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STRONG REDUCTION OF THE FERMI ENERGY OF TWO-DIMENSIONAL ELECTRONS IN PARALLEL MAGNETIC FIELD

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A strong reduction of the Fermi energy of two-dimensional electrons in parallel magnetic field was directly observed in magnetooptical experiment. The reduction is higher for lower electronic concentration. The observed effect could be associated with a modification of the energy spectrum of two-dimensional electrons by in-plane magnetic field.

1. The effective mass of two-dimensional (2D) electrons and their Fermi energy are very important parameters, which define different physical phenomena. For example, critical temperature of Wigner crystallization of 2D-electrons is governed by the ratio between Coulomb and kinetic energies of electrons. A possibility to change an effective mass of 2D-electrons by parallel magnetic field was indicated by Ando [1], who considered a magnetic field as a perturbation. An exact solution of the influence of strong parallel magnetic field on the energy spectrum of 2D-electrons was found in [2,3] for a model in which a potential confinement of 2D-electrons was a parabolic quantum well. For this model, in the limit of very strong magnetic fields, when magnetic energy $\hbar\omega_c$ strongly exceeds the energy of 2D-confinement $\hbar\omega_0$, the effective mass of electrons in the direction of magnetic field remains unchanged, whereas it is strongly increased (as $(\omega_c/\omega_0)^2$) in the perpendicular direction. This results in an enhancement of the density of states mass and therefore, in a reduction of the Fermi energy $E_F = E_F(\omega_0/\omega_c)$.

The effective mass of 2D-electrons in a parallel magnetic field was measured in plasmon resonance experiment [4], however, only a small increase (about 15%) of mass was detected. The main reason of the observed small changes of effective mass was rather high concentration of 2D-electrons, so that a confinement energy (intersubband splitting $E_{10} = 35\,\mathrm{meV}$ [4]) was much higher than a magnetic one ($\hbar\omega_c < 20\,\mathrm{meV}$).

A direct optical method useful for determination of the Fermi energy of 2D-electrons is based on the study of radiative recombination of 2D-electrons and holes bound to accepters [5]. In such measurements a distribution function of 2D-electrons directly visible in luminescence spectrum, because the probability of recombination does not depend on the energy of recombining electrons. The situation remains the same in perpendicular magnetic field, and the density of states could be directly observed in luminescence spectra. However, in the case of parallel magnetic field the wave functions of 2D-electrons depend on the energy of in-plain motion of 2D-electrons [3] (due to the Lorentz force) and luminescence spectrum does not directly reflect the density of states of 2D-electrons [6].

In present work we derived the Fermi energy of 2D-electrons in parallel magnetic field from the luminescence spectra by use of small component of perpendicular field, which results in a splitting of the spectra into Landau levels. From the Landau levels fan diagram the positions of the Fermi energy and of the subband bottom were established.

2. We studied high quality GaAs/AlGaAs single heterojunctions with 1000 nm GaAs buffer layer in which a monolayer of accepters (with concentration $10^{10}\,\mathrm{cm}^{-2}$) was created at the distance of 30 nm away from the interface. It was possible to vary the concentration of 2D-electrons in the range $(1.5\text{-}5)\cdot 10^{11}\,\mathrm{cm}^{-2}$ by the intensity of illumination. For excitation we used Ar^{+} or HeNe lasers. The luminescence was detected by photon counting system with the use of double spectrometer, which give us a spectral resolution about 0.05 meV. Simultaneously with optical investigations we performed transport measurements to control the concentration of 2D-electrons and for accurate determination of the parallel and perpendicular components of the magnetic field. Other details of experiment was published in [5,7].

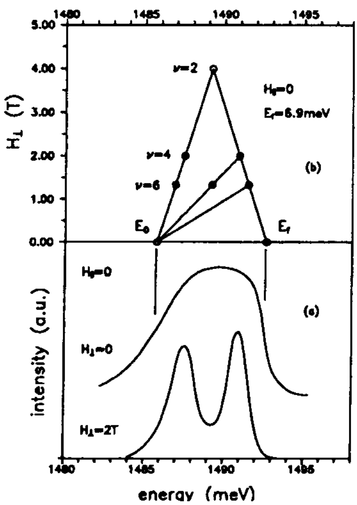

Fig.1

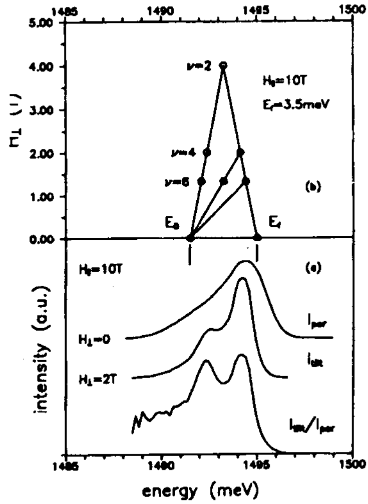

Fig.2

Fig.1. (a) Luminescence spectra measured for $n_s = 1.94\cdot 10^{11}\,\mathrm{cm}^{-2}$ at zero and perpendicular ($H_\perp = 2\mathrm{T}$) magnetic fields. (b) Landau levels fan diagram, obtained from the splitting of the luminescence line at $\nu = 2, 4, 6$. The positions of the subband bottom and of the Fermi energy derived from the diagram are shown by arrows

Fig.2.(a) Luminescence spectra measured in parallel (I_{par}, $H_\parallel = 10\mathrm{T}$, $H_\perp = 0\mathrm{T}$) and tilted (I_{tilt}, $H_\parallel = 10\mathrm{T}$, $H_\perp = 2\mathrm{T}$) magnetic fields. The ratio I_{tilt}/I_{par} is shown to enhance the resolution of the Landau levels. (b) Landau levels fan diagram, obtained from the splitting of the luminescence line due to the perpendicular component of the magnetic field. The positions of the subband bottom and of the Fermi energy derived from the diagram are shown by arrows

3. In Fig.1 we present the luminescence spectra measured for concentration of 2D-electrons $n_s = 1.94\cdot 10^{11}\,\mathrm{cm}^{-2}$ at zero magnetic field and in perpendicular field $H_\perp = 2\mathrm{T}$ ($H_\parallel = 0\mathrm{T}$). One can see that in these cases the luminescence spectra directly reflect the energy distribution of the electronic density of states. At $H_\perp = 2\mathrm{T}$ exactly two Landau levels are completely filled (filling factor $\nu = 4$) and two distinct lines are visible in the spectrum. The procedure of the exact determination of the positions of Fermi energy and of the subband bottom is

based on the plotting Landau levels fan diagram [8]. We present such a fan diagram measured for $n_s = 1.94 \cdot 10^{11}\,\mathrm{cm}^{-2}$ at the top part of the Fig.1. To determine the position of the bottom of the subband one needs to extrapolate to $H_\perp -> 0$ linear dependencies of spectral position of Landau levels with different numbers ($N = 0$, $N = 1$, $N = 2$, ...), because their shifts are described by $\hbar\omega_c(N + D^*_{\lambda'_h \lambda_x;\lambda'_q \lambda'_q} 12)$. In order to define the position of the Fermi energy one needs to fix the spectral position of the highest filled Landau level at integer filing factors (we fixed magnetic fields corresponding to the exact values $\nu = 4$ and $\nu = 6$ by use of transport measurements and these values of $H_\perp$ are indicated in the figure). At integer value of the filling factor the Fermi energy is located exactly between Landau levels and, therefore, the position of the E_F is shifted to the higher energy on $\hbar\omega_c/2$ in comparison with highest filled Landau level. Linear extrapolation to zero field gives the position of the Fermi energy. Using such a procedure we determine the Fermi energy of 2D-electrons for $n_s = 1.94 \cdot 10^{11}\,\mathrm{cm}^{-2}$: $E_F = 6.9\,\mathrm{meV}$, which exactly corresponds to the well know for GaAs value of the density of states mass $m_d = 0.067 m_e$.

In Fig.2 we present the luminescence spectrum measured for the same 2D-concentration in parallel magnetic field $H_\| = 10\,\mathrm{T}$ (I_{par}). One can see from this figure that luminescence spectrum in parallel field became very asymmetric - the recombination intensity is enhanced for higher energies. This is due to the fact that in parallel magnetic field the wave function of 2D-electron depends on their energy. We will not discuss now the details of the recombination spectrum in parallel magnetic field, because it will be a subject of separate publication, but will concentrate on the detection of the spectral positions of the E_F and E_0 energies. The procedure is based again on the detection of the Landau levels due to the small normal component of the magnetic field $H_\perp$.

According to our previous data, in strong tilted magnetic field ($\hbar\omega_c \gg E_{10}$) the Landau levels transfer into the levels of size quantization defined by the width of 2D-quantum well in the direction of total magnetic field. The splitting between such levels is not equidistant, but in the case when $H_\perp/H_\| \ll 1$ this splitting is proportional to $H_\perp/H$ [6], or to the normal component of the magnetic field. The luminescence spectrum measured in tilted magnetic field such as $H_\perp = 2\,\mathrm{T}$ ($\nu = 4$) and $H_\| = 10\,\mathrm{T}$ is presented in Fig.2 (I_{tilt}). The component of the strong parallel magnetic field results in exponential decay of the luminescence intensity for lower energies of 2D-electrons and this reduces strongly the contrast of intensity modulation due to Landau quantization. To derive this modulation we divided spectrum measured in tilted magnetic field I_{tilt} onto the spectrum measured in the same parallel magnetic field I_{par} ($H_\| = 10\,\mathrm{T}$). The resulting spectrum is also presented in Fig.2 and the modulation due to the Landau quantization is clearly visible. We used the described procedure to determine the Fermi energy of 2D-electron in different parallel magnetic fields and, for example, we found that for $n_s = 1.94 \cdot 10^{11}\,\mathrm{cm}^{-2}$ and $H_\| = 10\,\mathrm{T}$ the Fermi energy is $3.5\,\mathrm{meV}$ which is two times less than we measured at $H = 0$.

In Fig.3 we present the dependencies of the Fermi energy on the parallel magnetic field, measured for two concentrations of 2D-electrons: $1.94 \cdot 10^{11}\,\mathrm{cm}^{-2}$ and $3.07 \cdot 10^{11}\,\mathrm{cm}^{-2}$. One can see from this figure that the observed reduction of the Fermi energy measured in the same interval of magnetic fields is more pronounced for smaller 2D-concentrations. This result is in agreement with the exact theoretical solution obtained for parabolic quantum well [3]. In this model, a parallel magnetic field results in a reduction of E_F:

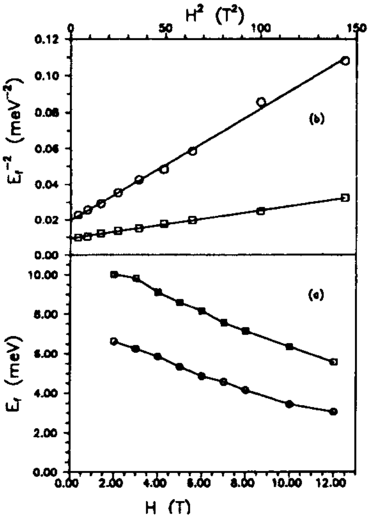

Fig.3. (a) The dependencies of the Fermi energy on the parallel component of the magnetic field, derived from luminescence spectra for $n_s = 1.94 \cdot 10^{11}\,\mathrm{cm}^{-2}$ (o) and $3.07 \cdot 10^{11}\,\mathrm{cm}^{-2}$(□); ($b$) the same dependencies plotted in coordinates E_F^{-2} vs H^2

$$E_F = E_F^0/(1 + (\hbar\omega_c)^2/E_{10}^2)^{1/2}$$

or

$$E_F^{-2} = (E_F^0)^{-2}(1 + H_0^{-2}H^2), \tag{1}$$

where

$$H_0 = \frac{mc}{e\hbar}E_{10}.$$

The dependencies of the Fermi energy on parallel magnetic field measured for different 2D-concentrations are presented in Fig.3 in the coordinates corresponding to Eq.(1). It is seen from this figure, that the experimental points are close to a linear dependence and this allow us to determine the values E_F^0 and E_{10}. The derived values of E_{10} was found to be equal to 10 meV for $n_s = 1.94 \cdot 10^{11}\,\mathrm{cm}^{-2}$ and to 12.5 meV for $3.07 \cdot 10^{11}\,\mathrm{cm}^{-2}$. These values agree very well with independent Raman and luminescence measurements of intersubband splitting [9,10], therefore, one can conclude that the observed reduction of the Fermi energy is due to the modification of the energy spectrum of 2D-electrons by parallel magnetic field.

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