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Interband magnetoabsorption study of the shift of the Fermi energy of a 2DEG with an in-plane magnetic field

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Abstract

We investigate experimentally and theoretically the effects of an in-plane magnetic field on the two-dimensional (2D) electron gas via a shift of the Fermi energy in the interband magnetoabsorption. It is shown that the Fermi edge may either shift up (blue) or down (red) in an in-plane magnetic field. The shift depends on the relative strength of two components: (i) the diamagnetic shift of subband edge and (ii) an increase of the 2D density of states which lowers the Fermi energy with respect to the subband edge.

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1. Introduction

The two-dimensional (2D) electron gas in a magnetic field has been an attractive system both for theoretical and experimental studies. The reduced dimensionality of the system makes its properties substantially different from those of bulk crystals.

The case of the magnetic field directed perpendicular to the plane of the structure has been most widely investigated. In this configuration, electron/hole motion in the quantum well plane is quantized by the magnetic field while motion along-the-field is quantized due to the confining potential of the well. As a result, the step-like 2D density of states transforms in a magnetic field into a highly degenerate δ-like 0D density of states corresponding to the Landau Levels.

The situation when the magnetic field is in the plane of the well has been less investigated. In this case, there are no dramatic changes in the nature of the motion of the electron. The in-plane motion remains quasi-free and the density of states maintains a step-like form. Here, the magnetic field has two effects. First, it produces a diamagnetic shift of the subband energies. In addition, it increases the 2D density of states, resulting from the anisotropy of the electron effective mass in the plane of the structure: motion along the field remains untouched while the effective mass in the direction perpendicular to the field increases with increasing magnetic field [1,2].

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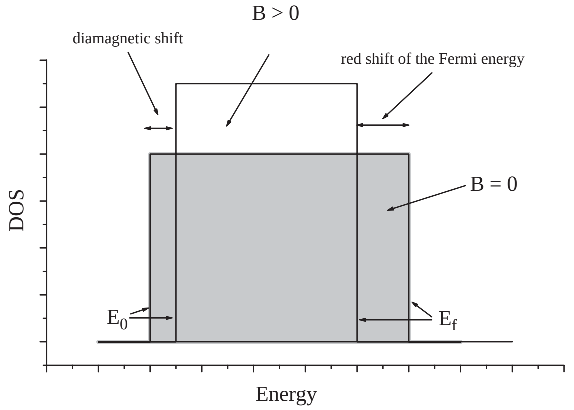

Fig. 1. Schematic diagram of evolution of the Fermi energy in the in-plane magnetic field. The gray region represents density of states in zero field. In the magnetic field, the subband energy E_0 is diamagnetically shifted. Nevertheless, due to increase of the 2D density of states, $E_{\rm f}$ may reveal red shift.

The most popular methods to probe the influence of in-plane magnetic field on the electronic states in quantum heterostructures are the study of Shubnikov–de Haas oscillations [3–5] and far-infrared cyclotron resonance [5] in tilted magnetic fields. The strong in-plane component of the magnetic field in these experiments induces changes in the in-plane electron effective mass. This in turn affects the Landau quantization resulting from the small perpendicular part of the magnetic field.

We investigate the effects of an in-plane magnetic field by direct measurement of the shift of the Fermi energy in interband magnetoabsorption experiments. This allows us to simultaneously study both the diamagnetic shift of the subband energies as well as changes to the density of states. Indeed, the evolution of the Fermi edge in the in-plane magnetic field depends on both of these processes, and as a result, can either go up or down with the application of an in-plane magnetic field. If the diamagnetic effect dominates, the Fermi energy reveals a blue shift, while in the opposite case it is red shifted (see Fig. 1). Due to the competition between these two mechanisms, the position of Fermi edge becomes sensitive to carrier concentration and details of energy band structure.

2. Theory

We consider electronic states in a quantum well with a confining potential $V(y)$ in the in-plane magnetic field $\mathbf{B}=(0,0,B)$. By choosing the Landau gauge for the vector potential $\mathbf{A}=(-yB,0,0)$ the electron energy and wave function can be presented in the form

$$\Psi=\frac{1}{\sqrt{S}}\,\mathrm{e}^{\mathrm{i}k_x x}\mathrm{e}^{\mathrm{i}k_z z}\chi(y), \tag{1}$$

$$E=\varepsilon+\frac{\hbar^2k_x^2}{2m^*}+\frac{\hbar^2k_z^2}{2m^*}, \tag{2}$$

where S is the sample area. Energy ε and function χ are solutions of 1D Schrödinger equation with Hamiltonian

$$\hat{H}=\frac{\hat{p}_y^2}{2m^*}+V(y)+\frac{\hbar k_x eB}{m^*c}\,y+\frac{\mathrm{e}^2B^2}{2m^*c^2}\,y^2. \tag{3}$$

For a parabolic confining potential $V(y)$ an exact solution exists [6]. In the general case, the last two terms in the Hamiltonian (3) can be treated as a perturbation for small magnetic fields. The use of perturbation theory is justified if the magnetic field-induced corrections are much smaller than the energy difference between the unperturbed states. Let $\varepsilon_i^{(0)}$ and ψ_i be solutions of the unperturbed Hamiltonian. Then the diamagnetic shift of size-quantized energy levels is given by the first-order expression

$$\varepsilon_i^{(1)}=\frac{\mathrm{e}^2B^2}{2m^*c^2}\langle y^2\rangle_{ii}, \tag{4}$$

where $\langle\ldots\rangle_{ij}=\langle\psi_i|\ldots|\psi_j\rangle$. For simplicity, we assume that the potential $V(y)$ has reflection symmetry and thus parity is a good quantum number. Hence, only the last term in Eq. (3) contributes to (4). Since the diamagnetic shift is proportional to $\langle y^2\rangle_{ii}$, it increases with increase of the subband quantum number i.

Our calculations show that the main contribution to the second-order correction $\varepsilon_i^{(2)}$ comes from the nearest lying localized states with $j=i\pm 1$. If the ith state in the quantum well has no higher lying localized states, then the contribution from the continuous spectrum should be taken into account. For the ground state ($i=0$), the second-order correction is

$$\varepsilon_0^{(2)}\approx-\frac{\hbar^2k_x^2}{2m^*}\,\frac{2\mathrm{e}^2B^2}{m^*c^2}\,\frac{\langle y\rangle_{01}^2}{\Delta E}, \tag{5}$$

where $\Delta E=\varepsilon_1^{(0)}-\varepsilon_0^{(0)}$ is the energy difference between the ground and the first excited states in the quantum well. Note that since the energy correction depends on k_x, the conditions for validity of perturbation theory can be violated for large k_x even in small magnetic fields.

The energy spectrum for the ground subband is

$$E \approx \varepsilon_0^{(0)} + \varepsilon_0^{(1)} + \frac{\hbar^2 k_z^2}{2m^*} + \frac{\hbar^2 k_x^2}{2m_\perp}, \tag{6}$$

where $\varepsilon_0^{(0)}$ is given by Eq. (4) and

$$\frac{1}{m_\perp} = \frac{1}{m^*}\left(1 - \frac{2e^2B^2}{m^*c^2}\frac{\langle y\rangle_{01}^2}{\Delta E}\right) \tag{7}$$

is the new effective mass in the direction perpendicular to the field and in the plane of the quantum well. Electrons become heavier in the direction perpendicular to the field. Note that the increase of the perpendicular effective mass $m_\perp$ in the magnetic field always occurs only for ground-state subband. For excited subbands, second-order correction may be positive and $m_\perp$ may decrease in the magnetic field.

The 2D density of states for dispersion (6) has the form

$$\rho_{2D} = \begin{cases} 0, & E < \varepsilon_0^{(0)} + \varepsilon_0^{(1)}, \\ \dfrac{S}{\pi\hbar^2}\sqrt{m^* m_\perp}, & E > \varepsilon_0^{(0)} + \varepsilon_0^{(1)}. \end{cases} \tag{8}$$

The Fermi energy thus reads

$$E_f = E_0(B) + \frac{\pi\hbar^2 n}{\sqrt{m^* m_\perp}}, \tag{9}$$

where n is 2D carrier concentration and $E_0(B) = \varepsilon_0^{(0)} + \varepsilon_0^{(1)}$. Here, we assume that only lowest subband is occupied $E_f < E_1$.

From Eq. (9), the Fermi energy shift is determined by both the diamagnetic shift of subband energy and the change of the density of states resulting from the in-plane magnetic field. The combined effect of these two mechanisms was studied by Salis et al. [3] where for the case of two occupied subbands ($E_1 < E_f < E_2$), they considered the process of carrier redistribution in the in-plane field. Note, that in their case both mechanisms act in the same direction, resulting in the depopulation of higher lying subband. In our case, the diamagnetic shift increases the Fermi energy while the change of the density of states acts in opposite direction. The evolution of E_f is thus determined by the competition between these two processes as shown in Fig. 1. As a result, the magnetic field dependence of Fermi edge becomes sensitive to the carrier concentration and details of energy structure. This can be seen explicitly if we expand the square root in Eq. (9) in powers of B

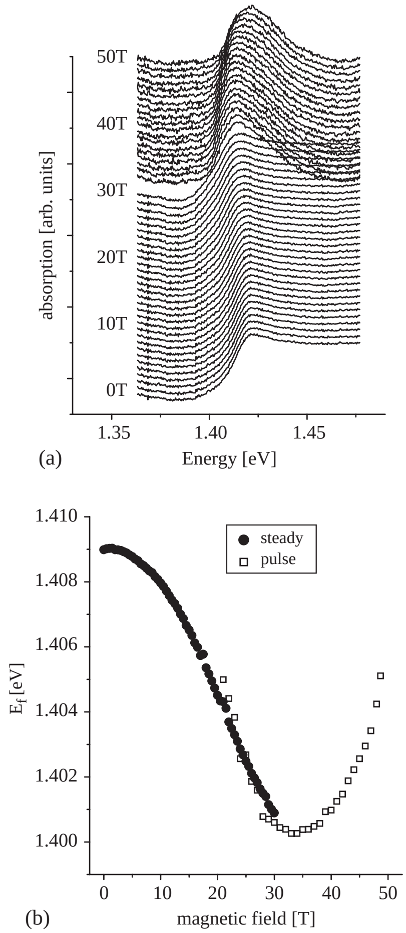

Fig. 2. Absorption spectra (a) and evolution of Fermi edge (b) in the in-plane magnetic field in n-doped 70-Å wide $In_{0.19}Ga_{0.81}As/Al_{0.41}Ga_{0.59}As$ quantum well.

$$E_f \approx E_f(0) + \frac{e^2B^2}{2m^*c^2}\left(\langle y^2\rangle_{00} - 2\langle y\rangle_{01}^2\frac{E_f(0)}{\Delta E}\right), \tag{10}$$

where $E_f(0)$ is zero field Fermi energy with respect to the subband bottom. The exact behavior of Fermi energy in the magnetic field is determined by the ratio $E_f(0)/\Delta E$ and by the matrix elements of coordinates on unperturbed functions.

Electrostatic interaction between carriers and ionized impurities in modulation doped structures changes the initial shape of quantum well potential affecting the energy spectrum and wave functions. To obtain quantitative results one should solve the Schrödinger and Poisson equations self-consistently

[7]. This is not our aim in the present work. To get a qualitative picture we consider a deep rectangular quantum well of width L with wave functions

$$\psi_0 = \sqrt{\frac{2}{L}} \cos\left(\frac{\pi y}{L}\right), \quad \psi_1 = \sqrt{\frac{2}{L}} \sin\left(\frac{2\pi y}{L}\right). \quad (11)$$

By substituting the wave functions (11) into Eq. (10), we obtain

$$E_f \approx E_f(0) + \frac{e^2 B^2 L^2}{60 m^* c^2} \left(1 - 2\frac{E_f(0)}{\Delta E}\right). \quad (12)$$

If the Fermi energy in zero magnetic field ($E_f(0)$) is higher than half of the energy separation between the ground and first excited states in quantum well, then the Fermi energy should red shift in the magnetic field. In the opposite case it should be blue shifted. Using oscillator wave functions instead of Eq. (11) will produce the same result. The critical value of ratio $E_f(0)/\Delta E$ that separates "blue shift" and "red shift" behavior of Fermi energy is also one half.

3. Experiment and discussion

Our experiment was performed on n-type modulation doped 70-Å wide $In_{0.19}Ga_{0.81}As/Al_{0.41}Ga_{0.59}As$ quantum well. Fig. 2 presents the absorption spectra and shift of the Fermi edge as a function of the in-plane magnetic field. Data for magnetic fields up to 30 T were obtained in a steady resistive magnet, while for higher fields, a pulsed magnet was used.

In agreement with the second-order perturbation result, the position of the Fermi edge changes quadratically for small fields. In our sample, the Fermi energy decreases with an increase of the field. As seen from Eq. (10), the exact behavior (increase or decrease as a function of in-plane field) of the Fermi energy is determined by the ratio $E_f(0)/\Delta E$ and details of the confining potential. Shubnikov–de Haas oscillations indicate that the 2D carrier concentration in our sample is $n = 1.42 \times 10^{12}$ cm^{-2}. For the electron effective mass, we used the $In_{0.19}Ga_{0.81}As$ bulk value $m^* = 0.057 m_0$, calculated by a 30-band $\mathbf{k} \cdot \mathbf{p}$ model [8]. This gives us an estimated Fermi energy in zero magnetic field of $E_f(0) \approx 60$ meV. Far-infrared intersubband resonance experiments gave us the value of the energy separation between the ground and first excited subbands $\Delta E \approx 170$ meV. The ratio $E_f(0)/\Delta E \approx 0.35$ and according to Eq. (12), we should expect, in deep rectangular quantum well, a blue shift of Fermi energy in the magnetic field. The fact that a red shift of E_f is observed indicates that the high carrier concentration and the strong electrostatic interaction with ionized impurities significantly modifies the shape of confining potential.

It is seen from Fig. 2 that at magnetic fields above 30 T, the Fermi energy increases. This behavior is beyond second-order perturbation theory. Since the corresponding magnetic fields ~ 30 T could still be treated as perturbation for our sample, we believe that higher order calculations may describe the change of character of Fermi energy evolution.

4. Conclusions

We have investigated the effects of in-plane magnetic field on the 2D electron gas by direct study of position of Fermi energy. As a result of competition of diamagnetic shift of subband energies and increase of 2D density of states, the Fermi energy evolution in the in-plane field is sensitive to the carrier concentration and details of energy structure. second-order perturbation theory was used to obtain the main features of magnetic field dependence of the Fermi energy. Experiments indicate the necessity of higher order calculations to describe the evolution of the Fermi edge in high in-plane magnetic fields.

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