Optical detection of cyclotron resonance at a GaAs–GaAlAs heterojunction

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A signal representing an optically detectable cyclotron resonance has been observed in the luminescence spectra of a GaAs–GaAlAs heterojunction. The signal arises because of an increase in the number of electrons in the upper quantum-well subband upon saturation of the cyclotron resonance.

Luminescence spectra have recently been used successfully to study the energy levels of a 2D electron gas at GaAs–GaAlAs heterojunctions.[1] Cyclotron resonance is used everywhere to study the properties of 2D electron systems of high density. At saturation of the cyclotron resonance in a semiconductor, an increase in the average energy of the electrons or holes cause significant changes in the luminescence spectra, making it possible to observe a signal representing an optically detectable cyclotron resonance (ODCR).[2] This letter is the first report of the observation of an ODCR in the system of 2D electrons in a GaAs–GaAlAs heterojunction. We also explain the reasons for the appearance for this resonance.

The test sample contained a single GaAs–GaAlAs heterojunction with a spacer of undoped GaAlAs and an n-type GaAlAs layer, donors from which furnish electrons to the 2D channel. The density of 2D electrons was $n_s = 2.5 \cdot 10^{11}\ \mathrm{cm}^{-2}$ in darkness and $5.5 \times 10^{11}\ \mathrm{cm}^{-2}$ after exposure to laser light. A thin GaAs layer (a δ-layer) doped selectively with acceptors (Be), with a Be concentration of $2 \times 10^{10}\ \mathrm{cm}^{-2}$, was 300 Å away from the heterojunction in GaAs. When the heterojunction was illuminated with the beam from a He–Ne laser, nonequilibrium holes were produced in the GaAs. The photoexcited electrons reduced the degree of ionization of the donors in the GaAlAs. As a result of recombination with nonequilibrium holes, the electron density in the 2D channel decreased. The density of these 2D electrons could be varied over a wide range by varying the power of the optical pumping.[3] The luminescence spectra are dominated by lines representing the recombination of the 2D electrons with holes bound at acceptors of the δ-layer.

The beam from the He–Ne laser, with a power up to 15 mW, was focused into an optical fiber 1 mm in diameter. This fiber was brought up to the surface of the sample at an angle of about 30° in a cryostat. A DFS-24 monochromator and a photomultiplier were used to record the spectrum of the luminescence, which propagated back through the same fiber. The source of the cyclotron radiation was a CO_2-pumped submillimeter laser. We used the laser lines $\hbar\omega = 10.4$ meV (at a power of 80 mW) and 7.6 meV (20 mW). The corresponding resonant magnetic fields were about 6.1 and 4.4 T, respectively. The changes in the resonant fields due to the changes in n_s upon changes in the power of the optical pumping were $\sim 4\%$.

The submillimeter radiation entered the cryostat from the top along a metal tube and was focused on the sample, in a spot ~ 5 mm in size, by a Teflon-type polymer lens. The submillimeter radiation was detected by a carbon bolometer behind the sample. Particular care was taken to bring the spot of the optical radiation and the spot of the probing submillimeter radiation into coincidence on the sample. For this purpose a metal diaphragm 1 mm in diameter was positioned in front of the sample. The fact that the lines of the cyclotron resonance and of the ODCR remain in the same positions as the power of the optical pumping is varied is evidence that the spots were brought into coincidence well. During the recording of a luminescence spectrum, the reference signal for the synchronous detector was taken from a shutter blocking the beam from the He–Ne laser. The reference signal from the shutter of the CO_2 laser was used to measure the ODCR. A magnetic field perpendicular to the surface of the sample was produced by a superconducting solenoid. The measurements were carried out at $T = 4.2$ K.

In the range of magnetic fields studied, the luminescence spectra have lines corresponding to Landau levels of the fundamental quantum-well subband, (0,0) and (0,1) [only the (0,0) line at the maximum optical-pumping power] and to the lowest-lying

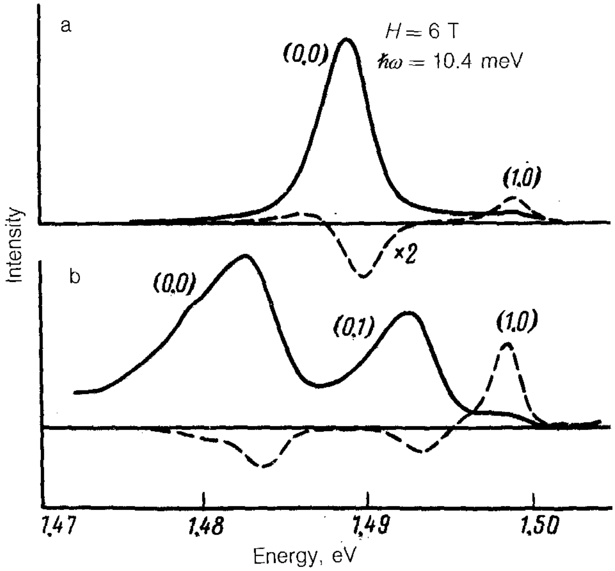

FIG. 1. Luminescence spectra (solid lines) and spectrum of the signal representing the optically detectable cyclotron resonance (dashed lines) for the submillimeter radiation line $\hbar\omega = 10.4$ meV in a magnetic field of 6 T. a—The power level of the optical pumping is 2 mW ($n_s = 2.6 \times 10^{11}$ cm^{-2}); b—20 μW ($n_s = 4.4 \times 10^{11}$ cm^{-2}).

level of the higher-lying (1,0) subband (Fig. 1). The luminescence intensity for the electrons in the (1,0) level is about an order of magnitude higher than that for the lowest-lying subband. The density of states at the Landau level in a field of 6 T is 1.45×10^{11} cm^{-2}. It thus follows from a comparison of the intensities of the lines of the filled level, (0,0) and (1,0) (Fig. 1b), that the electron density in the (1,0) level is well under 10^{10} cm^{-2}. The ODCR signal arises in the same magnetic fields in which we find the cyclotron resonance. The shape of the ODCR line as a function of the magnetic field is approximately the same as the shape of the cyclotron-resonance line (Fig. 2). It can be seen from the ODCR spectrum (Fig. 1) that cyclotron pumping significantly intensifies the (1,0) line (by a factor of up to 5), while it reduces the intensities of the (0,0) and (0,1) lines. The changes in the (0,0) and (0,1) lines occur mostly at the violet edge. This result is particularly clear in the spectra with a low pump power (about 20 μW), in which case the ODCR signal is completely missing from the red edge of these lines. Note that saturation of the cyclotron resonance does not result in an intensification of the (0,2) line (Fig. 1b), although this is the lowest-lying empty Landau level to which electrons undergo direct transitions at cyclotron resonance. On the other hand, the amplitude of the ODCR signal for the (0,0) and (0,1) lines is proportional to the intensities of these lines, although these levels lie at widely different distances from the Fermi level, so an increase in the electron temperature at cyclotron resonance should affect their intensities in different ways. We thus must conclude that the ODCR signal is due entirely to a change in the number of electrons in the (1,0) level.

The mechanism for the appearance of the ODCR signal appears to be as follows. The resonant cyclotron radiation sends electrons into the unfilled (0,2) level [or the (0,1) level], which lies above the (1,0) level. Since the lifetime of the electrons in this level is very short (less than 10^{-9} s), no significant population can be established in

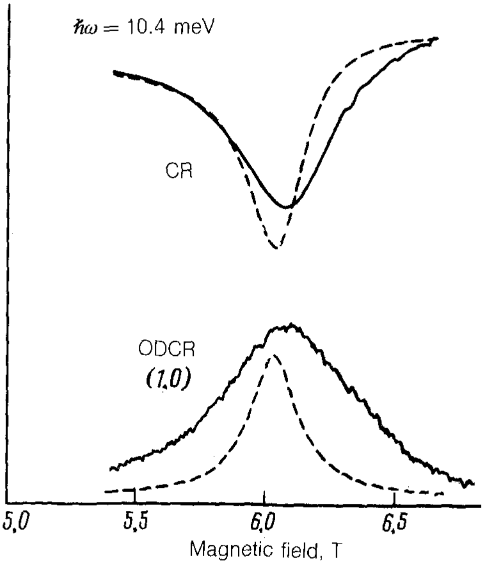

FIG. 2. Spectra of the cyclotron resonance and of the optically detectable cyclotron resonance recorded in the (1,0) line of the luminescence spectrum for the submillimeter radiation line $\hbar\omega = 10.4$ meV. Dashed lines—The power of the optical pumping is 2 mW; solid lines—20 μW.

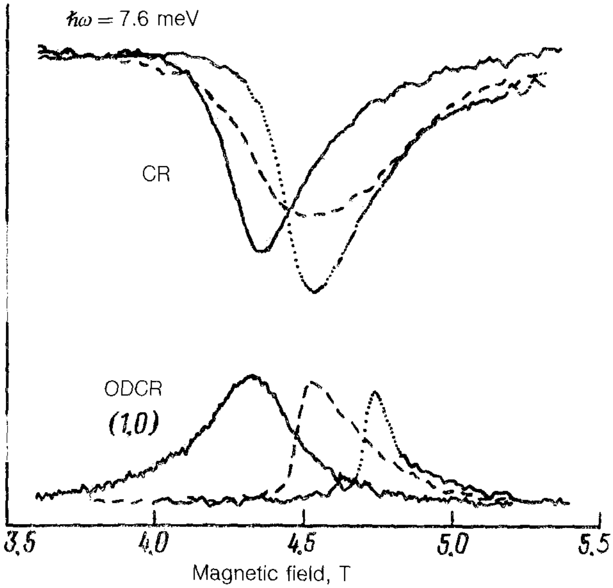

FIG. 3. Spectra of the cyclotron resonance and of the optically detectable cyclotron resonance recorded in the (1,0) line of the luminescence spectrum for the submillimeter radiation line $\hbar\omega = 7.6$ meV. Solid lines—The power of the optical pumping is 2 mW; dashed lines—20 μW; dotted lines—8 μW ($n_2 = 4.7 \times 10^{11}$ cm^{-2}).

this level. Electrons undergo a relaxation from the upper Landau level to lower-lying ones; some of these electrons go to the (1,0) level of the upper subband. The lifetime in the (1,0) level is long enough that a significant population can be built up there. On the one hand, an increase in the number of electrons in the upper subband leads to a change in the charge distribution in the z direction; this change alters the shape of the self-consistent potential. The latter change in turn causes the levels of the fundamental subband to descend, and the lines in the luminescence spectrum shift in the red direction. On the other hand, because of the high recombination rate of the electrons of the upper subband, an increase in the population of this subband reduces the number of holes in the δ-layer. The latter change results in a decrease in the intensities of the (0,0) and (0,1) lines.

Evidence in favor of this interpretation comes from the following fact. In the ODCR spectra for the submillimeter line $\hbar\omega = 7.6$ meV, the line is distorted at an optical-pumping power of about 20 μW. Specifically, part of the line on the side of weak magnetic fields is chopped off (Fig. 3). The intensification of the ODCR signal is linked with a crossing of the (0,2) and (1,0) levels, as was established in a study of the field dependence of the luminescence spectra. When the slightly populated (0,2) Landau level lies below the (1,0) level, nonequilibrium electrons cannot undergo transitions from the (0,2) level to the upper subband, and there is no ODCR signal. After the crossing of the (0,2) and (1,0) levels, nonequilibrium electrons find it possible to undergo transitions to the upper subband, and an ODCR signal arises. The width of the transition in the ODCR spectra corresponds to the temperature. The sharp intensification of the ODCR signal coincides roughly with the sharp decay of the intensity of the (1,0) line upon the crossing of levels.

The mechanism proposed here presupposes that the (1,0) level is the bottleneck in the process by which the hot electrons undergo relaxation. Evidence for this conclusion comes from direct measurements[4] of the electron lifetime in the (1,0) level, which have revealed that this lifetime is greater than 2×10^{-8} s. It is not clear at this point why the lifetime in the (1,0) level should be so long.

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[1] I. V. Kukushkin, K. von Klitzing, K. Ploog, and V. B. Timofeev, Phys. Rev. B **40**, 7788 (1989).

[2] R. Romenstein and C. Weisbuch, Phys. Rev. Lett. **45**, 2067 (1980).

[3] I. V. Kukushkin, K. von Klitzing, K. Ploog, *et al.*, Phys. Rev. B **40**, 4179 (1989).

[4] A. F. Dite, I. V. Kukushkin, K. von Klitzing, *et al.*, Pis'ma Zh. Eksp. Teor. Fiz., 1991. This Issue, p. 393 [JETP Lett. **54** (1991)].

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