Quasi-one-dimensional electrons in a quantizing oblique magnetic field

I. V. Kukushkin and V. I. Fal'ko
Institute of Solid State Physics, Academy of Sciences of the USSR

K. von Klitzing, K. Ploog, and D. Heitmann
Max-Planck-Institut für Festkörperprobleme, Stuttgart, FRG

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The spectrum of quasi-one-dimensional electrons in an oblique magnetic field is analyzed by a magnetoluminescence analysis. A magnetic anisotropy produced by altering the relative orientation of the field and the filaments is identified and employed to estimate the parameters of the holding potential.

1. The properties of quasi-one-dimensional electron systems have been widely analyzed in magnetotransport[1] and magnetocapacitance measurements,[2] in IR-absorption measurements, including cylcotron resonance,[3] as well as Raman scattering,[4] and luminescence[5] studies. In spite of such research, there are no direct methods of determining the primary parameters of the energy spectrum of quasi-one-dimensional electrons or the characteristics of the potential generating the filament. Our preceding experiment[6] demonstrated that oblique magnetic field measurements may contain information for testing a potential well of any dimensions.

2. In this paper we analyze the luminescence spectra of quasi-one-dimensional electron structures fabricated from a single heterojunction, in a strong oblique magnetic field. In our case, the characteristic linear dimensions L_Y of the quantizing potential in the heterostructure plane far exceed the magnetic length λ_H, while we have an arbitrary relationship between the width L_Z of the well in the growth direction and λ_H. The situation with respect to the electronic spectrum is obvious in two limits; a relatively weak magnetic field, $\lambda_H \gg L_Z$, and a relatively strong magnetic field, $\lambda_H \ll L_Z$. Motion transverse to the heterostructure is the faster motion in the first case while cyclotron rotation, which is weakly renormalized by the filament potential $\omega \approx eH_z/mc$, has a two-dimensional nature. The lower spectral levels in this case are different Landau levels from the lower subband. In the opposite limit, cyclotron rotation is the faster process. Such rotation is three-dimensional and the lower states of the one-particle spectrum take the form of a series of uniformly quantized states on the lower Landau level in a well that limits particle motion along the magnetic field: $E_n = \epsilon_n(\vec{H}/H) + \hbar eH/2mc$.

In the case of a homogeneous heterostructure, the shape of the effective one-dimensional potential well $U_{\vec{H}}(\eta)$ along the magnetic field is determined only by the angle of inclination, $U_{\vec{H}}(\eta) = U_0(\eta H_z/H)$, $U_0(z)$ is the shape of the well in the z direction. As a result, each of the spectral levels is infinitely degenerate in the position of the center of the cyclotron orbit, while the splittings $\epsilon_n(\vec{H}/H) - \epsilon_{n'}(\vec{H}/H)$ are independent of H and at $H_z/H \ll 1$ are small compared to the subband-to-subband splitting.[6] Modulation of the electron density in the heterojunction plane (in our case the filaments) makes this simple picture more complex. First, the potential $U_{\vec{H}}(\eta)$, which quantizes the electron motion along the magnetic field, is different for different relative orientations of $\vec{H}$ and the filament axis. Secondly, the electron energy depends on the position of the center of the cyclotron orbit, which lifts the degeneracy and accounts for asymmetrical line broadening (from the violet region).

As an illustration we consider the electron spectrum in the parabolic potential $\{m(\omega_y y)^2/2 + m(\omega_z z)^1/2\}$ and in an oblique magnetic field, $\vec{H} = (H_x H_y H_z)$, which can be found exactly. By appropriately selecting the canonical variables we can write the Hamiltonian of the system in terms of the increasing operator $b_j^+ = u_{ja} r_a + v_{ja} \partial_a$ and decreasing operator $b_j = u_{ja}^* r_a - v_{ja}^* \partial_a$ in the space of Hermitian polynomials with the commutation relations $[b_j^+ b_{j'}] = -\delta_{jj'}$ and $[b_j b_{j'}] = 0$, $j, j' = (-, +)$, in the diagonal form

$$\hat{H} = \hbar\omega_+\{b_+^+ b_+ + 1/2\} + \hbar\omega_-\{b_-^+ b_- + 1/2\} + p_z^2/2M. \tag{1}$$

Here the last term reflects the dependence of the energy of the boundary state in a magnetic field on the position of the center of the jumping orbit, and

$$\omega_\mp^2 = \frac{\omega_y^2 + \omega_z^2 + (eH/mc)^2}{2}$$

$$\mp\sqrt{\left(\frac{\omega_y^2 + \omega_z^2 + (eH/mc)^2}{2}\right)^2 - \left(\frac{\omega_y x e H_y}{mc}\right)^2 - \left(\frac{\omega_z e H_z}{mc}\right)^2 - \omega_y^2\omega_z^2}.$$

In the strongest-field limit the relation

$$E_n(\vec{H}) = \frac{\hbar e H}{2mc} + n\hbar\left((\omega_z H_z/H)^2 + (\omega_x H_x/H)^2\right)^{1/2} \tag{2}$$

gives a clear idea as to the behavior of the field and angular dependences of the spectral characteristics. Although the potential in our structures is far from a parabolic potential, in this brief report we will use Eqs. (2) as a simple illustration in discussing the measurement results.

3. We investigated quasi-one-dimensional systems based on a single GaAs–AlGaAs heterojunction, using a holographic method.[4] The quantum filaments 150 nm in width were separated by a distance of 150 nm. The doped AlGaAs layer was the only layer etched to the spacer during fabrication of the quasi-1D-structure. Individutal δ-doped heterojunctions[8] were used to make it possible to carry out a luminescence analysis of the quasi-1D-structure. A monolayer of atomic acceptors (Be) with a (BE) concentration of 10^{10} cm^{-2} was formed in these structures at a distance of 25 nm from the interface, so that photoexcitation of the sample would produce holes bound to these acceptors in the immediate vicinity of the electrons. The experimental results and parameters were reported in Refs. 5 and 7.

4. Figure 1 shows the dependences of the spectral position of the luminescence lines on the total magnetic field which were measured at a magnetic field inclination of

$\alpha = 78°$ relative to the heterojunction growth direction (along the z axis). This figure shows data for two cases: when the parallel magnetic field component is oriented along the quantum filaments (open circles) and when it is oriented transverse to these filaments (filled circles). As is evident from Fig. 1, a magnetic anisotropy is observed in the spectral position of the luminescence lines and in the splitting between the lines, as the relative orientation of the filaments and the magnetic field is varied. It was necessary to substantially incline the magnetic field through angles $\alpha = 75$–$80°$ in order to detect noticeable anisotropy, because dimensional quantization is substantially different along the y and z axes, and because the anisotropy manifests itself, as we can see from Eq. (2), only at large angles of inclination, $\tan\alpha > E^z/E^y \sim \omega_z/\omega_y$. As can be seen from Fig. 1, in a weak magnetic field the fan of Landau levels is determined by the normal component, while in fields that exceed a certain critical value the splitting between the levels no longer depends on the magnetic field. Such behavior is clearly evident in Fig. 2 which shows the curves of $\Delta E_{01}(\vec{H})$ and $\Delta E_{12}(\vec{H})$ measured for different orientations of the parallel magnetic field component: along the quantum filaments E^x and transverse to them E^{yz}. Using the measured quantities E^{xz}_{ik} and E^{yz}_{ik} and Eq. (2), we estimated the 1D quantization energies to be $E^y_{01} = 1.45$ meV, $E^y_{12} = 1.1$ meV.

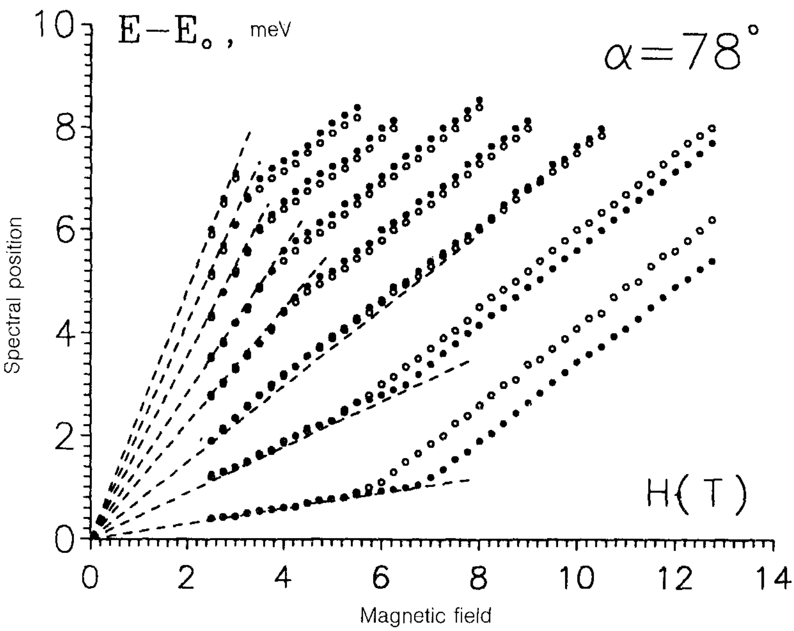

FIG. 1. The spectral position of the luminescence lines versus the total magnetic field measured at a magnetic field angle of inclination $\alpha = 78°$ relative to the direction of heterojunction growth (along the z axis). The open circles correspond to the parallel component of the magnetic field oriented along the quantum filaments, and the filled circles represent the transverse orientation of the magnetic field component.

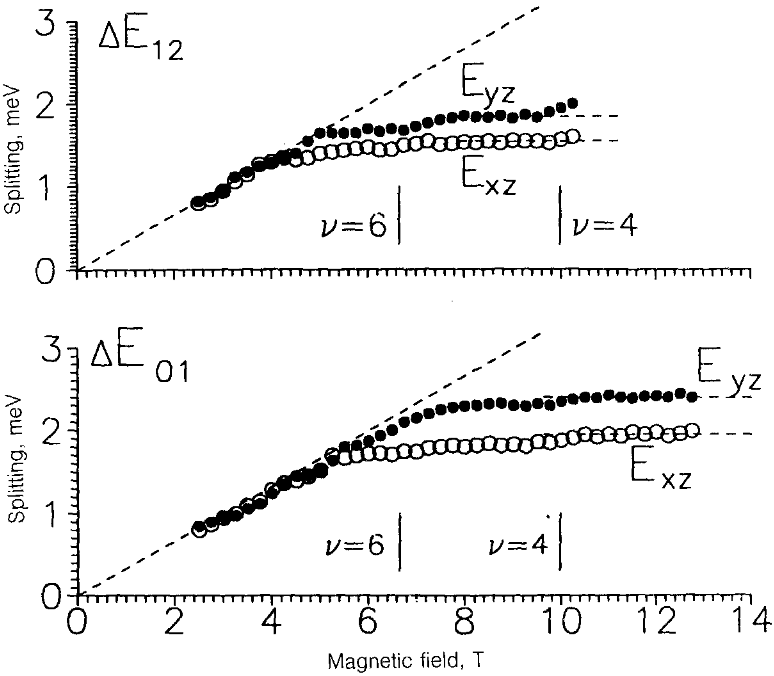

FIG. 2. The $\Delta E_{01}(\vec{H})$ and $\Delta E_{12}(\vec{H})$ curves measured for different orientations of the parallel magnetic field component: along the quantum filaments E^{xz} and transverse to these filaments E^{yz}.

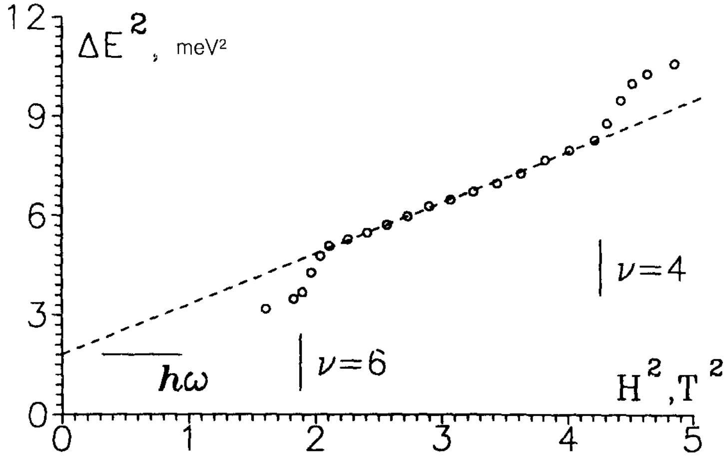

FIG. 3. The $\Delta E(H)$ curve measured in a perpendicular magnetic field for a concentration 2×10^{11} cm^{-1} in the range of filling factors $4<\nu<6$.

Using Eq. (2) to estimate the dimensional quantization is not well founded, since the potential well is nonparabolic along the z axis[6] (the difference in E^y_{01} and E^y_{12} noted by us is attributable to this circumstance). We have therefore analyzed the dependence of splitting between levels on the magnetic field in the case $\vec{H} \| z$. With this orientation, as demonstrated previously,[5] splitting between the quantum levels ΔE is determined by the cyclotron quantization $\hbar\omega_c$ and by one-dimensional quantization E^y_{ik}:

$$\Delta E^2 = \hbar\omega_c^2 + (E^y_{ik})^2. \tag{3}$$

Figure 3 shows the curve of $\Delta E(H)$ measured for the same concentration, 2×10^{11} cm^{-2}, and in the same range ν $(4<\nu<6)$, plotted in coordinates corresponding to Eq. (3). We determined $E^y_{01} = 1.35$ meV from an extrapolation of the experimental relation to $H=0$.

The estimates of 1D quantization obtained in oblique and perpendicular magnetic fields are therefore similar. We note that an abrupt change in the splitting was observed in each case as the number of occupied levels changed (see Figs. 2 and 3). This abrupt change is associated with the change in the shape of the well and will be discussed separately.

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