Intersubband light absorption in tunnel-coupled GaAs/AlGaAs quantum wells for electrooptic studies

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\textbf{Abstract.} Structures with doped multiple tunnel-coupled quantum wells GaAs/AlGaAs were grown. They were designed to investigate the intersubband absorption and modification of absorption spectra under transverse electric field. The samples were formed in mesa configuration. Preliminary results for the temperature modification of the intersubband absorption spectra were obtained.

1. Introduction
The optical properties of nanostructures with quantum wells (QW) change under the electric field influence. Study of optical properties under electric field associated with the intersubband electron transitions in tunnel-coupled quantum wells attracts attention due to the need of development of optoelectronic mid-IR devices (detectors and sources of radiation). Longitudinal electric field applied in the plane of the QW structure can heat the electrons, therefore electron distribution between the conduction band subbands may change. Changes in optical properties can be expected in this case \cite{1}. Transverse electric field applied along the growth axis of the QW structure can influence QW optical properties more significantly. It changes the QW potential profile, which can cause not only the redistribution of electrons between the subbands in the conduction band, but also a spectral shift of the intersubband absorption peaks and changes of the spectral peak width \cite{2}. The changes of the real part of dielectric permittivity of QW layers under the electric field can be used, for example, for the fast frequency modulation of the quantum cascade laser emission.

This work presents the results of design development of samples with tunnel-coupled quantum wells, intended to investigate the intersubband absorption under transverse electric field. Preliminary experimental results show changes of spectra with temperature which can be connected with the redistribution of electrons between subbands.

2. Sample and experiment
Structure was MBE grown on semi-insulating GaAs substrate and contained 100 pairs of double tunnel-coupled quantum wells GaAs/Al\textsubscript{0.25}Ga\textsubscript{0.75}As. The narrow and wide quantum walls have widths of 4.5 and 6.6 nm, respectively; the barrier is 3 nm thick (see schematic representation of the conduction band at figure 1). According to the theoretical calculations, the distance between the first two subbands e\textsubscript{1} and e\textsubscript{2} is about 30 meV. It is known that intersubband selection rules for electron transitions are not applicable in case of tunnel-coupled quantum wells. The energy of the e\textsubscript{1}-e\textsubscript{3} transition...
transition is about 125 meV, energy of e2-e3 one is about 95 meV. The wide quantum well was doped with Si in the central part of quantum well (~2.5 nm) up to the surface electron concentration of $4 \times 10^{11}$ cm$^{-2}$. The active area containing quantum wells was located between the doped GaAs contact layers with electron concentration of $10^{18}$ cm$^{-3}$. The top and bottom contact layers have a thickness of 1.5 and 0.5 μm, respectively. There is Al$_{0.9}$Ga$_{0.1}$As stop-layer right above the doped bottom layer that stops the selective etching of the structure.

Let us note that the application of the transverse electric field leads to the bending of valence and conduction bands (see fig. 1). Thus one quantum well shifts in relation to the other quantum well. In the equilibrium the transitions from the ground state of the wide quantum well e1 to the states with higher energy e2, e3 will primarily take place. If we apply electric field of enough magnitude, then the position of the ground state of narrow quantum well e2 may match the position of the ground state of wide quantum well e1. If we continue to increase the electric field, then ground state of narrow quantum well can become lower than the ground state of wide quantum well. In this case transitions from the ground state of the narrow quantum well e2 to the upper subband e3 will be more pronounced.

![Figure 1. Influence of the transversal electric field on the intersubband absorption in tunnel-coupled quantum wells.](image)

Postgrowth processing of structures included standard contact photolithography (direct and explosive), ion beam etching and chemical etching. Mesa structure with 7x10 mm$^2$ size was etched. The image from the light mask to the structure was transferred using the photoresist AZ 4562 mask with beam of Ar$^+$ ions from the ion beam etching equipment MIM TLA2 (Technics). The ion etching was 2.8 μm deep. After that structure was etched to the stop-layer using the selective chemical etching. A mixture of sodium citrate (Na$_3$S$_6$H$_5$O$_7$) and 33% hydrogen peroxide (H$_2$O$_2$) at a ratio of 5:1 was used as an etchant. The stop layer was removed by the mixture of HCl:H$_2$O = 10:1. The Cr(400Å)-Au(4000Å) conductive pads were formed using two-layer resist (LOR10B and AZ 1518) mask by thermal vacuum deposition on the VUP-5M equipment. Multipass sample geometry was created in order to study the absorption of s- and p-polarized emission separately.

Intersubband absorption spectra were studied using vacuum Fourier spectrometer Bruker Vertex 80v for two polarizations of light (s- and p-). The globar was used as a source of infrared light emission. The absorption signal was measured with the pyroelectric detector. The sample was placed in the closed-cycle cryostat Janis PTCM-4-7 that allowed us to obtain results in temperature range from 4 to 320 K.
3. Results and discussions

Scanning electron microscope (SEM) image of the cross-section of the structure is shown in figure 2. The active region that contains 100 double tunnel-coupled quantum wells and etched top and bottom contact layers are clearly visible. The walls of the mesa structure are not vertical, since the proposed measurement technique does not require it.

![Figure 2. SEM image of the cross-sectional mesa structure.](image)

The intersubband absorption spectra for different lattice temperatures are shown in figure 3. In accordance with the intersubband transitions selection rules, the absorption of radiation is possible only for the $p$-polarized light (which has the polarization component perpendicular to the plane of the structure). The shortwave absorption peak (see figure 3) corresponds to the electron transitions from the ground subband $e_1$ to the third subband $e_3$. Its position ($e_1-e_3 = 130$ meV for temperature of liquid helium) is in a good agreement with the theoretical calculation. Position of the longwave absorption peak has a deviation from the calculation results. We attribute it to some minor discrepancy in the calculation parameters. Both subbands ($e_1$ and $e_3$) are localized mainly in the wide quantum well. Change of lattice temperature partially simulates the effect of the electric field. Small distance between the first two subbands $e_1$ and $e_2$ results in the increase of the population of the second subband with the temperature.

![Figure 3. Intersubband absorption spectra ($L$ - optical length), measured at different temperatures.](image)
Analogous investigations have been carried out for a similar structure, but with wider quantum wells with another solid solution composition: GaAs/Al$_{0.38}$Ga$_{0.62}$As. The intersubband absorption spectra for different lattice temperatures for this model structure are shown in figure 4. One can observe the appearance of the intersubband peak near 130 meV and its increase with temperature. Its nature also can be explained by the redistribution of electrons from the ground state of quantum well to the second subband due to the small energy gap between them. So we attribute this peak at 130 meV to the transition e2-e3. At low temperatures (4-77 K, fig. 4), electrons are mainly located in the ground state and only transitions e1-e3 are possible.

The observed temperature modification of the absorption spectra indicates the decrease in the electron density on the first subband with the temperature that corresponds to the filling of the second subband.

![Figure 4](image-url)

**Figure 4.** Intersubband absorption spectra ($L$ - optical length), measured at different temperatures for similar structure.

**Acknowledgments**
This work has been supported by the Russian Foundation for Basic Research (Grants № 14-02-31489, 14-02-00336).

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