Observation of anisotropy of the electronic energy spectrum of GaAs

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The dependence of the position and spin splitting of the cyclotron resonance line of electrons on the orientation of the magnetic field relative to the crystallographic axes is observed for the first time in a cubic semiconductor with the minimum of the conduction band centered in the Brillouin zone.

The energy spectrum of electrons near the bottom of the conduction band of gallium arsenide in a magnetic field **H** is determined by the Hamiltonian

$$\mathcal{H} = \frac{\hbar^2 K^2}{2m} + \frac{1}{2} g\mu_B (\vec{\sigma}\mathbf{H}) + a_1 K^4 + a_2 H^2$$

$$+ a_3 (\{K_x^2, K_y^2\} + \{K_x^2, K_z^2\} + \{K_y^2, K_z^2\}) + a_4 K^2 (\vec{\sigma}\mathbf{H})$$

$$+ a_5 \{(\vec{\sigma}\mathbf{K}), (\mathbf{K}\mathbf{H})\} + a_6 (K_x^2 \sigma_x H_x + K_y^2 \sigma_y H_y + K_z^2 \sigma_z H_z), \quad (1)$$

where $\hbar\mathbf{K}$ is the kinematic momentum $\vec{\sigma}$ are the Pauli matrices, and μ_B is the Bohr magneton. The x, y, and z axes coincide with the principal crystallographic axes. The braces denote an anticommutator. The Hamiltonian is written with an accuracy to within terms appearing in fourth-order **K p** perturbation theory.[1] The third-order term with respect to **K**, which is attributed to the absence of an inversion center in the GaAs

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crystal (in a strong magnetic field its contribution is relatively small), is omitted in it. The third and fifth terms in expression (1) describe the **K** dependence of the effective mass of the electron, and the last three terms describe the **K** dependence of the effective g factor. The terms containing the coefficients a_3 and a_6 account for the anisotropy of the spectrum, i.e., they account for the dependence of the mass and g factor on the orientation of the magnetic field relative to the crystallographic axes. These terms appear in the Hamiltonian exclusively due to the interaction of the conduction band with higher bands.[3] For this reason, the anisotropy must be very small (for GaAs it is ~ 0.1–1% in a field of 10^5 Oe), and it is extremely difficult to observe it.

We have investigated the cyclotron resonance (CR) in free electrons and studied the spin splitting of the CR line into two components. The splitting is attributable to the nonparabolic nature of the conduction band, i.e., to the difference between the g factors of different Landau levels.[3–5] The main result is the observation of anisotropy of this splitting and of the position anisotropy of the doublet as a whole. The first case is related to the anisotropy of the g-factor and the second one stems from the anisotropy of the cyclotron mass. In addition, we have observed analogous effects for impurity CR(the photoexcitation lines of fine donors $1s \rightarrow 2p_{+1}$).

We have investigated pure layers of n-GaAs ($N_D - N_A = (0.2 - 2.7) \times 10^{14} \text{cm}^{-3}$, $\mu_{77} = (1.0 - 1.7) \times 10^5 \text{cm}^2\,\text{V}^{-1}\,\text{s}^{-1}$), which were grown by the method of gas-transport epitaxy. The measurements were performed in a high-resolution submillimeter laser magnetospectrometer.[5] The radiation sources ($\hbar\omega = 3.68 - 17.59$ meV) were the gas-discharge H_2O, D_2O, and HCN cw lasers and CH_3OH a laser used in conjunction with a tunable CO_2 laser for optical pumping. The photoconductivity (PC) spectra were recorded at fixed laser frequencies by scanning the magnetic field ($\mathbf{H} \leqslant 80$ kOe) at $T = 4.2$K in the Voight geometry.

Figure 1a shows the sections of the PC spectra of GaAs sample ($N_D - N_A = 6.6 \times 10^{13}$ cm^{-3} and $\mu_{77} = 1.7 \times 10^5$ cm^2 V^{-1} s^{-1}), corresponding to the CR line with energy of the radiation quanta $\hbar\omega = 12.85$ meV. By rotating the sample in the (001) plane we were able to observe a displacement δ of the center of the doublet of the CR line from the minimum **H** at H||[100] to the maximum H at H||[110]. The distance between the components of the doublet Δ, which depends on the orientation of **H**, is maximum at H||[110] and minimum at H||[100] (Δ_{110} and Δ_{100} in Fig. 1a).

A calculation based on (1) leads to the expressions

$$\delta = \frac{6a_3 e^2}{\hbar^2 c^2} \frac{H_x^2 H_y^2 + H_x^2 H_z^2 + H_y^2 H_z^2}{H^2},$$

$$\Delta = \frac{4e}{\hbar c}\left(a_4 H^2 + a_6 \frac{H_x^2 H_y^2 + H_x^2 H_z^2 + H_y^2 H_z^2}{H^2}\right) \tag{2}$$

for transitions between the zeroth and first Landau levels of electrons with zero momentum along **H**. These dependences are in excellent agreement with the experimental dependences (see Fig. 2) at $a_3 = -1.2 \times 10^{-29}$ eV cm^4, $a_4 = 9.7 \times 10^{-23}$ eV cm^2 Oe^{-1}, and $a_6 = 4.9 \times 10^{-23}$ eV cm^2 Oe^{-1}. The parameters of Hamiltonian (1) obtained in this

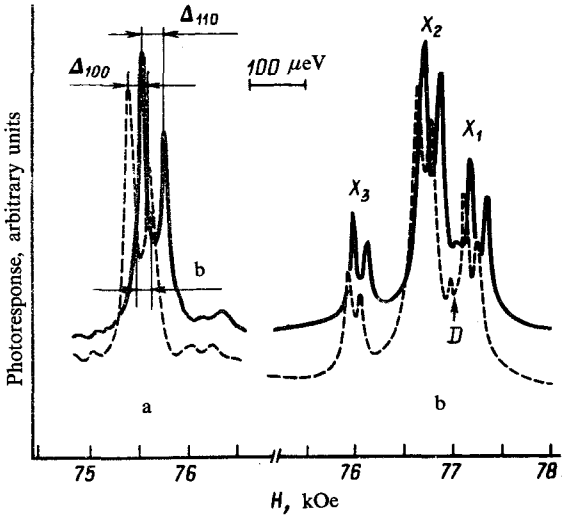

FIG. 1. Photoconductivity spectra of GaAs in a magnetic field. (a) Cyclotron resonance line and (b) line corresponding to photoexcitation of fine donors $1s \rightarrow 2p_{+1}$. The solid curves are for **H**||[110] and the dashed curves are for **H**||[100].

this manner are approximately equal to the values computed using **K p** perturbation theory, which takes into account the interaction of only the three nearest bands. When **H** is rotated in the (111) plane, the anisotropy, in accordance with (2), was not observed.

Figure 1b shows the spectra of impurity CR ($\hbar\omega = 17.59$ meV). The orientational dependence of the spin splitting and of the displacement of the centers of the doublets

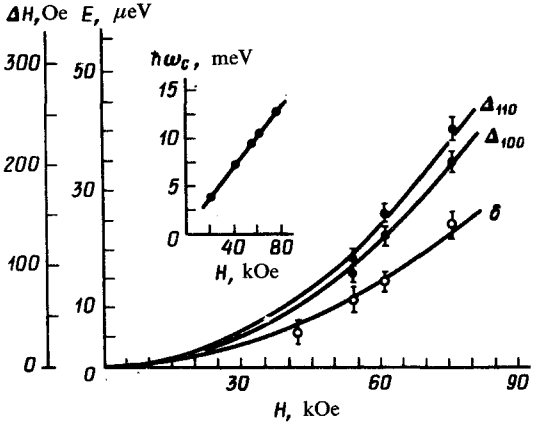

FIG. 2. The spin splitting (Δ) and the displacement (δ) of the cyclotron resonance line versus the orientation and intensity of the magnetic field. The inset shows the dependence of the cyclotron energy $\hbar\omega_c$ on the magnetic field.

of the lines $1s \rightarrow 2p_{+1}$ corresponding to different donors (X_1, X_2, X_3, and D, using the notation in Refs. 7 and 8), is analogous to that shown in Fig. 1a. We note that in strong magnetic fields, when the cyclotron energy is on the order of the Bohr energy, the displacement and splitting of the lines are comparable to the differences in the chemical shifts.

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