Landau quantization and the intensity of interband absorption in gallium arsenide in superstrong magnetic fields

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The dependence of the coefficient of absorption of light with $\lambda = 0.6328\ \mu$m in GaAs has three characteristic features at fields of $B = 0.5$, 1.5, and 4.3 MG. At $B > 4.3$ MG the sample is transparent. The interpretation is based on the calculation of the Landau shift of the hole and conduction electron band edges, taking into account the field dependence of the effective masses.

It is well known that the effective-mass approximation in an ideal semiconductor takes into account the interaction of bands due to the operator $\hat{H}_1 = \hbar(\mathbf{k}\cdot\hat{\mathbf{p}})/m_0$ (the *kp* method). In the presence of impurities and external (magnetic or electric) fields it is necessary, strictly speaking, to introduce a new effective mass m^*, if the additional perturbation substantially changes the interaction of bands. The strong dependence $m_c^*(B)$ was observed in InSb in fields up to 300 kG[1] and in fields up to 1.4 MG[2] based on measurements of the cyclotron resonance. In GaAs such a dependence (in the range of 20%) was found in a field of 0.94 MG for the transition $N = 2 \rightarrow N = 3$ in the conduction band.

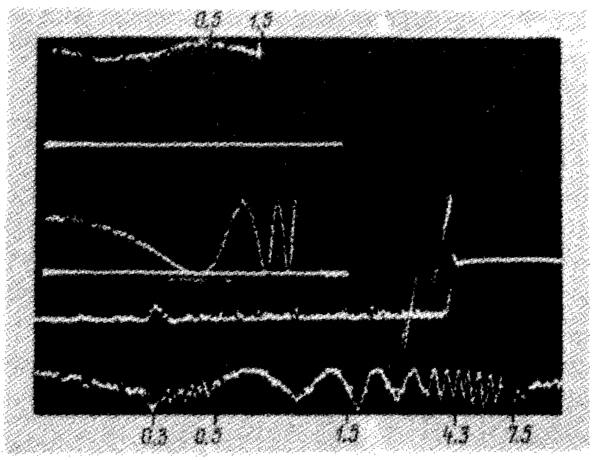

FIG. 1. Upper oscilloscope trace: absorption coefficient ($\lambda = 0.633\ \mu$m); bottom oscilloscope trace: Faraday effect in Tf-5 glass ($V = 0.0526$ min/cm · B), sample length $l = 0.315$ cm. The distance between max and min (90° angle) corresponds to $B = 0.326$ MG. A reference marker appears in both traces at a field of $\simeq 0.3$ MG. The inset (upper left) shows the same situation but with a more sensitive photomultiplier, $l = 0.205$ cm. The numbers indicate the field induction in MG.

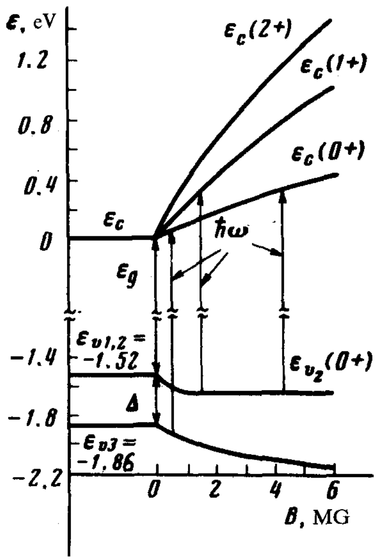

FIG. 2. Splitting of bands in GaAs in fields up to 6 MG [the solution of Eq. (2)].

We have measured the absorption of pure GaAs (semitransparent film $\simeq 11$ μm thick) at a wavelength $\lambda = 0.6328$ μm for the purpose of determining the dependence of $m^*(B)$. The field, which was generated in an explosive device[3] was built up to 8 MG. Since $\hbar\omega = 1.95$ eV, and since the width of the forbidden band is $\epsilon_g = 1.52$ eV, there is a strong interband absorption at $B = 0$. The dependence of the intensity of the transmitted radiation on the induction of the external field is shown in Fig. 1. We see in this figure two distinct features: a sharp increase in transmission in fields of 1.5 and 4.3 MG (the fields were determined to within $\simeq 5\%$). At $B > 4.3$ MG the sample is transparent to red light. There is one other weak feature: the transmission increases in a field $B \simeq 0.5$ MG.

The interpretation of these phenomena is based on the structure of the bands of GaAs (Fig. 2). For GaAs a nonparabolic dispersion law, which in a magnetic field gives the dependence $m^*(B)$, is characteristic. The band structure and the dispersion law of semiconductors such as GaAs were analyzed in Refs. 4 and 5 in the four-band approximation: conduction electrons ϵ_c and light ϵ_{v2}, heavy ϵ_{v1}, and spin-detached ϵ_{v3} holes, with allowance for the four terms in the Hamiltonian $\hat{H}_0 \simeq 1.63$ eV (splitting of the bands ϵ_c and ϵ_v), spin-orbit splitting of the valence band $\Delta = 0.34$ eV, $H_1 \simeq kP(P^2 = \hbar^2\langle c|p_z|v\rangle^2/m_0^2 = 10^{-14}$ eV^2 cm^2, and the Zeeman interaction energy.

$$\hat{H}_z = \frac{x\hat{p}_y}{L^2 m_0} + \frac{x^2}{2L^4 m_0} \pm \mu_B B, \qquad (1)$$

where m_0 is the mass of the free electron, and $L = \sqrt{\hbar c/eB}$ is the magnetic length. Since the states ϵ_{v1} do not interact with the remaining energy levels of the remaining three bands, we find the following equation for both spin projections:

$$\epsilon_{N^\pm}(\epsilon_{N^\pm} + \epsilon_g)(\epsilon_{N^\pm} + \epsilon_g + \Delta) - P^2 [k_z^2 + (2N+1)/L^2]$$
$$\times (\epsilon_{N^\pm} + \epsilon_g + 2\Delta/3) \pm \frac{1}{2} g^* \mu_B B \epsilon_g (\epsilon_g + \Delta) = 0. \quad (2)$$

In (2) $N = 0, 1, 2, \ldots$ is the number of the Landau level, and $m_c^* = 0.066 m_0$, $g^* = [-2m_0\Delta/m_c^*(2\Delta + 3\epsilon_g)] + 2$. The zero point is assumed to be ϵ_c at $B = k = 0$. The field dependence of $\epsilon_{c,v2,3}(N+)$ (calculation) is shown in Fig. 2. We see an appreciable nonlinearity of the splitting ϵ_c into Landau subbands with increasing B. In a field of 4.3 MG we would have $m_c^*(B)/m_c^* = 1.12$, 1.44, and 1.60 for $N = 0$, 1, and 2, respectively. The effective mass of light holes, beginning with fields $\simeq 1$ MG, increases linearly with B, so that $\Delta\epsilon_{v2} = -eB/2m_{v1}^* c$ does not depend on the field and is equal to -0.12 eV. Physically, this is linked with the "repulsion" of Landau levels in the adjacent ϵ_{v2} and ϵ_{v3} bands.

The structural feature in the field $B = 0.5$ MG could be due to the vanishing of absorption between the spin-detached band and the conduction band. The energy gap is $\epsilon = \epsilon_c(0) - \epsilon_{v3}(0) = 1.97$ eV. In fields $B > 0.5$ MG some growth of the transmission coefficient $\kappa(B)$ is observed. The drop followed by the sharp increase in $\kappa(B)$ in the region of 1.5 MG, characterizes the change in the state density ϵ_c as a result of the transition through the Landau level with $N = 1$. If the transition $\epsilon_{v2}(0) \rightarrow \epsilon_c(1)$, is taken into account, then in this field there is also a resonance: $\hbar\omega \simeq \epsilon_c(1) - \epsilon_{v2}(0) = 0.34 + (1.52 + 0.12) = 1.98$ eV. The peak in the transmission can be observed only if the sensitivity of the photomultiplier is high (the inset in Fig. 1). In this field $m_c^*(1)$ increases by 15%. The value of κ increases sharply in fields exceeding 4.3 MG because the width of the forbidden band $\epsilon_c(0) - \epsilon_{v2}(0)$ exceeds the energy of the quantum. The mass $m_c^*(0)$ increases by 12% and $\epsilon_c(0)$ is 0.333 eV. In these fields GaAs becomes optically transparent and its coloring in reflected light changes from a red to a yellow shade ($\lambda = 0.58\ \mu$m at $B = 10$ MG if the dependence $m_c^*(B)$, $N = 0$ is taken into account. Data on the cyclotron resonance[2] ($\lambda = 10.6\ \mu$m, $\hbar\omega = 0.118$ eV) in GaAs in fields of 0.68 and 0.95 MG fit well into the band-interaction scheme (Fig. 2). Our calculations give $\Delta\epsilon(0+, 1+) = 0.102$ eV and $\Delta\epsilon(2+, 3+) = 0.116$ eV, respectively, in these fields.

Thus the weak ($\simeq 15\%$) dependence $m_c^*(B)$ is attributable to the small value of the ratio H_z/H_1, which, as shown in Ref. 5, is on the order of $\alpha^2 = a^2(2N+1)/L^2$, where $a = 5.7$ Å is the lattice constant. Since $L(1.5) = 21$ Å and $L(4.3) = 12.3$ Å in both cases ($B = 1.5$ MG, $N = 1$, and $B = 4.3$ MG, $N = 0$) we have $\alpha^2 \simeq 0.2$, i.e., the change in mass must not exceed 20%, which in order of magnitude coincides with the value found experimentally.

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