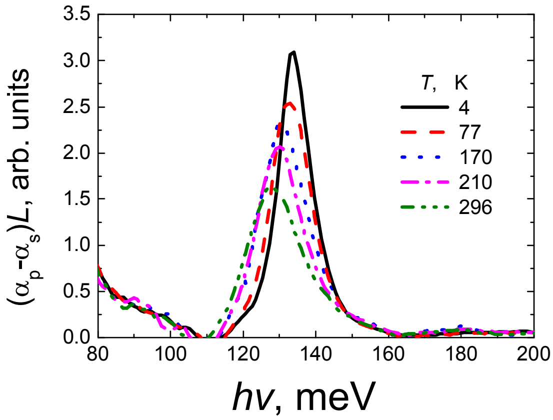

Figure 5. Intersubband absorption spectra, measured at different temperatures.

We also studied the spectra of intersubband absorption modulation under the conditions of transverse electric field application for *p*-polarized light in multipass geometry at liquid nitrogen temperature (figures 6 and 7). As expected, electro-optic modulation was not registered in the investigated spectral range for *s*- polarized light.

We have not found significant changes in absorption in the electric field of negative polarity (see figure 7). It can be explained by the fact that negative electric field does not change the relative position of the levels e1 and e2 (see inset in figure 7). In the positive electric field, a decrease of absorption associated with e1-e3 transitions was observed (see figure 6). This can be attributed to the transitions of the carriers from the ground QW level e1 to the second QW level e2 (see inset in figure 6). The spectra for the voltage value of 20 V and 25 V are almost identical. This saturation of modulation can be explained by the complete redistribution of carriers from level e1 to e2.

4. Conclusion

The optical properties of double tunnel-coupled GaAs/AlGaAs quantum wells in mid-infrared spectral range have been investigated under the conditions of applied vertical electric field. Intersubband absorption modulation was registered and attributed to the electrons redistribution between first two energy levels. The temperature modification of the intersubband absorption spectra was studied as well.

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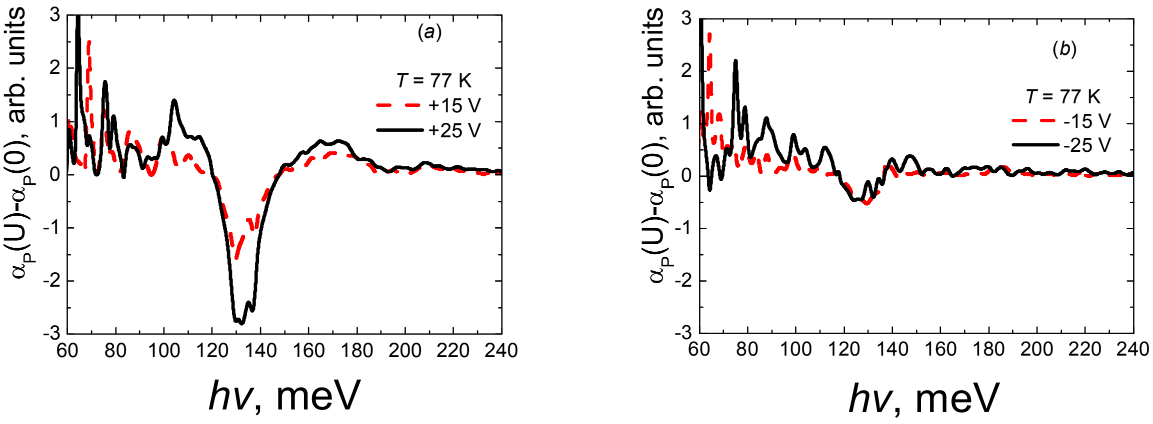

Figure 6. Modulation of intersubband absorption spectra under positive (*a*) and negative (*b*) transverse electric field.

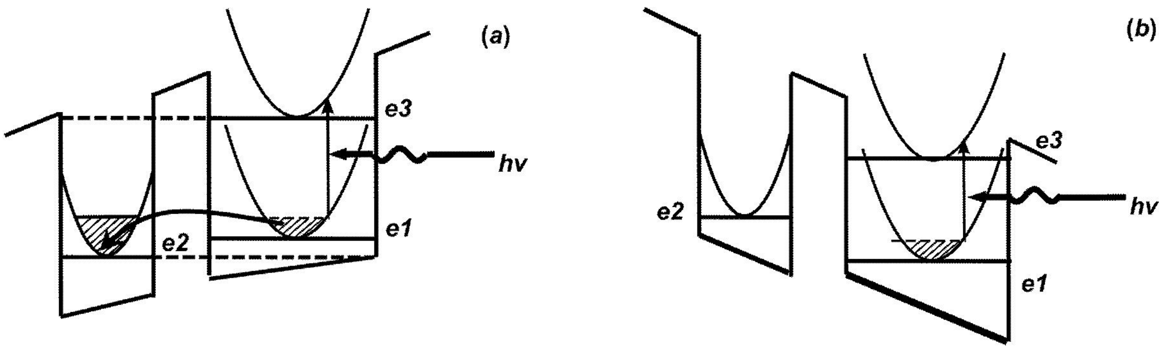

Figure 7. Redistribution of electrons in real space in the system of double tunnel-coupled QWs caused by positive (*a*) and negative (*b*) transverse electric field.

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