Optically detected cyclotron resonance in tilted magnetic field in a GaAs–GaAlAs heterojunction

A. A. Dremin and A. V. Malyavkin
Institute of Solid State Physics RAS, 142432, Chernogolovka, Moscow District, Russia

(Submitted 24 June 1992)
Pis'ma Zh. Eksp. Teor. Fiz. **56**, No. 2, 113–117 (25 July 1992)

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

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

The ODCR experiments in a normal magnetic field have shown that, although in this geometry the z coordinate, normal to the interface, is separated in the complete Hamiltonian form x and y (the microwave radiation acts on these degrees of freedom), partial saturation of cyclotron resonance results in a charge density redistribution in the z direction. This occurs because some of the electrons excited to higher Landau levels descend to the lowest level of the first electric subband, and the transition from it to the ground subband is rather slow. This level therefore plays a role of a "bottleneck" in the process of relaxation of CR excited electrons. As a result, the intensity of the first subband line increases, while the intensities of the lower lines decrease. The charge density redistribution in the z direction changes the shape of the self-consistent potential of the quantum well, causing the levels of the ground subband to be slightly lowered (this effect is similar to the depolarization shift of the absorption line of the interband transition[5]). This process is possible when the lowest level of the upper subband lies between the filled and the empty Landau levels of the ground subband.

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

2. We have 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 to provide a tilted magnetic field configuration. The two-dimensional electron density wave varied between 2.5 and 5.5×10^{11} cm^{-2}, depending on the 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 we recorded the luminescence spectra, we used the reference signal for the lock-in amplifier from the chopper of the HeNe laser beam. To measure the signals connected with the cyclotron resonance, we had to chop the CO_2 laser beam. All measurements were taken at a temperature $T=4.2$ K.

3. The records of cyclotron resonance and ODCR at a two-dimensional electron density $N_s=2.6\times10^{11}$ cm^{-2} and different tilt angles are compared in Fig. 1. In a normal magnetic field, the lines of CR and ODCR nearly coincide, but at tilt angles exceeding 20° the maximum of ODCR is shifted toward a higher field with respect to CR, and this mismatch increases wtih increasing tilt angle. When the pump power was reduced and 2D electron density increased to 3.5×10^{11} cm^{-2}, this discrepancy in the positions of CR and ODCR disappeared.

To clarify the cause of this discrepancy, we studied the spectral dependence of the ODCR signal, $I_M(\omega)$, along with the luminescence spectra. A typical dependence of the position of the luminescence-line maximum on the magnetic field is shown in Fig. 2. Also shown in this figure are the positions of the extrema of $I_M(\omega)$. In Fig. 3 the appropriate records of the luminescence spectra and $I_M(\omega)$ are reproduced. The CR lines of the δ-doped samples in a titled magnetic field are relatively broad. They enable 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 the low field is similar to that in a normal magnetic field: Because of the FIR pumping, the intensity of the (1,0) line (here the first index denotes dimensional subband, and the second one is the Landau level) increases, while the (0,1) and (0,0) lines are slightly quenched. With the increase in the magnetic field, the signal at the (0,1) line changes sign and merges with the maximum corresponding to the (1,0) line. Afterwards one can see only the negative signal near the (0,0) line and the positive signal at the (0,1) line. In the case

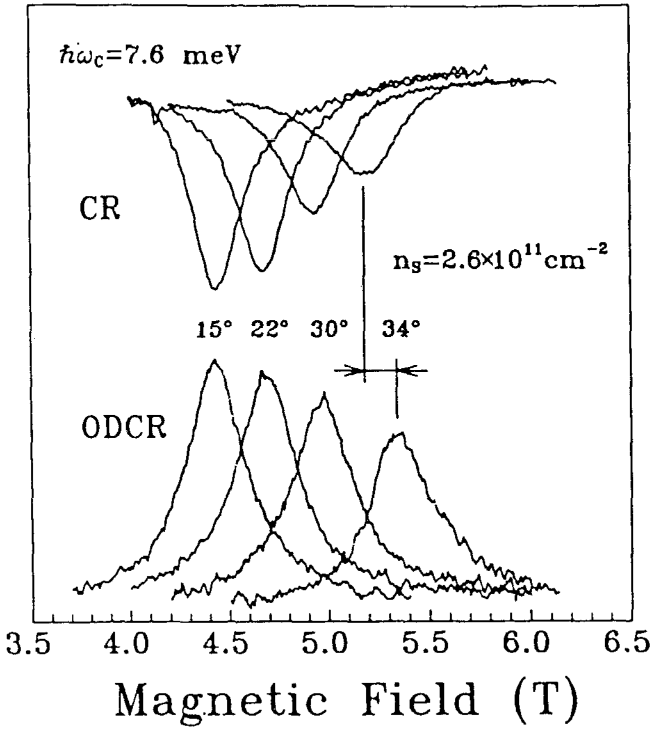

FIG. 1. Cyclotron resonance (upper curves) and optically detected cyclotron resonance (lower curves) line shapes measured in a tilted magnetic field configuration at different tilt angles. The electron density is $N_s = 2.6\times10^{11}$ cm^{-2}, FIR laser energy is $\hbar\omega_c = 7.61$ meV.

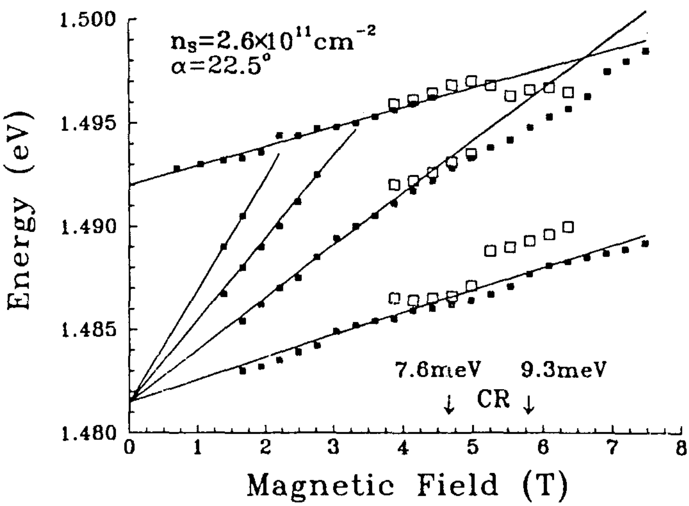

FIG. 2. Dependence of the spectral position of the luminescence lines (dark squares) on the magnetic field at a tilt angle $\alpha = 22.5°$ and electron density $N_s = 2.6\times10^{11}$ cm^{-2}. Open squares indicate the extrema in the differential luminescence spectra. Arrows mark the resonant magnetic field positions for the two FIR laser lines, $\hbar\omega_c = 7.61$ meV and $\hbar\omega_c = 9.32$ meV.

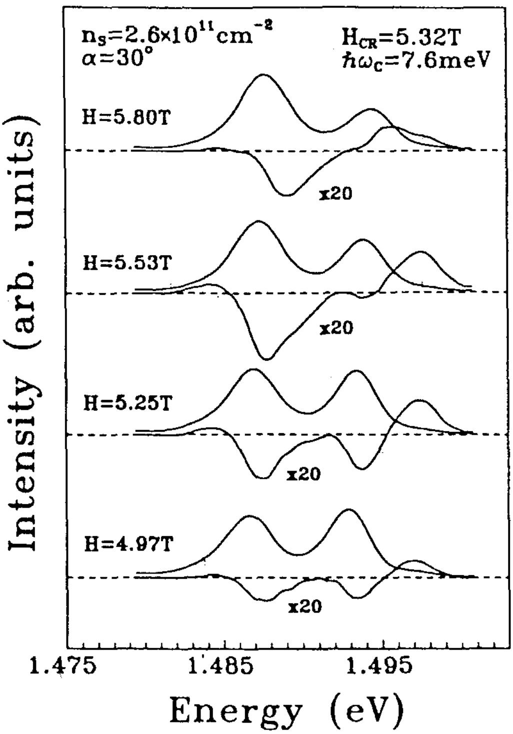

FIG. 3. Luminescence spectra (upper curves) and corresponding differential luminescence spectra (lower curves), measured at different magnetic field strengths H near the resonant magnetic field $H = 5.32$ T. The tilt angle $\alpha = 30°$, the electron density $N_s = 2.6 \times 10^{11}$ cm^{-2}, and FIR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

where the mismatch between the 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.

4. The interband interference is strongest when the cyclotron energy coincides with the energy of the interband transition. It should therefore peak near the (1,0)–(0,1) anticrossing. It was demonstrated in Ref. 6 that the energy difference between adjacent Landau levels is generally not equal to the cyclotron energy. It seems to be connected with the multiparticle interaction of two-dimensional electrons in the recombination with the holes that belong to the valence band. Comparing our recombination spectra with the position of CR, we see that cyclotron energy exceeds the energy difference between the Landau levels. It is therefore difficult to unambiguously determine the position of the first subband.

Since energy difference between the (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 the case of the absence of interband mixing or its slight mixing, the state in the upper subband has the longest relaxation time, and the cyclotron transitions produce significant population on this level. But even slight admixture of states of the ground subband increases its relaxation rate, so the line in the ODCR spectral dependence corresponding to the (1,0) level is not observed at higher magnetic fields.

In these circumstances, the (0,1) level becomes a recipient of excited nonequilibrium electrons since the cyclotron absorption accounts for the rise in this luminescence line. The amplitude of the optically detected signal could be greater at these magnetic fields than in the maximum of CR absorption. The strong dependence of the relaxation rates on the magnetic field thus accounts for the mixmatch between the profiles CR and the ODCR lines.

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

5. Method of optical detection of CR in a 2D electron gas, introduced in Ref. 2, is a technique that enables one to obtain, along with the cyclotron mass value, information concerning the processes of electron inter- and intrasubband relaxation. In a perpendicular magnetic field, the ODCR lineshape coincides with that of the ordinary CR absorption contour (except for the case of a low-field cutoff regime; see Fig. 3 in Ref. 2), and it does not matter which Landau level line is used for optical CR detection. In a tilted magnetic field the wave function interference of different subband states transforms the differential luminescence spectra significantly because of changes in the relaxation rates between the levels of different subbands. The lowest level of the ground subband (0,0) turns out to be the only one that adequately reflects the influence of cyclotron pumping. At high tilt angles the positions of CR and ODCR do not coincide. The difference in the electron energy relaxation times, which is responsible for the appearance of the ODCR signal, becomes the essential factor that determines its lineshape and the location of the magnetic field.

We wish to thank I. V. Kukushkin and V. B. Timofeev for useful discussions. We also thank K. Ploog for providing the sample.

[1]R. Romenstein and C. Weisbuch, Phys. Rev. Lett. **45**, 2067 (1980).
[2]S. I. Gubarev, A. A. Dremin, I. V. Kukushkin *et al.*, JETP Lett. **54**, 355 (1991).
[3]I. V. Kukushkin, K. von Klitzing, and K. Ploog, Phys. Rev. **B37**, 8509 (1988).
[4]I. V. Kukushkin, K. von Klitzing, K. Ploog *et al.*, Phys. Rev. **B40**, 4179 (1989).
[5]T. Ando, Phys. Rev. **B19**, 2106 (1979).
[6]A. S. Plaut, I. V. Kukushkin, K. von Klitzing, and K. Ploog, Phys. Rev. **B42**, 5744 (1990).

Translated by the authors