Strong reduction of the fermi energy of two-dimensional electrons in a parallel magnetic field

I. V. Kukushkin, B. N. Shepel, and O. V. Volkov
Institute of Solid State Physics, RAS, 142432 Chernogolovka, Moscow Region, Russia

K. von Klitzing
Max-Plank Institut für Festkörperforschung, Stuttgart, FRG

(Submitted 29 August 1994)
Pis'ma Zh. Eksp. Teor. Fiz. **60**, No. 7, 541–544 (10 October 1994)

A strong reduction of the Fermi energy of two-dimensional electrons in a parallel magnetic field was directly observed in a magnetooptical experiment. The reduction is higher for a lower electron concentration. The observed effect can be associated with a modification of the energy spectrum of two-dimensional electrons by an in-plane magnetic field. © *1994 American Institute of Physics.*

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 the Wigner crystallization of 2D electrons is governed by the ratio between the Coulomb energy and the kinetic energy of electrons. The fact that the effective mass of 2D electrons can be changed by a parallel magnetic field was indicated by Ando,[1] who considered a magnetic field as a perturbation. The exact solution of the influence of strong, parallel, magnetic field on the energy spectrum of 2D electrons was found in Refs. 2 and 3 for a model in which the potential confinement of 2D electrons was a parabolic quantum well. For this model, in the limit of very strong magnetic fields, when magnetic energy $\hbar\omega_c$ greatly exceeds the energy of 2D confinement $\hbar\omega_0$, the effective mass of electrons in the direction of the magnetic field remains constant, while it greatly increases [as $(\omega_c/\omega_0)^2$] in the perpendicular direction. This results in the enhancement of the density of states of the mass, and therefore in the 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 a plasmon resonance experiment.[4] In this experiment, however, only a small increase (about 15%) of the mass was detected. The main reason for the observed small changes in the effective mass was the rather high concentration of 2D electrons, so that the confinement energy (intersubband splitting $E_{10}=35$ meV;[4]) was much higher than the magnetic energy ($\hbar\omega_c<20$ meV).

The direct optical method, which is useful for determination of the Fermi energy of 2D electrons, is based on the study of the radiative recombination of 2D electrons and holes that are bound to acceptors.[5] In such measurements the distribution of 2D electrons is directly visible in the luminescence spectrum, because the probability for recombination does not depend on the energy of the recombining electrons. The situation remains the same in a perpendicular magnetic field, and the density of states can be directly observed in the luminescence spectra. However, in the case of a parallel magnetic field

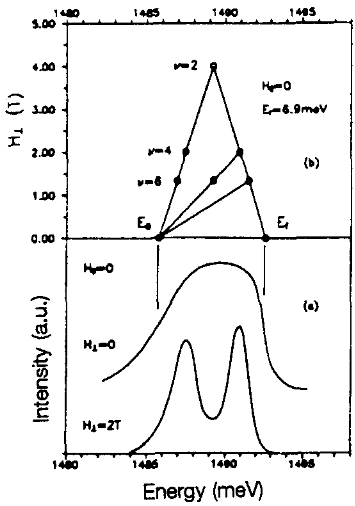

FIG. 1. (a) Luminescence spectra measured at $n_s=1.94\times10^{11}$ cm^{-2} in zero magnetic field and in a perpendicular ($H_\perp=2$ T) magnetic field. (b) Landau level fan diagram, obtained from the splitting of the luminescence line at $\nu=2$, 4, 6. The positions of the bottom of the subband and of the Fermi energy derived from the diagram are shown by the arrows.

the wave functions of 2D electrons depend on the energy of the in-plane motion of 2D electrons[3] (due to the Lorentz force), and the luminescence spectrum does not directly reflect the density of states of 2D electrons.[6]

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

2. We studied high quality GaAs/AlGaAs single heterojunctions with a 1000-nm GaAs buffer layer, in which a monolayer of acceptors (with a concentration of 10^{10} cm^{-2}) was formed at a distance of 30 nm from the interface. The concentration of 2D electrons was varied in the range $(1.5–5)\times10^{11}$ cm^{-2} by varying the illumination intensity. For excitation we used Ar^+ or HeNe lasers. The luminescence was detected by a photon counting system with use of a double spectrometer, which gave us a spectral resolution of about 0.05 meV. Simultaneously with the 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 the experiment were published in Refs. 5 and 7.

3. In Fig. 1 we show the luminescence spectra measured at a concentration of 2D electrons $n_s=1.94\times10^{11}$ cm^{-2} in a zero magnetic field and in a perpendicular field $H_\perp=2$ T ($H_\parallel=0$ T). We see that in these cases the luminescence spectra directly reflect the energy distribution of the electronic density of states. At $H_\perp=2$ T, exactly two Landau levels are completely filled (the filling factor is $\nu=4$) and two distinct lines are visible in the spectrum. The positions of the Fermi energy and of the subband bottom were determined exactly from the Landau level fan diagram.[8] Such a fan diagram, measured for $n_s=1.94\times10^{11}$ cm^{-2}, is shown at the top in Fig. 1. To determine the position of the bottom of the subband, we must extrapolate to $H_\perp>0$ the linear dependences of the

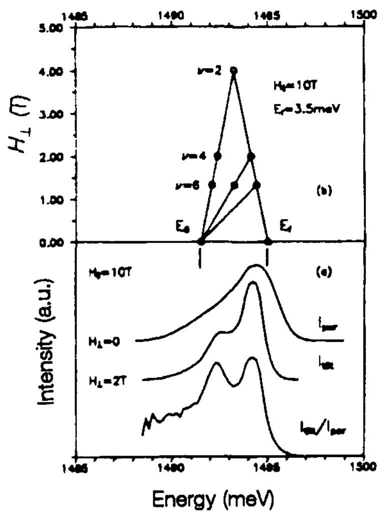

FIG. 2. (a) Luminescence spectra measured in a parallel (I_{par}, $H_{\parallel}=10$ T, $H_{\perp}=0$ T) and tilted (I_{tilt}, $H_{\parallel}=10$ T, $H_{\perp}=2$ T) magnetic fields. The ratio I_{tilt}/I_{par} is shown to enhance the resolution of the Landau levels. (b) Landau level fan diagram, obtained 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 the arrows.

spectral position of the 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, we must fix the spectral position of the highest filled Landau level at integer values of the filling factors (we set the magnetic fields corresponding to the exact values $\nu=4$ and $\nu=6$ by using transport measurements; these values of $H_{\perp}$ are indicated in the figure). At integer values of the filling factor the Fermi energy is located exactly between the Landau levels; the position of the E_F is therefore shifted to a higher energy by $\hbar\omega_c/2$ in comparison with the 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 $n_s=1.94\times10^{11}$ cm^{-2}. $E_F=6.9$ meV, which corresponds exactly to the well-known value of the density of states mass, $m_d=0.067m_e$, for GaAs.

In Fig. 2 we show the luminescence spectrum measured for the same 2D concentration in a parallel magnetic field $H_{\parallel}=10$ T (I_{par}). We see from this figure that the luminescence spectrum in a parallel field becomes strongly asymmetric: the recombination intensity increases at higher energies, because in a parallel magnetic field the wave function of 2D electrons depends on their energy. We will not discuss now the particular features of the recombination spectrum in a parallel magnetic field, because it is a subject of separate publication. We will, however, concentrate on the detection of the spectral positions of the E_F and E_0 energies. The procedure is based, as before, 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 a strong, tilted magnetic field ($\hbar\omega_c \gg E_{10}$) the Landau levels become quantum-size levels which are defined by the width of the 2D quantum well in the direction of the total magnetic field. The splitting between such levels is not equidistant. In the case $H_{\perp}/H_{\parallel}\ll 1$, this splitting is proportional to $H_{\perp}/H$ (Ref. 6) or to the normal component of the magnetic field. The luminescence spectrum measured in a tilted magnetic field, such as $H_{\perp}=2$ T ($\nu=4$) and $H_{\parallel}=10$ T, is shown in

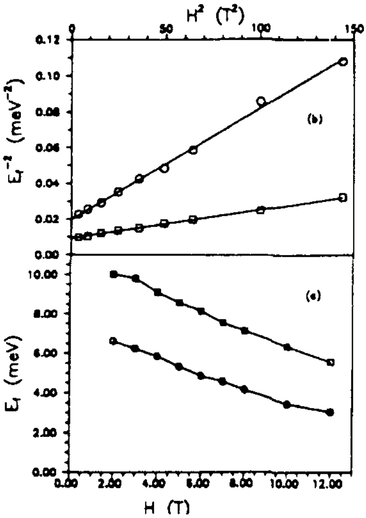

FIG. 3. (a) The dependences of the Fermi energy on the parallel component of the magnetic field, derived from luminescence spectra for $n_s=1.94\times10^{11}$ cm^{-2} (○) and 3.07×10^{11} cm^{-2} (□); (b) the same dependences plotted in E_F^{-2} versus H^2 coordinates.

Fig. 2 (I_{tilt}). The component of the strong, parallel magnetic field gives rise to an exponential decay of the luminescence intensity at lower energies of 2D electrons, which strongly reduces the intensity modulation contrast due to the Landau quantization. To determine this modulation, we divided the spectrum measured in a tilted magnetic field I_{tilt} by the spectrum measured in the same parallel magnetic field I_{par} ($H_{\parallel}=10$ T). The resulting spectrum is also shown in Fig. 2. The modulation due to the Landau quantization is clearly visible. We used the described procedure to determine the Fermi energy of 2D electrons in various parallel magnetic fields. We found, for example, that at $n_s=1.94\times10^{11}$ cm^{-2} and $H_{\parallel}=10$ T the Fermi energy is 3.5 meV, which is one-half the value we measured at $H=0$.

In Fig. 3 we show the dependences of the Fermi energy on the parallel magnetic field, measured for two concentrations of 2D electrons: 1.94×10^{11} cm^{-2} and 3.07×10^{11} cm^{-2}. We see from this figure that the observed reduction of the Fermi energy, measured in the same interval of magnetic fields, is more pronounced at lower 2D concentrations. This result is in agreement with the exact theoretical solution obtained for a parabolic quantum well.[3] In this model E_F decreases in a parallel magnetic field:

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

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 dependences of the Fermi energy on the parallel magnetic field measured at different 2D concentrations are shown in Fig. 3 in the coordinates corresponding to Eq. (1). We see in this figure that the experimental points are close to a linear dependence, which allows us to determine the values E_F^0 and E_{10}. The derived values of E_{10} were found to be equal to 10 meV at $n_s=1.94\times10^{11}$ cm^{-2} and to 12.5 meV at 3.07×10^{11} cm^{-2}. These values agree very well with the independent Raman and luminescence measurements of the intersubband splitting.[9,10] We conclude, therefore, that the observed reduction of the Fermi energy is due to a modification of the energy spectrum of 2D electrons by the parallel magnetic field.

We would like to thank V. I. Falko for very useful discussions. The research described in this publication was made possible by Grant REE 000 from the International Science Foundation.

[1] T. Ando *et al.*, Rev. Mod. Phys. **54**, 437 (1982).
[2] J. C. Maan, Sol. St. Sciences **53**, ed. G. Bauer *et al.*, 1984.
[3] H. Tang and P. N. Butcher, J. Phys. C **21**, 3313 (1988).
[4] E. Batke and C. W. Tu, Phys. Rev. B **34**, 3027 (1986).
[5] I. V. Kukushkin *et al.*, Phys. Rev. B **40**, 7788 (1989).
[6] V. E. Kirpichjev *et al.*, JETP Lett. **51**, 383 (1990).
[7] I. V. Kukushkin *et al.*, Phys. Rev. B **40**, 4179 (1989).
[8] I. V. Kukushkin *et al.*, Phys. Rev. B **37**, 8509 (1988).
[9] I. V. Kukushkin *et al.*, EP2DS-10, Surf. Sci. **305**, 55 (1984).
[10] I. V. Kukushkin *et al.*, Sol. St. Commun. **70**, 1015 (1989).

Published in English in the original Russian journal. Reproduced here with stylistic changes by the Translation Editor.