Journal of Physics: Conference Series

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To cite this article: M Ya Vinnichenko *et al* 2016 *J. Phys.: Conf. Ser.* **741** 012124

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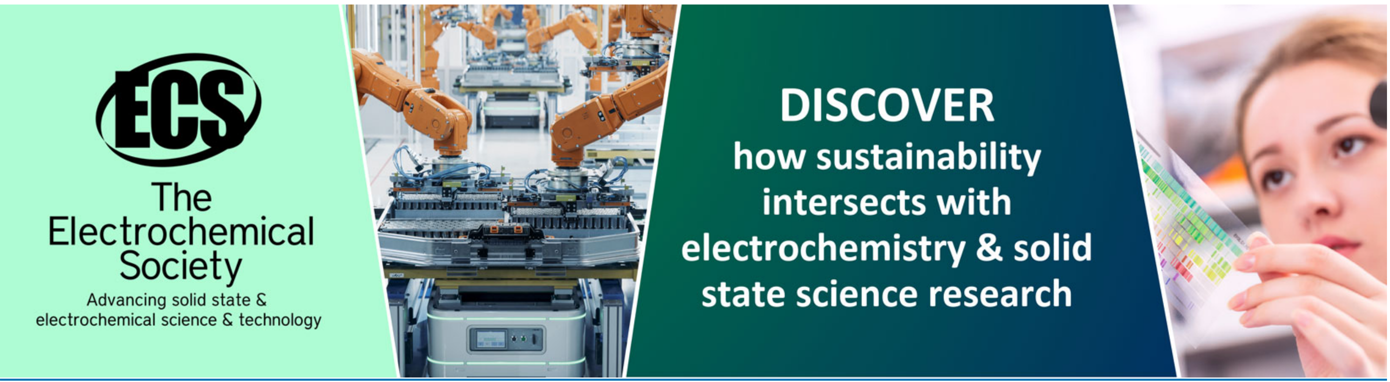

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Electric-field-induced mid-infrared birefringence of the double quantum wells

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Abstract. Birefringence in double tunnel-coupled GaAs/AlGaAs quantum wells was studied in the mid-infrared spectral range close to the intersubband resonance. Phase-sensitive optical studies allowed us to deduce simultaneously the differences of the refraction index and absorption coefficient for the normal waves polarized in the plane of the structure and along the structure growth, including electric-field induced effects. The optical absorption data are in a good agreement with the direct optical transmission measurements.

1. Introduction

The semiconductor structures with multiple quantum wells (QW) represent the uniaxial media with respect to the optical properties. The permittivity tensor $\hat{\varepsilon}$ has the non-zero components $\varepsilon_{xx} = \varepsilon_{yy}$ and ε_{zz}, where *z* is the growth direction, and *x* and *y* are in-plane directions. Microscopically, the difference in the permittivity components is related to the contribution of the electron intersubband optical transitions, which are allowed only for the light with non-zero *z*-component of polarization vector. In general, application of the lateral electric field (for example, along the *x* axis) to the quantum well structure reduces the symmetry, so all three components of the permittivity tensor become unequal and the structure becomes optically biaxial. However, under practical conditions, not so strong electric field affects only the values of the permittivity tensor components due to electron heating, and its symmetry is conserved. The variation of the $\hat{\varepsilon}$ under the electric field opens the way for both amplitude and phase modulation of the infrared radiation with photon energies close to intersubband resonances, since both the absorption coefficient and refraction index are influenced.

The modulation of the mid-infrared absorption under the strong lateral electric field is well studied in the quantum well structures. For example, in the recent works [1, 2] the intersubband absorption modulation was measured by means of the Fourier transform transmission spectroscopy in the tunnel-coupled quantum well structures. The modification of the absorption coefficient was associated firstly, with the redistribution of the charge carriers between the QW states, and, secondly, with the modification of distribution function of the hot electrons, which becomes slightly anisotropic. In the present work, we focus on the phase-sensitive optical studies of the tunnel-coupled quantum well structures.

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2. Experimental details

Research was carried out on the MBE-grown multiple GaAs/AlGaAs QW structure. One period of the structure contains a pair of narrow and wide GaAs layers separated with the tunnel-transparent AlGaAs barrier. The electronic structure of the one pair of QWs contains three electronic subbands *e*1, *e*2, and *e*3. The first electronic state is localized mostly in the wide well, while the second one is localized in the narrow well.

The sample was prepared in multi-pass geometry. The sidewall of the sample was illuminated with the linearly polarized mid-infrared light. The angle between the polarization vector and the *x*-*y* plane was 45°, so the incident beam created both *s*- and *p*- normal waves in the sample. The polarization of the output beam was analyzed with the metal grid polarizer. Electric field was applied through indium contacts made on the surface of the sample.

In this work, the Fourier transform spectroscopy was used to measure the spectral dependence of the both equilibrium and electric field induced birefringence. The globar was used as a source of mid-IR radiation. We recorded spectra of the light intensity passed through the system "polarizer – sample – analyzer" at different analyzer angles. Spectra were measured by photovoltaic liquid-nitrogen-cooled HgCdTe photodetector in a time resolved step-scan mode in order to detect the response on the electric field pulse applied to the sample.

3. Theory

In contrast to the birefringence in transparent media, in our case the resulting elliptical polarization of output beam is caused by the difference of both refraction index and absorption coefficient for the normal waves. Moreover, the absorption contribution should be rather significant as the photon energy is close to the intersubband resonance, which takes place only for *p*-polarized light.

In order to resolve carefully the phase-related effect on the emergent polarization ellipse against the strong intersubband absorption we obtain analytical expressions for the dependence of the light intensity I after the analyzer upon its azimuth angle α in the framework of the Jones matrix formalism [3]. In order to take into account difference in the both phase and amplitude for the *s*- and *p*-light polarizations we used a complex refraction index $n^* = n + ik$, where *n* and *k* are real refraction and extinction coefficients, respectively. The resulting expression for $I(\alpha)$ is

$$I(\alpha) \sim \cos^2(\alpha)(1 + 2\beta\gamma\, tg(\alpha) + \beta^2 tg^2(\alpha)), \tag{1}$$

where

$$\begin{aligned} \beta &= \exp\left(-\Delta k L \frac{2\pi}{\lambda}\right), \\ \gamma &= \cos\left(\Delta n L \frac{2\pi}{\lambda}\right), \end{aligned} \tag{2}$$

and $\Delta n = n_p - n_s$, $\Delta k = k_p - k_s$, L – optical path length, λ – radiation wavelength.

To obtain a spectral dependence of β and γ (and, respectively, Δn and Δk) one can measure a spectra with three analyzer angles $\alpha = \pm 45°, 0°$. In this case

$$\begin{aligned} \beta^2 &= \frac{I(45^\circ) + I(-45^\circ)}{I(0^\circ)} - 1, \\ \gamma &= \frac{I(45^\circ) - I(-45^\circ)}{\beta I(0^\circ)}. \end{aligned} \tag{3}$$

4. Results and discussion

Figure 1 shows the sample response on the electric filed pulse as an integral photodetector AC-coupled signal change with the analyzer angle $\alpha = +45°$. The optical and electric filed pulse shapes are very close so we can expect the effect to be related to the redistribution of charge carriers but not to the sample heating.

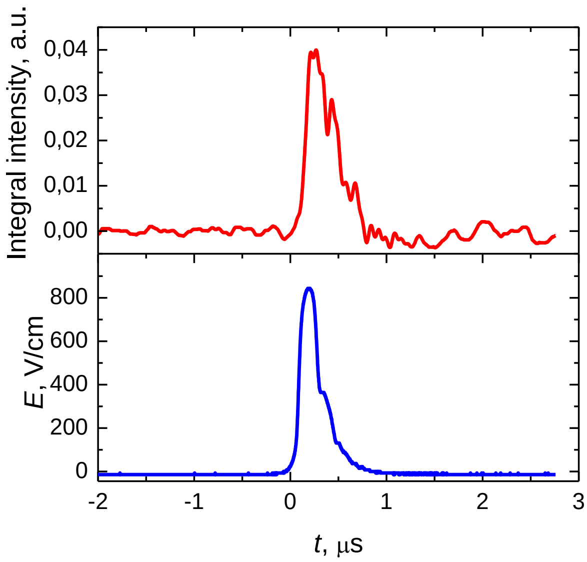

Figure 1. Optical response (red line) of the sample with double GaAs/AlGaAs QWs on the electric filed pulse (blue line) as an integral photodecetor AC-coupled signal change with the analyser azimuth angle $\alpha = +45°$.

We measured spectra of the DC-coupled photodetector output at the different time moments with respect to the electric field pulse with different analyzer angles ($\alpha = \pm 45°$ and $0°$) under different lateral electric field at the temperature of the liquid nitrogen. Thus, we studied both equilibrium and field-induced birefringence in one experiment series. Figure 2 shows the equilibrium spectra ΔnL and ΔkL at $T = 80$ K calculated using the equations 3 and 2 from the measured data before the field pulse. Absorption peak corresponds to the $e1$-$e3$ transitions measured elsewhere with traditional optical transmission spectroscopy [2].

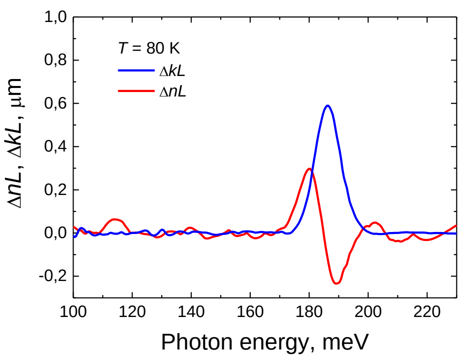

Figure 2. Equilibrium spectra of the differences in the real refraction Δn and extinction Δk coefficients for p- and s- normal waves. L is the optical path length.

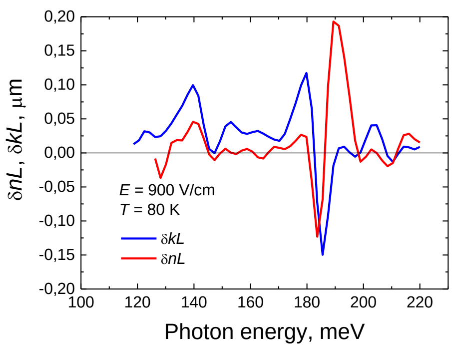

Figure 3. Modification spectra of the refraction δn and extinction δk coefficients under lateral electric field. L is the optical path length.

Taking the measured data at the time moment when the applied electric filed is maximal, we can obtain the modifications δn, δk of the "natural" refraction and extinction differences in the electric filed: $\delta n(E) = \Delta n(E) - \Delta n(E=0)$, $\delta k(E) = \Delta k(E) - \Delta k(E=0)$. The corresponding spectra are shown in figure 3. One can see the decrease and slight red shift of absorption peak *e*1-*e*3.

Comparison of the modification spectra of real refractive index δn (figure 3) under lateral electric field and the spectrum of refractive index variation using Kramers–Kronig relations showed the similar result. The variation in refractive index was determined from the spectra of intersubband absorption change under lateral electric field [1] using the Kramers–Kronig relation and method described in [2]. Observed modification spectra of real refractive index δn (figure 3) under lateral electric field could be explained by redistribution of hot charge carriers between the two lowest electronic states belonging to different quantum wells of the pair and by subsequent variation of space charge in the structure. Further microscopic description of the electric field induced birefringence, including the contribution of the anisotropy of the hot electron distribution function, is under consideration.

5. Conclusion

In summary, the analysis of the state of the elliptical polarization of the output beam allowed us to determine both the refraction index and the absorption coefficient differences for the *s*- and *p*- waves in the tunnel-coupled QW structure, including the electric field induced differences. The absorption data are consistent with the direct optical transmission measurements [1]. The observed electric field induced birefringence can be used for phase modulation of the mid-infrared radiation.

Acknowledgments

The reported study was funded by RFBR project No. 14-02-00336, Russian Federation President Grant for young scientists No MK-4616.2016.2 and the Ministry of Education and Science of the Russian Federation (state assignment).

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