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Transport of the quasi-three-dimensional hole gas in a magnetic field in the ultra-quantum limit

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Abstract

We observed anomalous oscillations in the magnetoresistance of quasi-three dimensional holes in a magnetic field in the ultra-quantum limit. For this study we used wide p-type AlGaAs parabolic quantum wells in the presence of the in-plane magnetic field. We attribute the anomalous oscillations to the formation of the correlated electronic states.

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1. Introduction

The behaviour of the high mobility three-dimensional (3D) electron system in strong magnetic field in the ultra-quantum limit is a subject of considerable interest. It is generally believed that in both three and two dimensions in the presence of the infinitely strong magnetic field electrons undergo a phase transition to a Wigner crystal state. In two dimensions (2D) in the intermediate magnetic field region the fractional quantum Hall effect has been observed [1]. The nature of the ground state in 3D system in the intermediate magnetic field region is not well understood. Within the Hartree–Fock framework Celli and Mermin [2] proposed a possible spin density wave state. More recently MacDonald and Bryant [3] predicted more complicated phase diagram, when electron system undergoes various phase transition, such as charge density wave state, Kaplan–Glasser phase state [4] and Wigner crystal with magnetic field increasing. These transitions have not yet been identified unambiguously. More recently, AlGaAs based wide parabolic well has been proposed and grown [5,6] as best candidate for searching many-body effects since parabolic well allows to form a wide layer of dilute, high mobility carriers. Bray and Halperin [7] proposed the spin density wave state as a ground state in a wide parabolic quantum well system, when an intermediate in-plane magnetic field is applied. Although the transport properties of the parabolic well have been extensively studied [8,9], not much experimental work has appeared on the many-body problem except for our recent publication [10]. In our paper [10], we

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studied wide (2000–4000 Å) electronic parabolic wells in the presence of the in-plane magnetic field and low temperature (50 mK) and observed magnetotransport features, which can be interpreted as many-body states in ultra-quantum limit.

The parabolic well allows to form a wide (1000–5000 Å) layer of carriers with a uniform (in direction of growth) density. The parabolic confinement potential is characterized by a harmonic oscillator frequency ω_0, $V(z) = \frac{1}{2}m^*\omega_0^2 z^2$, where m^* is effective mass. The dimensionless interelectron spacing r_s, which is equal to the ratio between Coulomb and Fermi energies, is given by $r_s = 4\pi^2 m^* e^2/\varepsilon h^2 (3/4\pi n_0)^{1/3}$, where $n_0 = \omega_0^2 m^* \varepsilon/4\pi e^2$ is the characteristic bulk density. Parameter r_s in 4000 Å wide well approaches 3 and may play important role in the ultra-quantum magnetic limit, in contrast to two-dimensional case when electron's kinetic energy is frozen in their orbital motion, and any electron–electron interaction is strong. Parameter r_s is much larger in p-type parabolic quantum well due to the heavy effective mass, therefore many-body effects are expected to be more pronounced in three-dimensional hole systems.

2. Energy spectrum of the wide parabolic well in the tilted magnetic field

The first wide parabolic wells were grown by Sundaram et al. [5] and by Shayegan et al. [6]. The parabolic variation of the well potential was introduced to avoid soft barrier in the center originating from Coulomb interaction among electrons in the wide quantum well. It allows to create wide electron system with several subbands. The energy of the electrons in a parabolic quantum well with the potential $V = (az)^2$ in tilted magnetic field is given by Ref. [11]:

$$E = h\omega_1(n_1 + 1/2) + h\omega_2(n_2 + 1/2), \tag{1}$$

where $\omega_{1,2}$ are characteristic frequencies of the PQW in the tilted magnetic field.

Fig. 1 shows the evolution of the energy spectrum with tilt angle Θ. We may see that in parallel magnetic field the Landau levels (LL) are collapsed into two states, which is almost coincident with the 3D Landau states. Fig. 2 shows the angular dependence of the magnetoresistance for 1000 Å wide p-type parabolic quantum well.

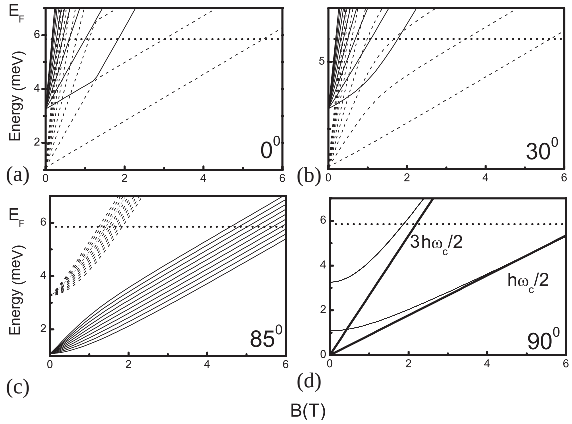

Fig. 1. Evolution of the energy spectrum from 2D towards 3D in tilted magnetic field. 10 LLs for each subbands are shown for clarity. Spin splitting is neglected.

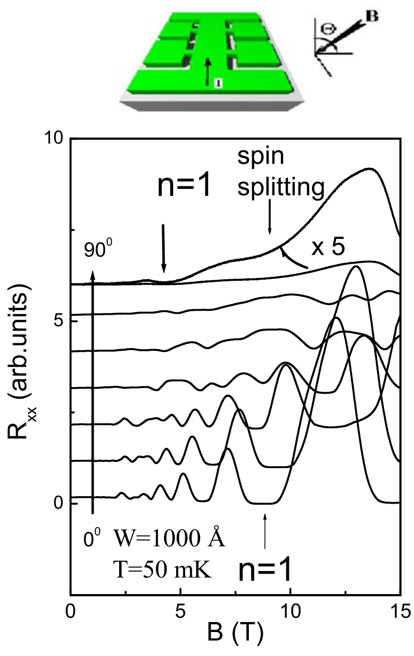

Fig. 2. Magnetoresistance of a 1000 Å PQW with 2D holes as a function of magnetic field for different tilt angle $0^\circ < \Theta < 90^\circ$, $T = 50$ mK. Arrows indicate the fundamental magnetic field B_1 corresponding the depopulation of the last Landau level. Current flows along [0 1 $\bar{1}$] direction.

We may see that the ultra-quantum limit in perpendicular magnetic field for 2D system with 2 subbands occurs in $B_1 = 8.7$ T. It is worth noting that each LL

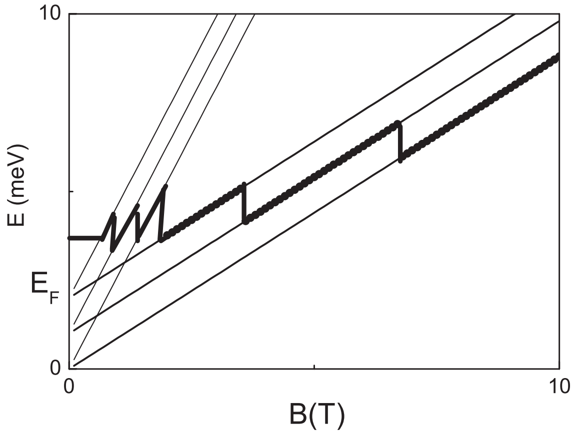

Fig. 3. Magnetic-field subband spectrum for three subbands and 2 LL. Thick line—Fermi energy.

level becomes spin split in the strong magnetic field, therefore one more minimum at $B=17$ T occurs in perpendicular magnetic field. Unfortunately the value of g-factor in p-type GaAs and AlGaAs is not well known [12], however it is expected to be larger than for electrons. Let us adopt g-factor 6–7 for our PQW in the presence of the parallel magnetic field. In this case the cyclotron energy becomes comparable with Zeeman splitting. In accordance with Landau level degeneracy the additional minimum should appear in magnetoresistance in field two times larger than the fundamental magnetic field. In Fig. 2 the possible position of spin splitting minima is indicated by arrow. It occurs in field which is two times smaller than the spin splitting field in perpendicular magnetic field. This reflects the increasing of the Fermi energy in the strong magnetic field due to the depopulation of the 2D subbands. Fig. 3 shows the magnetic-field subband spectrum for PQW and schematically demonstrates behaviour of the Fermi energy with magnetic field.

We can divide the magnetic axis into two regions, in each of which the spectra behaves distinctly. In low magnetic field Fermi energy makes discrete jumps as a function of field to be in the LL closest in value to the Fermi energy in zero magnetic field $E_F(0)$. In strong magnetic field cyclotron energy is larger than the energy separation between the Fermi energy and the lowest subband, so only lowest LL of each subband is populated. Between the depopulation of the levels Fermi energy grows linearly with field. Since in zero field three subbands are depopulated, before the transition to the last LL Fermi energy becomes three times larger than $E_F(0)$. In our hole PWQ we have two subbands in zero field, therefore Fermi energy grows two times with field, when the second subbands becomes depopulated. In parallel magnetic field Fermi energy remains close to the $E_F(0)$.

3. Experimental results and discussions

The samples were grown by a molecular-beam epitaxy (MBE) technique on semi-insulating $(3\,1\,1)A$ substrate. Several samples were grown with a PQW 1000, 2000 and 3000 Å width, aluminium content ranging from 0.29 to 0, and symmetrically doped with a silicon located at 150 Å from their border. We observed systematical decrease of the hole density in PQW with increase of the width from 4×10^{11} cm^{-2} for $W=1000$ Å sample to 1.5×10^{11} cm^{-2} for $W=3000$ Å quantum well. The density was smaller than $n_s = W \times n_0$, therefore our PQW's were only partially full with two occupied subbands belonging to the heavy holes, which was also confirmed from self-consistent calculations. The mobility of the holes was of order of $(70\text{–}100)\times10^3$ cm^2/Vs. The measurements in this study were performed using Hall bar geometry with current flow in the $[\bar{2}\,3\,3]$ and $[0\,1\,\bar{1}]$ directions. The n-type samples were grown on semi-insulating (1 0 0) substrate and have almost the same density and mobility.

The samples were immersed in a mixing chamber of a top-loading dilution refrigerator with a base temperature $T=50$ mK. We measure magnetoresistance and Hall resistance at different angles Θ between the field and the normal to the sample, rotating our sample in situ. AC current did not exceed 10^{-7} A.

Fig. 4 shows the magnetoresistance as a function of the in-plane magnetic field for electronic and hole 1000 Å PQWs. We can see that the magnetoresistance of the electron system grows monotonically with field in the ultra-quantum limit. Magnetoresistance of the hole system exhibits large peak. It is worth noting that the minimum at $B=9$ T can be interpreted as the spin splitting of the last LL, however, the anomalous large peak cannot be explained in the framework of the single-electron picture. The position of peak is found at $B\approx 3B_1$.

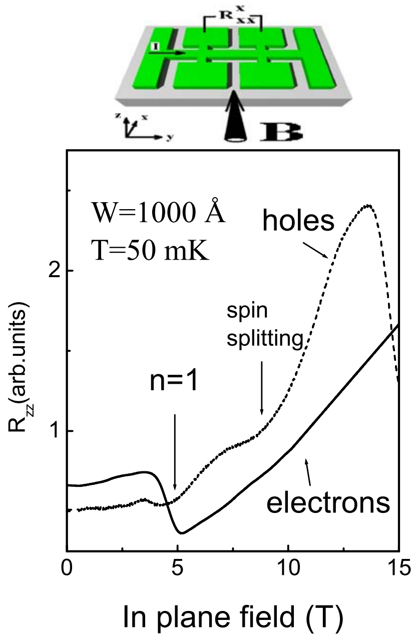

Fig. 4. Magnetoresistance of a 1000 Å PQW with 2D holes and electrons as a function of the in-plane magnetic field, $T = 50$ mK. Current in hole PQW flows along [0 1 $\bar{1}$] direction.

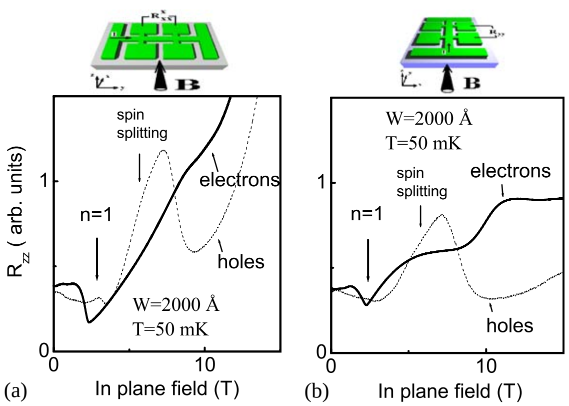

Fig. 5. Magnetoresistance of a 2000 Å PQW with 2D holes and electrons as a function of the in-plane magnetic field for the different experimental geometries: (a) in-plane component of the magnetic field is directed perpendicular to the current flow and (b) in-plane component of the magnetic field is directed parallel to the current flow. Current in hole PQW flows along [0 1 $\bar{1}$] direction, $T = 50$ mK.

We also check the magnetoresistance anisotropy applying magnetic field in the direction perpendicular and parallel to the current. Fig. 5 shows such plot of R_{xx} for electronic and hole 2000 Å PQWs. We may see that electron system demonstrates strong anisotropy, as already has been reported in paper [10]. In addition magnetoresistance exhibits anomalous features at magnetic field approximately 3–4 times larger than the fundamental magnetic field B_1. In hole system we found large peak in the ultra-quantum limit. This peak is two times larger for in-plane field perpendicular to the current and slightly shifted to the lower magnetic field in comparison with electrons. Possible position of the spin splitting is also indicated.

Let us focus on the possible explanation of the anomalous resistance behaviour in the quantum limit. It is worth noting that the spin splitting cannot be the origin of the additional large peak and minima. Firstly the positions of the peak/minima are not consistent with the spin gap position indicated in Figs. 2, 4 and 5. The position of the minima is determined by the Landau level degeneracy, and does not depend on the value of the g-factor. Secondly, the value of the peak/minima is much larger than the amplitude of the diamagnetic Shubnikov de Haas oscillations at low field and does not consistent with conventional behaviour of the SdH oscillations [10].

Another possible explanation is electron–electron interaction in strong magnetic field. The Hartree–Fock approximation predicts several electronic phases for three-dimensional system in a strong magnetic field in the extreme quantum limit due to the electron–electron interaction effects [3]. It has been shown, that a homogeneous 3D system should be transformed into a two-dimensional hexagonal lattice of charged rods parallel to the magnetic field with the diameter $2l_H$, where l_H is the magnetic length (Kaplan–Glasser phase) [4]. Each charged rod behaves as a one-dimensional electron gas with a variation of the charge described by the wave vector $Q_y = 2k_F$ along each rod, where k_F is the Fermi vector of the electrons. It has been predicted, that the ground state changes from uniform density states to a charge density state with wave vector parallel to the field, and then to a Wigner crystal, when magnetic field increases.

The anomalous feature that we observed in the ultra-quantum magnetic limit can, in principle, be interpreted as the formation of CDW or another many-body state in pure 3D system. It is worth to emphasize here that the main difference between electrons and holes may be the Coulomb interaction. In PQW the dimensionless parameter $r_s \approx 14$ for holes ($m^* = 0.4m_0$) leads to more pronounced many-body effects, which we indeed observed in experiments. However, these results demand a detailed theoretical calculations of the ground state in the wide parabolic well in the presence of the in-plane magnetic field.

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