Refractive index modulation induced with transverse electric field in double tunnel-coupled GaAs/AlGaAs quantum wells

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Abstract. Modulation of refractive index under transverse electric field was studied in structures with multiple tunnel-coupled GaAs/AlGaAs quantum wells in the spectral range corresponding to intersubband light absorption. The change of refractive index in electric field was calculated using Kramers-Kronig relation and experimentally determined spectra of intersubband light absorption in equilibrium conditions and under transverse electric field.

1. Introduction

Quantum cascade lasers are efficient radiation sources. They cover wide spectral range, and can be used in data transmission systems in infrared spectral range. In order for their performance to be efficient, an effective and easy to implement modulation system should be introduced [1]. In case of GaAs/AlGaAs-based quantum cascade lasers there is a way to create frequency modulation system by introducing the layers with tunnel-coupled quantum wells (QW) into the laser waveguide. Application of transverse electric field to the tunnel-coupled QW can induce intersubband absorption modulation, which, in turn, will produce refraction index modulation. Lattice temperature variation can have the same effect in the lesser extent. Here we present the results of the investigation of transverse electric field influence on intersubband light absorption in GaAs/AlGaAs tunnel-coupled QWs and calculation of refraction index modulation in these conditions.

2. Sample and experiment

The investigated structure contains 100 pairs of tunnel-coupled GaAs/Al$_{0.25}$Ga$_{0.75}$As QWs. It was grown using molecular beam epitaxy on semi-insulating GaAs substrate. The narrow and wide quantum wells have widths of 4.5 and 6.6 nm, respectively; the barrier between them is 3 nm thick. Structure was selectively doped in the wider QWs up to the surface electron concentration of $4 \cdot 10^{11}$ cm$^{-2}$. Potential profile of the conduction band is shown in figure 1. The energies of the levels of size quantization were calculated using the self-consistent solution of the Schrödinger and Poisson equations. The space charge emergence due to partial ionization of the donor impurity and the electron
The investigated structure contains three electron levels of size quantization. The energy of the $e_1-e_3$ transition is about 125 meV (corresponding to wavelength approximately of 10 μm), energy of $e_2-e_3$ transition is about 95 meV at liquid nitrogen temperature. Third electron level is close to the continuous spectrum, which leads to a significant modification of its wave function under transverse electric field and causes the absorption modulation increase. In order to apply transverse electric field mesa structure with 7x10 mm dimensions was etched on the surface of structure at the stage of post-growth processing. Al$_{0.9}$Ga$_{0.1}$As stop layer was grown right above the doped bottom layer to stop the selective etching of the structure. For detailed information about postgrowth processes (mesa etching, contacts coating, sample processing in multipass geometry) see [2]. Multipass geometry was formed in such manner that light passed through the QW layers 4 times.

**Fig. 1. Potential profile of the conduction band of structure.**

Structure characterization was performed using photoluminescence (PL) spectra obtained with Horiba Jobin Yvon FHR640 monochromator with CCD-camera Symphony II as a detector. Interband pumping was performed with 532 nm YAG laser. Vacuum Fourier transform spectrometer Bruker Vertex 80v with different photodetectors (MCT, pyroelectric, silicon bolometer) was used to obtain equilibrium intersubband absorption spectra. Closed cycle cryostat Janis PT407RM with operational temperature range of 4–320 K and a temperature setting accuracy of 0.1 degrees was used in the experiment. Modulation spectra under transverse electric field were obtained in step-scan spectrometer mode with boxcar integrator and current preamplifier added to the experimental setup. We used two ADC inputs in the measurements: one to record interferogram of modulation spectra, and the other one to register interferogram and phase of equilibrium spectra. Due to conjugation properties of Fourier transform, positive and negative modulation signals are indistinguishable in the interferogram. In order to determine true signal sign the phase correction of modulation spectra was performed using the phase spectra of interferogram of equilibrium spectra which is positive in the spectral region in question.

### 3. Results and discussions

Photoluminescence spectra were measured for original structure. Analysis shows that there is a significant spectral shift of the PL maximum from the position of the GaAs band gap. The value of spectral shift corresponds to the Fermi level of the doped GaAs top layer of the structure. Thus we can conclude that the observed PL originates in the bulk GaAs surface layer. Mechanical removal of this heavily doped top layer allowed us to obtain true PL spectrum. The positions of the peaks in PL spectrum of the structure are in good agreement with the theoretical calculation of electron transition energies at room temperature: $e_1 - hh1 = 1.486$ eV and $e_2 - hh2 = 1.525$ eV. Peak $e_2 - hh2$ disappears with the temperature decrease. It is associated with variation of the carrier distribution function and decrease in electron concentration on the level $e_2$. 

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*Note: The diagram and table are not transcribed as they are not necessary for the text content.*
In earlier work [2] we presented the results of intersubband absorption investigation without electric field and studied the influence of temperature variation (from 4 to 300 K) on the absorption spectra. Intersubband absorption related only to quantum wells was estimated by dividing the spectrum of \( p \)-polarized light transmission by the transmission spectrum for \( s \)-polarized light (see curve 1 in figure 2 at liquid nitrogen temperature). These spectra contained one distinct peak at the photon energy corresponding to the \( e_1 - e_3 \) electron transitions. This peak widened and slightly shifted with the temperature variation. We associate the observed variation of absorption with the redistribution of electrons between first two electron levels (\( e_1 \) and \( e_2 \)) and with a change in the matrix element of \( e_1 - e_3 \) transition. Slight broadening of the \( e_1 - e_3 \) absorption peak with the temperature increase can be attributed to the thermal effects.

\[ \text{Figure 2. Spectra of intersubband absorption (1) and refraction index } n \text{ (2) at } T = 77 \text{ K.} \]

It stands to mention that interference influence should also be considered in intersubband absorption studies. It can be observed in case of standing wave occurrence in the waveguide geometry as a result of the interference between the incident and totally reflected light at the semiconductor–air interface [3]. The structure described in the present paper has highly doped surface GaAs layer and metal coating which together should result in standing wave with antinode for \( p \)-polarized light and node for \( s \)-polarized light at the structure surface. However, the thickness of the active layer containing 100 pairs of tunnel-coupled QWs is about 3 \( \mu \text{m} \) which results in the averaging of interference effects for several periods of standing wave located there [4].

\[ \text{Figure 3. Absorption modulation spectra for } p \text{-polarized light at } T = 77 \text{ K. Inset shows schematically electron redistribution under transverse electric field. } L \text{- optical length.} \]

\[ \text{Figure 4. Spectrum of refraction index variation } \Delta n \text{ under transverse electric field corresponding to applied voltage } U = 20 \text{ V at } T = 77 \text{ K.} \]

The figure 3 shows measured intersubband absorption modulation spectra \( \Delta \alpha(\omega) \) for \( p \)-polarized light at \( T = 77 \text{ K} \) (in case of \( s \)-polarized light there are no changes in QW-related absorption in multipass geometry) under transverse electric field. It is also important to mention that electric field influences light absorption as well as the reflection at the interface between active region and
substrate. It will be found that electric field changes the value of refraction index \( n \) on approximately 0.3. Providing that refraction index of bulk GaAs is 3.27 it could be calculated that electric field changes reflection coefficient \( R \) on 0.2% thus its effect can be neglected.

The dip in modulation spectra (see figure 3) corresponds to the decrease in absorption. Its energy position is in good agreement with \( e_1-e_3 \) transition energy. Observed absorption decrease is associated with electron redistribution between first two subbands \( e_1 \) and \( e_2 \) (see inset in figure 3). One can see that spectra for voltage \( U = 20 \) V and \( U = 25 \) V are almost identical. It can indicate that \( U = 20 \) V corresponds to complete depletion of \( e_1 \) subband. This also corresponds to our numerical estimations. The electric field of the other polarity does not lead to a significant increase in the population of first subband, therefore intersubband absorption change in this field was not observed.

Spectra of refraction index change \( \Delta n(\omega) \) in electric field were calculated from the obtained intersubband absorption modulation spectra using Kramers-Kronig relation:

\[
\Delta n(\omega) = \frac{c}{\pi} \text{v.p.} \int_{-\omega}^{\omega} \frac{\Delta \alpha(\omega')}{\omega^2 - \omega'^2} d\omega'
\]

where \( \omega \) is light frequency, \( c \) is light speed, \( \Delta \alpha(\omega) \) stands for the changes of intersubband absorption (see figure 3). Results of calculation (see figure 4) show that maximal change of refraction index under transverse electric field is approximately 10% of the whole refraction index of GaAs (\( n = 3.27 \)). Spectrum of refraction index without electric field was also calculated (see curve 2 in figure 2). It is associated with intersubband absorption in equilibrium conditions. It is clear that modulation of infrared radiation in electric field is efficient and effective in structures with tunnel-coupled QWs.

4. Conclusion

The obtained results confirm the feasibility of tunnel-coupled QW-based infrared modulators. Experimental results show that low voltage value of transverse electric field is enough to significantly change the energy spectrum of structure and provide the electron distribution between QW. Thus we have confirmed significant changes in refraction index of mid-IR radiation. Besides, redistribution of the charge carriers between lowest electronic states in tunnel-coupled QW structures under transverse electric field can also affect the refractive index in near infrared spectral range, namely the part of refractive index related to virtual interband transitions induced by the radiation with photon energy slightly less then the effective energy gap. The corresponding spectral range is of interest for application in commercially developed medical laser systems, for example 980 nm lasers for stomatology.

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