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Quantum Hall ferromagnet in a two-dimensional electron gas coupled with quantum dots

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Abstract

We have studied the magnetoresistance in the two-dimensional electron gas (2DEG) coupled with quantum dots. The structures consist of asymmetrically doped GaAs double quantum wells separated by tunneling $\mathrm{Ga}_x\mathrm{Al}_{1-x}\mathrm{As}$ barrier of 50 Å width. On the top of the structure the hexagonal superlattice of the antidots with periodicity 0.6 μm and diameter 0.2 μm was patterned in the PMMA resist, which was then covered by the gold gate. When the negative gate voltage is applied, potential of the neighbor antidots is overlapped, and the array of disconnected quantum dots with triangular shape has been formed in the top quantum well. Therefore, bilayer system is transformed to the single layer of electrons, which is strongly coupled with quantum dots separated by tunneling barrier. We observed the sudden jump in the magnetoresistance at filling factor 3, which also reveals a pronounced hysteresis. The data may signal an quantum Hall ferromagnetism associated with pseudospin (layer) ferromagnetic order.

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Keywords: Bilayer system; Hysteretic phenomena; Quantum Hall ferromagnet

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1. Introduction

Recently, a variety of the quantum Hall effect (QHE) correlated phases were predicted when additional degrees of freedom associated with numbers of two-dimensional (2D) layers and subbands are introduced. The interesting example of such a multicomponent quantum Hall system is two quantum wells separated by a tunneling barrier [1]. In such bilayer system the Landau level in different layers can be characterized by pseudospin index $\frac{1}{2}$. Therefore, the state corresponding to the isospin $\Uparrow$ has electron occupying the Landau level $n = 0$ in the first well with subband index $m = -1$, and the state with isospin $\Downarrow$ has electron occupying $n = 0$ level in the second quantum well with subband index $m = +1$ (neglecting real spin). The broad class of phenomena associated with crossing of Landau levels with opposite spin orientations called quantum Hall ferromagnetism (QHF) [2], has been given much attention. Bilayer system at total Landau filling factor $\nu = 1$ is equivalent to an easy-plane ferromagnet, since pseudospin ferromagnetic order prefers lie in the wells plane (XY-ferromagnet). The physics becomes richer, when in addition to pseudospin the real spin $\sigma = \frac{1}{2}$ is included. Depending on the orbital states and the spin, various ground states with different spin configuration has been predicted. For example, at filling factor $\nu = 2$ isospins $\Uparrow$ and $\Downarrow$ represent the states $n = 0$, $\sigma = \uparrow$, $m = -1$ and $n = 0$, $\sigma = \downarrow$, $m = +1$, respectively. The theory predicts in this case a spin ferromagnet or spin singlet, depending on the relative strength between the Zeeman splitting and the tunneling gap [2]. Another class of the multicomponent quantum Hall system are electrons in a wide wells. In this system, the tunneling gap should be replaced by the intersubband energy separation, and similar phase transitions are expected in the QHE regime. The charge

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excitation in QHF has been studied most extensively from the transport properties of the multicomponent quantum Hall system. In the conventional QHE regime the diagonal resistance R_{xx} becomes zero at integer filling factors. In pseudospin quantum Hall ferromagnet regime R_{xx} demonstrates the broad peaks or sharp spikes at $\nu = 2, 3$ or 4 [3–5]. The spikes are attributed to electron scattering by domain walls separating regions of opposite magnetization for easy-axis ferromagnets. In contrast, the broad peak is attributed to the continuous evolution of the ground state, and, therefore, smooth variation of the activation energy, reflecting an XY-ferromagnet. However, in several experiments the resistance feature which is observed within the R_{xx} minima and attributed, according to the QHF classification established in Ref. [2], to Ising-like ferromagnets, looks like a broad resistance peak [4] rather than spikes. Additionally, hysteresis has also been reported in various 2D systems in QHF regime [5,6]. However, the hysteretic behavior of the accompanying resistance feature remains sample specific, probably suggesting that the domain wall motions strongly depends on the disorder.

In this work we present hysteretic magnetoresistance data in the another system, which consists of the array of disconnected quantum dots strongly coupled with 2DEG separated by tunneling barrier. We observed the sudden jump in the magnetoresistance at $\nu = 3$, which corresponds in bilayer system to XY-ferromagnet, with pronounced hysteresis.

2. Experimental results

The structures consist of asymmetrically doped GaAs double quantum wells separated by tunneling $\mathrm{Ga}_x\mathrm{Al}_{1-x}\mathrm{As}$ barrier of 50 Å width. The width of the GaAs well is 140 Å. Sample has density $4.8 \times 10^{11}\,\mathrm{cm}^{-2}$ in the back well, $4.1 \times 10^{11}\,\mathrm{cm}^{-2}$ in the front well, and average mobility $\sim 180 \times 10^3\,\mathrm{cm}^2/\mathrm{V\,s}$. The energy separation between bonding and antibonding subbands becomes $\Delta = \sqrt{\Delta_{\mathrm{SAS}}^2 + \Delta_{\mathrm{E}}^2}$, where Δ_{SAS} is the tunneling symmetric–asymmetric band and Δ_{E} is energy separation resulting from doping asymmetry. From the beating of the SdH oscillations in low field we find $\Delta = 2.2\,\mathrm{meV}$. Self-consistent calculations predict $\Delta_{\mathrm{SAS}} = 0.4\,\mathrm{meV}$, therefore in our case we have $\Delta > \Delta_{\mathrm{SAS}}$, and our bilayer system is imbalanced. The level broadening determined from the amplitude of the SdH oscillations is 0.5 meV.

On the top of the structure the hexagonal superlattice of the antidots with periodicity 0.6 μm and diameter 0.2 μm was patterned in the PMMA resist, which was then covered by the gold gate. Fig. 1 shows schematically the part of the antidot lattice and realistic micrography of this structure. When the negative gate voltage is applied, potential of the neighbor antidots is overlapped and the array of disconnected quantum dots with triangular shape has been formed in the topmost quantum well. Fig. 2 shows schematically profile of the structure (top) and the conduction-band profile for a double-layer 2DEG, when quantum dots are formed in front well.

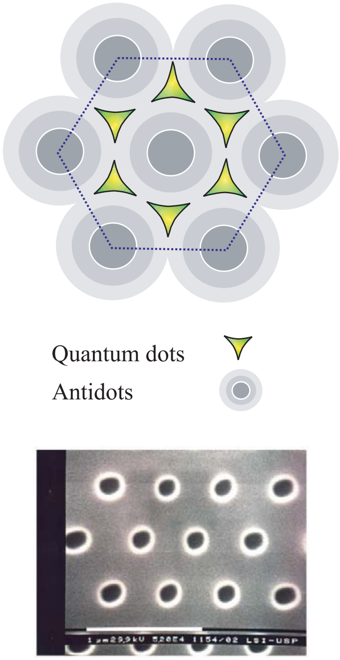

Fig. 1. Schematic view of the hexagonal antidot lattice. The potential of the neighbor antidots is overlapped, which leads to the formations of the array of disconnected quantum dots with triangular shape in the top quantum well. Bottom—micrography of the structure with antidot array.

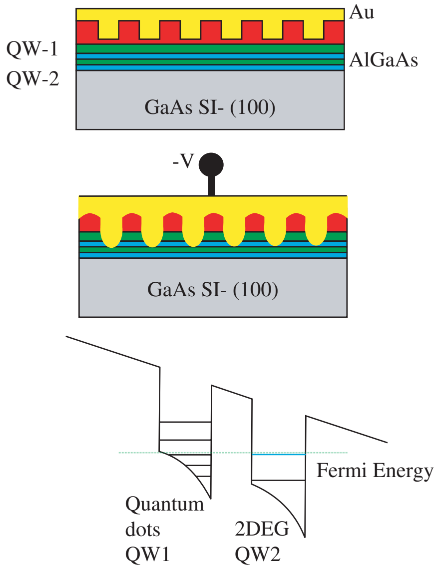

Fig. 2. Top—profile of the device with double quantum wells. Applied negative gate voltage forms lattice with overlapped antidots and triangular disconnected dots. Bottom—schematic conduction-band profile for a double-layer 2DEG, when quantum dots are formed in front well.

Since the concentration of the electrons in the front well is smaller than in the bottom, we believe, that electrons in the topmost well are collected into triangular dots before electrons in back well. Indeed electrons in back well are moving in antidot lattice potential [7]. The test samples were Hall bars with the distance between the voltage probes $L = 500\,\mu\text{m}$ and the width of the bar $d = 200\,\mu\text{m}$. Four-terminal resistance R_{xx} and Hall R_{xy} measurements were made down to 50 mK in a magnetic field up to 15 T. The sample was immersed in a mixing chamber of a top-loading dilution refrigerator. The measurements were performed with an AC current not exceeding 10^{-8} A. We measured the magnetoresistance at different angles Θ between the field and normal to the parabolic well plane, rotating our sample in situ.

Fig. 3 shows the diagonal and Hall resistances of the unpatterned sample for two different temperatures. We may see that at lower temperature the resistance revels large anomalous peak at $\nu = 4$ filling factor and the deep minima at $\nu = 3$. Additionally the small feature at $\nu = 3$ appears at higher temperatures, which exhibits hysteresis when magnetic field is swept up and down (Fig. 3b). These results reproduce the data obtained in a wide quantum wells [3] and double well structures [8] with lower density. However, at $\nu = 4$ instead of spike we observed the peak, which are relatively temperature independent. In contrast to the observation in Ref. [8] traces at $\nu = 3$ shows clear hysteresis. Our data suggest that the behavior of the features in QHF is a sample specific. The difference of the features at ν and $\nu = 4$ is attributed to the different type of the quantum Hall ferromagnetism. Particularly, feature at $\nu = 4$ associated with the crossing between $m = -1$, $n = 1$, $\sigma = \downarrow$ and $m = +1$, $n = 0$, $\sigma = \uparrow$ states, which corresponds to the easy-axis ferromagnet. Consequently, the feature at $\nu = 3$ associated with the crossing between $m = -1$, $n = 1$, $\sigma = \downarrow$ and $m = +1$, $n = 0$, $\sigma = \downarrow$ states, which corresponds to the easy-plane ferromagnet.

Now we proceed to the experimental results in the patterned samples. Fig. 4 shows the traces of R_{xx} versus magnetic field for different temperatures between 1 and 0.35 K. The resistance at zero magnetic field is 16 kΩ, which almost 400 times larger than the resistivity of the unpatterned sample. We believe that in such system the regions between neighboring antidots are squeezed, regulating the barrier between antidots. When this barrier is higher than the Fermi level in electron puddle, transport properties occurs via the hopping of the electrons between adjacent lakes. Fig. 4b shows the temperature dependence of the conductivity at zero field. We may see that this dependence can be described by the Mott hopping formula $\sigma = \sigma_0 \exp(-T_0/T)^{1/3}$. Since the difference between Fermi level of the electron in the front and the bottom wells is 2 meV, the barrier between the antidots in the front well is at least equal to 2 meV, and triangular quantum dots are disconnected. In the strong magnetic field we may see the weak oscillations at $T > 0.3$ K. However, below 270 mK the magnetoresistance reveals striking sudden jump exactly at $\nu = 3$. Note that the magnetoresistance increase 3 times in very narrow ($\Delta B \sim 0.1$ T) interval of magnetic field.

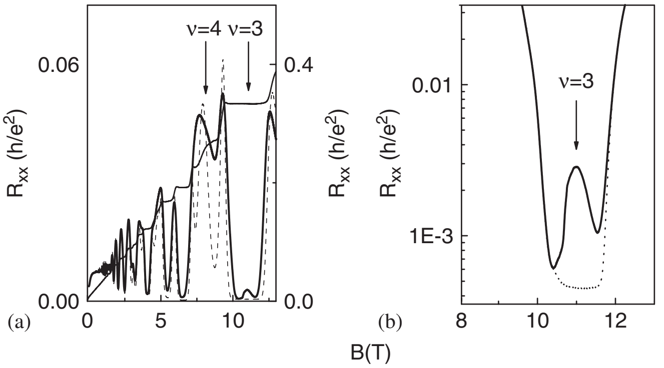

Fig. 3. (a) R_{xx} and R_{xy} for double well structure as a function of magnetic field at $T = 1$ K (solid line) and at $T = 300$ mK (dashes). (b) R_{xx} as a function of B near filling factor $\nu = 3$ at $T = 1$ K. The solid line (dashes) represents the trace taken when magnetic field is swept down (up).

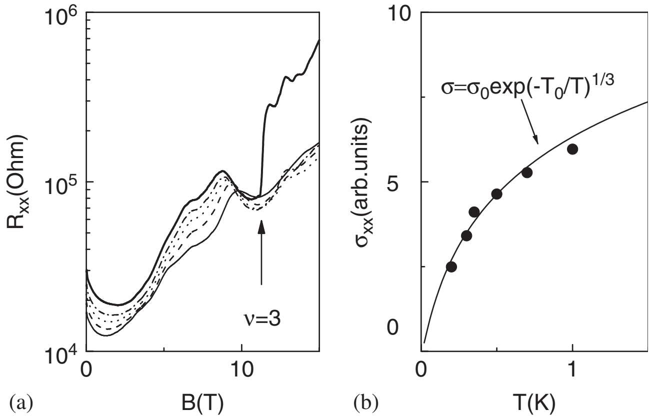

Fig. 4. (a) R_{xx} of the patterned sample as a function of B for different temperatures (T(K): 1 (thin line), 0.6 (dashes), 0.5 (dots), 0.35 (dash-dot), 0.23 K (thick line), $V_g = -0.7$ V. Longitudinal σ_{xx} at zero field as a function of the temperature.

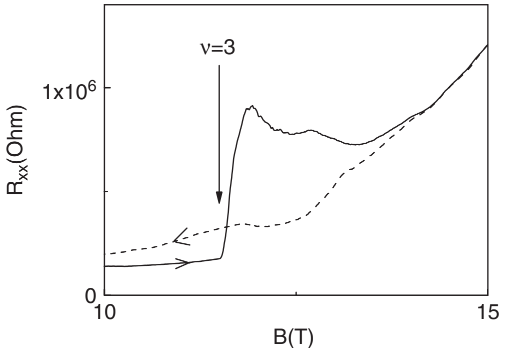

Fig. 5. R_{xx} as a function of B near filling factor $\nu = 3$ at $T = 250$ mK. The solid line (dashes) represents the trace taken when magnetic field is swept up (down).

Fig. 5 shows the experimental traces of the resistance versus B when magnetic field is swept up and down. We may see pronounce hysteresis. Note that the hysteresis loops covers all range of the magnetic field $0 < B < 12$ T. We see no any time evolution of the magnetoresistance during the 20 min at a fixed B. However, we cannot exclude the time evolution over a time scale of hours.

We attribute such unusual behavior of the magnetoresistance to XY ferromagnet, which also occurs in bilayer system at $v = 3$. This ferromagnet stems from the fact that the up and down pseudospin states have a different charge distribution normal to the plane. It leads to the domain with different layer densities. Indeed the percolation through the sample with closed antidots becomes more difficult, and resistance increases.

Acknowledgments

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