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OPTICALLY DETECTED CYCLOTRON RESONANCE IN TILTED MAGNETIC FIELD IN GaAs-GaAlAs HETEROJUNCTION

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We present results on optically detected cyclotron resonance (ODCR) measurements with luminescence spectra of GaAs-GaAlAs heterojunction in tilted magnetic fields. ODCR spectra drastically change with the increasing tilt angle due to the magnetic field component parallel to the interface which mixes up the states of different dimensional subbands.

1. Under the conditions of cyclotron resonance in semiconductors, absorption of the microwave energy by electrons or holes takes place, and it brings up an increase of their average energy. When it has a notable effect on the luminescence spectra of a semiconductor, an optical detection of cyclotron resonance (ODCR) becomes possible [1]. We have reported earlier on the optically detected cyclotron resonance in GaAs-GaAlAs heterojunction $2D$ electron gas [2]. The luminescence monitored in the experiment was due to the recombination of the two-dimensional electrons, localized near the interface, with the holes bound to δ layer of acceptors implanted into GaAs [3,4].

The ODCR experiments in normal magnetic field have demonstrated that, although in this geometry z coordinate, normal to the interface, is separated in full Hamioltonian from x and y (the microwave radiation acts on these degrees of freedom), partial saturation of cyclotron resonance results in charge density redistribution in z-direction. It happens because part of electrons excited to higher Landau levels goes down to the lowest level of the first electric subband, and the transition from it to the ground subband proved to be rather slow. So this level plays a role of "bottle neck" in the process of relaxation of CR excited electrons. As a result, intensity of the first subband line increases, while intensities of lower lines reduce. Charge density redistribution in z-direction changes the shape of selfconsistent potential of the quantum well, and because of this, levels of the ground subband slightly go down (this effect is similar to depolarization shift of absorption line of the interband transition [5]). This process is possible when the lowest level of the upper subband lies between filled and empty Landau levels of the ground subband.

In tilted magnetic field a component parallel to the interface mixes up states of different dimensional subbands. In the present work we study the effect of subband interference on the signal of optically detected cyclotron resonance.

2. We used the same GaAs-$Ga_{1-x}Al_xAs$ single heterojunction and experimental setup described in our previous paper [2]. The sample holder could be rotated providing tilted magnetic field configuration. The two-dimensional electron density was varied between 2.5 and 5.5×10^{11} cm^{-2} depending on HeNe laser light exposure.

Four types of records were made: luminescence spectra $I_L(\omega)$, cyclotron resonance with swept magnetic field $I_F(H)$, ODCR $I_M(H)$, and spectral dependence of ODCR signal (differential luminescence) $I_M(\omega)$. When recording luminescence spectra, the reference signal for the lock-in amplifier was taken from the chopper of the HeNe laser beam, to measure signals connected with the cyclotron resonance the CO_2 laser beam had been chopped. All measurements were taken at a temperature $T = 4.2\,K$.

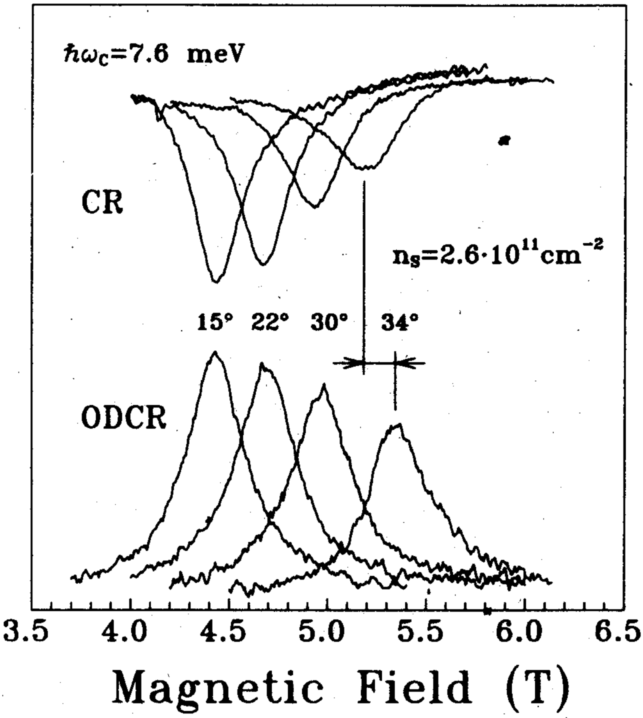

Fig.1. Cyclotron resonance (upper curves) and optically detected cyclotron resonance (lower curves) line shapes measured in tilted magnetic field configuration at different tilt angles. The electron density $N_s = 2.6 \times 10^{11}$ cm^{-2}, FIR laser energy is $\hbar\omega_c = 7.61$ meV

3. The records of cyclotron resonance and ODCR at a two - dimensional electron density of $N_s = 2.6 \times 10^{11}\,cm^{-2}$ and different tilt angles are compared in Fig.1. Under normal magnetic field the lines of CR and ODCR practically coincide, but at tilt angles exceeding 20° the maximum of ODCR is shifted to the side of higher field with respect to CR, and this mismatch grows with rising tilt angle. When pumping power was reduced and $2D$ electron density increased to $3.5 \times 10^{11}\,cm^{-2}$, this discrepancy in positions of CR and ODCR disappeared.

To clarify the cause of this discrepancy we studied spectral dependence of ODCR signal $I_M(\omega)$ along with the luminescence spectra. A typical dependence of luminescence line maximum positions on magnetic field is shown in Fig.2. The positions of extrema of $I_M(\omega)$ are also indicated. In Fig.3 appropriate records of luminescence spectra and $I_M(\omega)$ are reproduced. CR lines of δ-doped samples in tilted magnetic field are relatively broad, it enables us to observe the influence of CR pumping on the luminescence spectra in a wide range of magnetic fields.

Spectral dependence of ODCR signal on the side of low field is similar to that in normal magnetic field: due to FIR pumping the intensity of (1,0) line (here the first index denotes dimensional subband, the second one labels Landau level) grows, while the (0,1) and (0,0) lines are slightly quenched. With the increase of magnetic field the signal at (0,1) line changes its sign, and merges with the maximum corresponding to the (1,0) line, afterwards one can see only negative signal about (0,0) line and positive signal at (0,1) line. In those cases when the mismatch between CR and ODCR lines is especially great, the maximum of ODCR is observed in such a field where the latter kind of ODCR spectral dependence is observed.

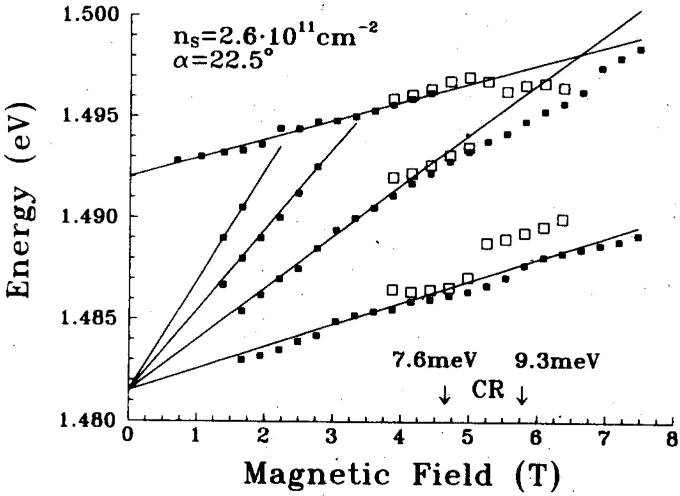

Fig.2. Dependence of the spectral position of the luminescence lines (dark squares) on magnetic field at tilt angle $\alpha = 22.5°$ and electron density $N_s = 2.6 \times 10^{11}$ cm^{-2}. Open squares indicate the extrema in differential luminescence spectra. Arrows mark the resonant magnetic field positions for two FIR laser lines $\hbar\omega_c = 7.61$ meV and $\hbar\omega_c = 9.32$ meV

4. Interband interference is strongest when the cyclotron energy coincides with that of interband transition, so its strongest influence should be expected near the (1,0)-(0,1) anticrossing. It was demonstrated in [6], that, generally speaking, energy difference between adjacent Landau levels is not equal to cyclotron energy, it seems to be connected to multiparticle interaction of two-dimensional electrons in the process of recombination with holes belonging to the valence band. Comparing our recombination spectra with the position of CR we could see that cyclotron energy exceeds energy difference between Landau levels. So it is difficult to make a certain statement about the position of the first subband.

Since energy difference between (0,0) and (0,1) lines as a function of magnetic field deviates from linear dependence, we conclude that intersubband interference becomes essential above 4.5 T. In case of the absence or weak interband mixing the state in the upper subband has the longest relaxation time, and the cyclotron transitions produce significant population on this level. But even the slight admixture of states of the ground subband increases its relaxation rate, so the line in ODCR spectral dependence corresponding to (1,0) level is not observed at higher magnetic fields.

In these circumstances the level (0,1) becomes a recipient of excited non-equilibrium electrons, since the cyclotron absorption results in this luminescence line rising. The amplitude of optically detected signal could be greater at these magnetic fields than in the maximum of CR absorption. Thus strong dependence of relaxation rates on magnetic field brings up mismatch between profiles CR and ODCR lines.

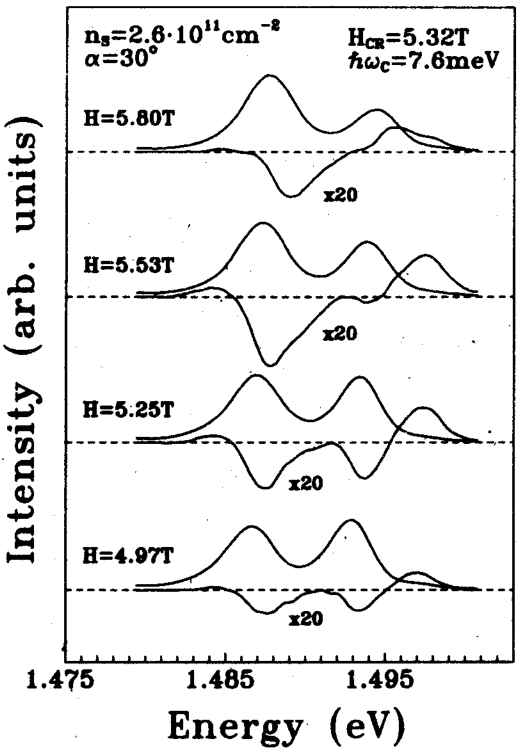

Fig.3. Luminescence (upper curves) and corresponding differential luminescence (lower curves) spectra measured at different magnetic field strength H near the resonant magnetic field $H = 5.32$ T. The tilt angle $\alpha = 30°$, the electron density $N_s = 2.6 \times 10^{11}$ cm^{-2} and FIR laser energy $\hbar\omega_c = 7.61$ meV

In perpendicular magnetic field the electron density at Landau level (1,0), normally not populated, increases not because of direct transitions, but via the upper level (0,2). In tilted magnetic field direct excitation of electrons to the (0,1) Landau level from the fully populated (0,0) level of ground subband takes place. Maxima and minima of ODCR signal do not precisely coincide with peaks in luminescence spectra (Fig.2), it indicates that the depolarization shift increases in case of tilted magnetic field.

5. Method of optical detection of CR in $2D$ electron gas introduced in [2] is a technique that enables one to obtain, along with cyclotron mass value, information concerning processes of electron inter- and intrasubband relaxation. In perpendicular magnetic field ODCR lineshape coincides with that of ordinary CR absorption contour (except the case of low field cut-off regime, see Fig.3 in [2]), and it does not matter which Landau level line is used for optical CR detection. In tilted magnetic field wave function interference of different subband states transforms differential luminescence spectra significantly because of changes in relaxation rates between levels of different subbands. The lowest level of ground subband (0,0)

remains the only one which adequately reflects the influence of cyclotron pumping. At high tilt angles positions of CR and ODCR do not coincide. Differences of electron energy relaxation times responsible for the appearance of ODCR signal becomes the essential factor determining its lineshape and position in magnetic field.

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