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Charge density wave instability in a parabolic well in perpendicular magnetic field

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Abstract

We report magnetotransport measurements of a wide parabolic quantum well with quasi-two-dimensional holes in a tilted magnetic field. We find that in a perpendicular magnetic field the magnetoresistance minima at filling factor $\nu = 1$ are missed. This effect is attributed to the formation of the charge density wave (CDW) state proposed theoretically by Brey for quantum Hall system with several subbands (Phys. Rev. B 44 (1991) 3772). In the tilted magnetic field CDW state is destroyed and quantum Hall effect is recovered.

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Keywords: Charge density wave; Parabolic quantum well; Holes

1. Introduction

Recently, a variety of correlated phases are predicted in quantum Hall systems, when additional degrees of freedom associated with numbers of two-dimensional layers and subbands are introduced. An interesting example of such multicomponent quantum Hall system is the two-dimensional (2D) layers based on quantum wells separated by a tunnelling barrier [1]. This system undergoes phase transition when the exchange energy overwhelm the single electron tunnelling gap between symmetric and antisymmetric subbands [2]. Another class of the multicomponent quantum Hall system are electrons in a wide parabolic well. In this system the tunnelling gap should be replaced by the intersubband energy separation, and similar phase transitions are expected in quantum Hall effect (QHE) regime. For example, Brey [3] proposed a possible exchange-induced charge density wave state in a wide parabolic quantum well (PQW) in a perpendicular magnetic field at Landau filling factor $\nu = 1$. In contrast to bilayer systems, such phase transitions has not been observed experimentally.

The parabolic well allows to form a wide (1000–5000 Å) layer of dilute, high-mobility carriers with a uniform (in direction of growth) density. The parabolic confinement potential is characterised 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 is given by $r_s = 4\pi^2 m^* e^2/\varepsilon h^2 (3/4\pi n_0)^{1/3}$, where $n_0 = \omega_0^2 m^* \varepsilon/4\pi e^2$

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is the characteristic bulk density. For a sufficiently thick electron slab the system undergoes a phase transition [3]. For example, in PQW with 2000 Å geometrical width W and characteristic energy $h/2\pi\omega_0 = 5.7$ meV, transition should occur at critical thickness $W_c \approx 700$ Å $< W$, which corresponds to the critical electron sheet density $n_s^c = W_c n_0 = 2.1 \times 10^{11}$ cm^{-2}. However, this theoretically proposed instability has not yet been observed experimentally in samples with density $n_s > n_s^c$ [4,5]. The reason for such a discrepancy could be correlation effects, which may shift phase line separation to the higher W_c. The absence of the CDW instability in n-type $Al_xGa_{1-x}As$ parabolic wells can be also attributed to the relatively low level of the electron–electron interaction strength or small r_s value. The 2D holes are characterised by the large r_s value, usually >10, due to the heavy effective mass, therefore hole system is expected become a quantum CDW phase at critical thickness smaller than the geometrical well width W.

To check this possibility we grew and measured p-type $Al_xGa_{1-x}As$ parabolic wells with different widths. We found that in perpendicular magnetic field the minima in diagonal resistance at $\nu = 1$ are missed in samples with $W_c \geqslant 1000$ Å. This observation agrees with the one proposed in Ref. [3]. CDW instability, although at higher value of r_s has been predicted in theoretical model. We also found that in tilted magnetic field the quantum Hall effect is recovered, which supports cooperative character of the observed effect.

2. Experimental results

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 and symmetrically doped with 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. For 2000 Å hole PQW the characteristic energy value of $h/2\pi\omega_0 = 2.4$ meV and characteristic density $n_0 = 3 \times 10^{16}$ cm^{-3}. The density was smaller than $n_s = W \times n_0$, therefore our PQWs were only partially full with two occupied subbands belonging to the heavy holes, which was also confirmed from self-consistent calculations. The mobility

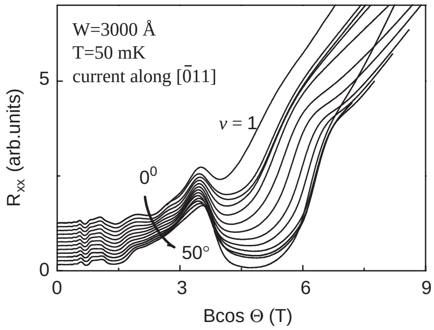

Fig. 1. Magnetoresistance of a 3000 Å PQW with 2D holes as a function of the normal component of magnetic field for different tilt angle $0° < \Theta < 50°$, $T = 50$ mK. Current flows along [0 1 $\bar{1}$] direction.

of the holes was of order of $(70–100) \times 10^3$ 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 samples were immersed in a mixing chamber of a top-loading dilution refrigerator with a base temperature $T = 50$ mK. We measure magnetoresistance 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.

In Fig. 1 we show plots of longitudinal R_{xx} resistance of holes along [0 1 $\bar{1}$] direction versus perpendicular component of the field $B_\perp$ for different tilt angles Θ. We can see that in a perpendicular magnetic field at Landau filling factor $\nu = 1$ resistance minimum is missed. Surprisingly, at a small tilt angle $\Theta \sim 30°$ the quantum Hall effect is recovered.

Fig. 2 shows longitudinal R_{yy} resistance of holes along [$\bar{2}$ 3 3] direction versus $B_\perp$ for different tilt angles Θ. We can see the conventional quantum Hall effect behaviour. Therefore, the magnetoresistance data shows significant anisotropy at $\nu = 1$. Hall plateau is also missed in the perpendicular magnetic field for current along [0 1 $\bar{1}$] and recovered in the tilted magnetic field.

The same behaviour was found in 2000 Å PQW (Fig. 3a, b). Fig. 3a also shows the temperature dependence of the magnetoresistance along [0 1 $\bar{1}$] direction. No activation behaviour is observed at $\nu = 1$ in a perpendicular magnetic field.

It is worth noting that the mobility of the 2D hole system grown on GaAs (3 1 1)A substrates is anisotropic [6] due to the anisotropic surface

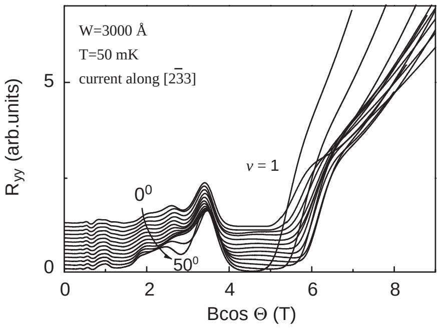

Fig. 2. Magnetoresistance of a 3000 Å PQW with 2D holes as a function of the normal component of magnetic field for different tilt angle $0° < \Theta < 50°$, $T = 50$ mK. Current flows along $[\bar{2}\,3\,3]$ direction.

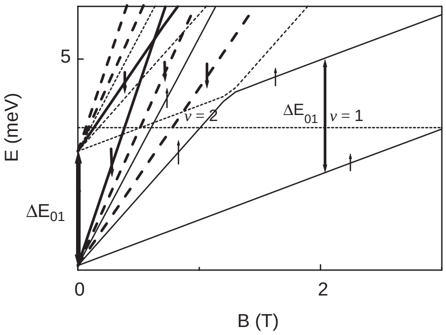

Fig. 4. Diagram of the Landau levels in the wide (2000 Å) parabolic quantum well with 2D holes as a function of magnetic field. The Zeeman splitting for 3 lowest levels is included.

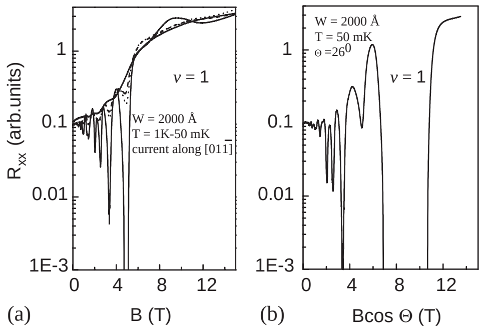

Fig. 3. (a) Magnetoresistance of a 2000 Å PQW with 2D holes as a function of $B_\perp$ for different temperatures: 1 K, 650 mK, 340 mK, 50 mK. Current flows along $[0\,1\,\bar{1}]$ direction. (b) Magnetoresistance along $[0\,1\,\bar{1}]$ direction of a 2000 Å PQW as a function of $B_\perp$ for tilt angle $\Theta = 26°$, $T = 50$ mK.

morphology. The GaAs/AlGaAs interface are corrugated, with ridges along $[\bar{2}\,3\,3]$. The scattering by this ridges leads to the mobility reduction for current parallel to $[0\,1\,\bar{1}]$.

3. Possible CDW state in parabolic quantum well

Let us focus on the possible explanation of the anomalous resistance behaviour at $\nu = 1$. Firstly, we discuss single particle spectrum in parabolic well in the presence of the magnetic field. In a perpendicular magnetic field each subband represents a staircase of the Landau levels associated with the subband energy E_i (i is the subband index). In a single particle description the energy is given by

$$E_{in} = E_i^{(\mathrm{sub})} + \frac{h}{2\pi}\,\omega_c(n + 1/2) + g^*\mu_\mathrm{B}B\,\frac{\sigma}{2}, \tag{1}$$

where $g^*\mu_\mathrm{B}B\sigma/2$ is the Zeeman contribution, n is the Landau level number. In 2D hole system Zeeman splitting is larger than subband separation $\Delta E_{01} = E_1^{\mathrm{sub}} - E_0^{\mathrm{sub}}$ because of the big effective Landé g-factor [7], which also may be enhanced due to exchange interaction [1]. From this reasoning in hole PQW the minimum R_{xx} at Landau filling factor $\nu = 1$ corresponds to the gap between $i = 1$, $n = 0$, $\sigma = \uparrow$, and $i = 0$, $n = 0$, $\sigma = \uparrow$. This energy spectrum is shown schematically in Fig. 4.

We attribute the destruction of the $\nu = 1$ state to the formation of the CDW state suggested by Brey [3]. The tilt field experiments avoid the another possibility, such as low mobility, which in principle smeared out the small gap. Single particle theory [8] predicts that in the titled magnetic field the energy spacing of the parabolic potential (and square well too) diminishes with tilt angle. We have measured this gap for different filling factors in electronic parabolic wells and indeed observed such dependence [9]. Therefore, recovery of the gap in hole PQW at $\nu = 1$ cannot be explained by single particle model. We also check anisotropy by tilting magnetic field in the direction perpendicular $[\bar{2}\,3\,3]$ and parallel $[0\,1\,\bar{1}]$ to the current. Again we found that the transport at $\nu = 1$ shows anisotropic behaviour: data reveal that in-plane $B_{[\bar{2}\,3\,3]}$-field, which destroys the CDW state, is smaller than $B_{[0\,1\,\bar{1}]}$-field.

The (3 1 1)A interface corrugations may lead to the anisotropic CDW state in PQW. It is worth mentioning that Brey proposed isotropic correlated state in wide well [3]. We may speculate here that CDW state is the stripe-like state, which is formed at filling factor 1. Stripe phases are characterised by the oscillations in the charge distribution along one direction. The origin of such a stripe order is the competition between the exchange energy and direct Coulomb repulsion. In our case the exchange interaction tends to minimise the energy of both the subbands, and for the narrow stripes this energy gain may exceed the direct Coulomb energy penalty. Indeed, it demands a detailed theoretical calculations of the ground state in the two-component quantum Hall systems. Correlation of the surface morphology and CDW stripe phases has been found at filling factor $\nu = n + 1/2$ in high mobility 2D n-type [10,11] and p-type heterostructures [12]. However, the correlation of the roughness and the high resistance direction in 2D electron system still remains controversial [10,11]. In 2D holes the ridges are orthogonal to the hard resistance direction [12]. The transport properties of the CDW stripe-like state are not well understood. However, for anisotropic stripe phases smectic and nematic states has been proposed [13]. In the smectic phase the edge states may exist, and transport described by the travelling along the edges. In this case resistance in the direction along stripes is zero, like in the conventional QHE, and for perpendicular direction R_{xx} is nonzero and determined by the scattering between edge states.

Finally, we should mention that hole PQW with geometrical width $W = 1000$ Å exhibits conventional QHE behaviour with $\nu = 1$ resistance minimum, shown in Fig. 5, although the peak at $\nu = 3/2$ is wider than in electron PQW with the same width. We may see also some structure in the low field part of the peak, which disappears with tilting of the magnetic field (Fig. 5). This well is partially full with hole density 4×10^{11} cm^{-2}, which corresponds to the hole sheet width $W_h \sim 700$ Å. It allows us to note the phase transition to CDW state occur at $W_c \geqslant 1000$ Å.

In summary we report the destruction and recovery of the $\nu = 1$ QHE in wide parabolic wells with 2D hole system. This effect is absent in wide electronic PQW and narrow hole wells. We attribute it to the formation of the charge density wave state proposed theoretically in Ref. [3] for multicomponent quantum Hall system.

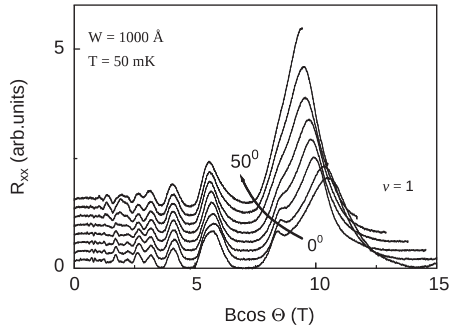

Fig. 5. Magnetoresistance of a 1000 Å PQW with 2D holes as a function of $B_\perp$ for different tilt angles $0° < \Theta < 50°$, $T = 50$ mK. Current flows along [0 1 $\bar{1}$] direction.

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References

[1] S. Das Sarma, A. Pinzuk (Eds.), Perspectives in Quantum Hall Effects, Wiley, New York, 1997.
[2] G.S. Boebinger, H.W. Jiang, L.N. Pfeifer, K.W. West, Phys. Rev. Lett. 64 (1990) 1793.
[3] L. Brey, Phys. Rev. B 44 (1991) 3772.
[4] T. Sajoto, J. Jo, L. Engel, M. Santos, M. Shayegan, Phys. Rev. B 39 (1989) 10464.
[5] G.M. Gusev, A.A. Quivy, T.E. Lamas, J.R. Leite, A.K. Bakarov, A.I. Toropov, O. Estibals, J.C. Portal, Phys. Rev. B 65 (2002) 205316.
[6] J.J. Heremans, M.B. Santos, K. Hirakawa, M. Shayegan, J. Appl. Phys. 76 (1994) 1980.
[7] R. Winkler, S.J. Papadakis, E.P. De Poortere, M. Shayegan, Phys. Rev. Lett. 85 (2000) 4574.
[8] R. Merlin, Solid State Commun. 64 (1987) 99.
[9] C.S. Sergio, G.M. Gusev, A.A. Quivy, T.E. Lamas, J.R. Leite, O. Estibals, J.C. Portal, J. Microelectron. 34 (2003) 763.
[10] R.L. Willet, J.W.P. Hsu, D. Natelson, K.W. West, L.N. Pfeiffer, Phys. Rev. Lett. 87 (2001) 126803.
[11] K.B. Cooper, et al. 119 (2001) 89.
[12] M. Shayegan, H.C. Manoharan, S.J. Papadakis, E.P. De Poortere, Physica E 6 (2000) 40.
[13] F. von Oppen, B.I. Halperin, A. Stern, Phys. Rev. Lett. 84 (2000) 2937.