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Electric field influence on mid-infrared absorption and interband photoluminescence in tunnel-coupled GaAs/AlGaAs quantum wells

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Abstract. The influence of transverse and lateral electric field on the mid-infrared intersubband light absorption is experimentally investigated in tunnel-coupled GaAs/AlGaAs quantum wells. Observed absorption modulation in electric field is related to the electron redistribution between the quantum well states resulting in variation of space charge in the structure. This phenomenon in transverse electric field is connected with a change of potential profile, whereas in lateral field effect is caused by electron heating. Electron heating also leads to a modulation of near-infrared interband photoluminescence under lateral electric field.

1. Introduction

Charge carrier heating in electric field in quantum wells can affect the characteristics of various optoelectronic devices (lasers, modulators etc.). Lateral and transverse electric fields have different impact on mid-infrared absorption and interband photoluminescence in quantum wells (QW). It is known that radiation frequency modulation is more efficient than intensity modulation in communication systems [1]. One of the techniques that can rapidly change the frequency of quantum cascade laser radiation is external electric field modulation of the refractive index of quantum well layers, introduced into the quantum cascade laser waveguide. A possible way to create such a system is an introduction of the layers with tunnel-coupled quantum wells into the laser waveguide. Complicated band structure of tunnel-coupled quantum wells facilitates the observation of the electric field influence on the QW optical properties. The first step toward achieving this objective is to study the refractive index and absorbance variation of the layers with tunnel-coupled quantum wells in the mid-IR region under electric field.

The investigation of these phenomena in double tunnel-coupled QW is still ongoing. Electric field causes the redistribution of electrons between size quantization levels due to carrier heating. The photoluminescence (PL) study provides an easy way to analyze heating. Earlier the influence of lateral electric field on the photoluminescence spectrum was investigated in [2]. In contrast to our work, the modulation of PL in [2] was not directly connected with electron heating. Carrier heating effect on the intersubband absorption in tunnel-coupled quantum wells was studied in [3] at a fixed radiation wavelength. Comparing the effect of an electric field and lattice heating on the spectra of intersubband absorption and interband PL, the temperature of the hot electrons was estimated [3].

This work is devoted to the complex investigation of the influence of different configurations of electric field on optical properties of tunnel-coupled GaAs/AlGaAs quantum wells.

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2. Samples and experiment

Structures with 100 pairs of doped GaAs/AlGaAs QWs with different width were studied. The structures were grown by molecular-beam epitaxy on a semi-insulating GaAs substrate. In order to characterize the structure, interband photoluminescence spectra without electric field were measured with Horiba FHR-640 grating monochromator 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 using a Si photodetector. In order to apply of transverse electric field, mesa was etched from one of the structures and Cr/Au contacts were deposited on its surface in vacuum. Indium contacts to the structure intended for the lateral electric field application were manually deposited and annealed at the nitrogen atmosphere. The facets of the samples were mechanically grounded and polished at 45˚ angle to create a multipass sample geometry for intersubband optical absorption studies. Such geometry is based on total internal reflection of radiation in the sample and increases the absorption in the sample by increasing effective optical path. Also this method allows to investigate absorption for two polarisations independently. The intersubband absorption variation spectra under lateral and transverse electric field were studied using a Bruker Vertex 80v vacuum Fourier-transform spectrometer in step-scan mode. In order to avoid sample overheating, the lateral electric field was applied to the sample in pulsed mode. Contribution of intersubband transitions to light absorption by the quantum well structures without electric field was determined from the ratio of transmission spectra for two light polarizations.

3. Results and discussions

Calculation showed the presence of 3 electron energy levels in paired QWs. The equilibrium interband photoluminescence spectra were measured at different lattice temperatures for both structures. Spectral peaks demonstrate a temperature shift corresponding to the bandgap change. At low temperatures, there is only one peak associated with the optical *e*1-*e*3 transitions, which means that the carriers are localized mainly at the *e*1 level. Carriers begin to fill the overlying energy level with the increase in temperature.

The spectra of intersubband absorption modulation demonstrate a decrease in *e*1-*e*3 absorption under transverse electric field (see figure 1). This phenomenon can be attributed to electron redistribution between the *e*1 and *e*2 levels in electric field induced by the modification of the QW potential profile. Saturation of modulation at particular transverse electric field can be caused by total depletion of *e*1 level. An electric field of opposite polarity does not induce a significant variation of the electron concentration on *e*1 level, therefore, no change in intersubband absorption was detected. Spectra of refraction index change in electric field were calculated from the obtained intersubband absorption modulation spectra using Kramers-Kronig relation. Results of the calculation show that maximal change of refraction index under transverse electric field is approximately 10% of the bulk GaAs refraction index. This result suggests that tunnel-coupled quantum well structures can be implemented in the development of frequency electro-optical modulators for the mid-IR region radiation emitters.

In lateral electric field (see figure 2), we found a decrease in *e*1-*e*3 absorption, an increase in *e*2-*e*3 absorption and a slight red shift of *e*1-*e*3 absorption peak. These phenomena can be related to the hot electron redistribution between the *e*1 and *e*2 levels and subsequent variation of space charge in the structure since the wave functions of e1 and e2 electron levels are localized at wide and narrow QW of the pair, respectively.

The electron temperature T_e was estimated from the comparison of the absorption change related to the lateral electric field and to the lattice temperature. 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 at lattice temperature $T = 77$ K.

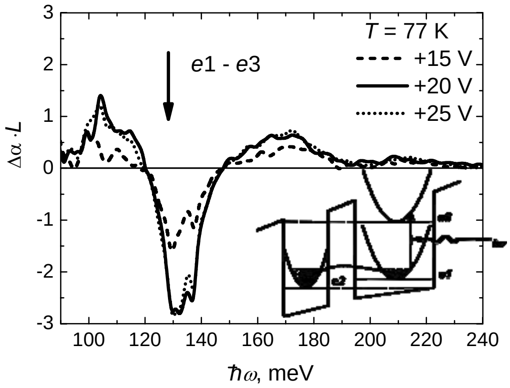

Figure 1. Absorption modulation spectra for *p*-polarized light under different transverse electric fields. The arrow shows the calculated electron transition *e*1-*e*3 energy. Electron redistribution under transverse electric field is schematically shown in inset. *L* is the optical path.

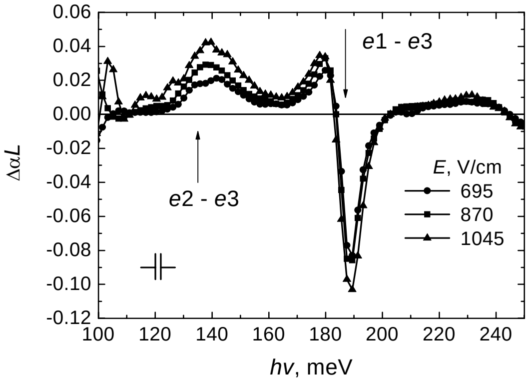

Figure 2. Spectra of intersubband absorption modulation under different lateral electric fields *E* at $T = 77$ K. The arrows indicate the calculated electron transition energies.

The interband photoluminescence variation spectra were measured at different lateral electric fields at $T = 77$ K. Under applied electric field, the hot carrier temperature was not high enough to significantly change the concentration of carriers at hole and electron levels *lh*1, *hh*2 and *e*2. Only modulation of interband photoluminescence associated with the *e*1-*hh*1 optical transitions was observed (see figure 3). It should be noted that interband PL modulation was observed at a high level of optical pumping. In such conditions, rather high nonequilibrium carrier concentration is created, therefore we can consider the equality of electron and hole temperatures due to the 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, $dI_{PL}/dT_e = 0$. Photoluminescence intensity I_{PL} is proportional to the number of spontaneous photons of interband radiation in elementary volume during elementary time period at the frequency range from ν to $\nu + \Delta\nu$, which, in turn, is proportional to the carrier distribution function. Taking a derivative 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. At $T = 77$ K, the electron temperature rise 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.

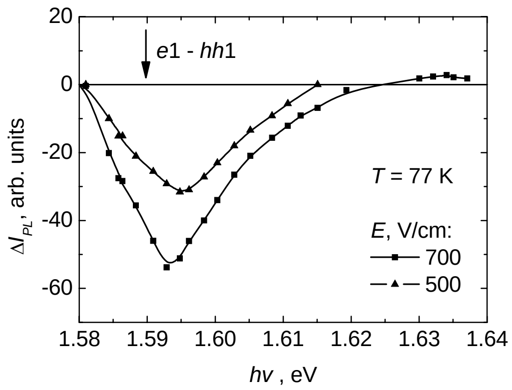

Figure 3. Modulation of interband photoluminescence at $T = 77$ K under lateral electric field E. Arrow shows the calculated energy of interband transitions $e1$-$hh1$.

4. Conclusion

The influence of the lateral and transverse electric fields 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. The effect of a transverse electric field on the intersubband absorption is explained by the redistribution of electrons between the first quantum levels and a change in the energy spectrum of the structure. Modulation of intersubband absorption and interband photoluminescence under lateral electric field is explained by the 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 obtained from the absorption spectra analysis. The temperature values obtained by two methods were close. The value of the observed absorption variation proves the application prospects of tunnel-coupled quantum wells as a basis for fast infrared light modulators.

Acknowledgments

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