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Shubnikov de Haas oscillations in double wells with opposite signs of the electronic g-factor

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Abstract

We report on the measurements of the Shubnikov de Haas oscillations (SdH) in symmetrically doped $Al_xGa_{1-x}As$ double wells with different Al compositions in wells, which lead to the opposite signs of the electronic g-factor in each layer. Surprisingly, the spin splitting appears and collapses several times with increase in the magnetic field. We attribute such behaviour to the oscillations of the exchange-correlation term with Landau filling factor.
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1. Introduction

Double wells separated by the thin layer exhibits many exotic properties in the strong magnetic field due to interplay between interlayer and intralayer exchange interaction, which is controlled by the ratio of the interlayer distance and the magnetic length [1]. The states are described in the pseudospin language where the right and left wells are associated with pseudospin up and down states. The pseudospin and real spin are equally important, which lead to the unique phase state at filling factor 1 with spin-ferromagnet and pseudospin-ferromagnet ordering. Recently new phases have been predicted also for high Landau levels manifesting the nontrivial effects of the Coulomb interactions in the multicomponent quantum Hall systems [2]. In the present paper we introduce additional possibility to vary intralayer interaction by fabrication of the double well with opposite signs of the electronic g-factor in each layer. The spin properties of the $Al_xGa_{1-x}As$ quantum well depends strongly on the Al composition x. For example, the effective g-factor changes with composition as $g_{\mathrm{eff}}(x) = -0.44 + 2.7x$, therefore it is negative for pure GaAs well (−0.44) and positive for $Al_xGa_{1-x}As$ well with x larger than 10%. Fabrication of the double well structure with different Al composition in the left and the right wells may have application in manipulation of the spin in quantum information processing.

Very recently Stoner criterion for ferromagnetism in metals at zero magnetic field has been successfully applied for two-dimensional electron gas under strong magnetic field. It has been predicted that the spontaneous polarization occurs in such systems even for vanishing Zeeman energy, which is called quantum Hall effect ferromagnetism [3]. Generally speaking, the emergence of the interaction driven gaps at certain integer filling factors is expected in the quantum Hall ferromagnets, when the exchange energy becomes larger than the disorder potential. The Zeeman energy Δ_{spin} is given by

$$\Delta_{\mathrm{spin}} = g^{*}\mu_{\mathrm{B}}B = g_0\mu_{\mathrm{B}}B + E_{\mathrm{ex}}, \tag{1}$$

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where μ_B is the Bohr magneton, g_0 is bare Landé factor, $E_{ex} = \alpha\hbar\omega_c$, $\omega_c = eB/mc$ is the cyclotron frequency, m is the effective mass, $\alpha = (1/\pi k_F a_B)\ln(2k_F a_B)$, k_F is the Fermi vector, a_B is Bohr radius. From Eq. (1) we may see that spin splitting appears in the limit of the vanishing bare g-factor, when the exchange energy is comparable with disorder broadening of the Landau levels. Generally, it is expected that the spin splitting is collapsed at the critical Landau filling factor ν_c, when $\Delta_{spin} = \hbar/\tau$, when τ is a single particle relaxation time [4]. In conventional $Al_xGa_{1-x}As/GaAs$ heterostructures Shubnikov de Haas (SdH) oscillations start spin split at $\nu < \nu_c$, and corresponding spin-split minima becomes more deep with an increase in the magnetic field.

In the present paper we study the SdH in $Al_xGa_{1-x}As$ double wells with the opposite signs of the electronic g-factor in the right and the right layers. We find that the spin split becomes resolved at critical filling factor ν_c, however, spin gap collapses again, with an increase in the magnetic field. We attribute such reentrant Stoner transition to the oscillations of the exchange correlation energy with magnetic field.

2. Experimental results and discussions

The samples are symmetrically doped $Al_xGa_{1-x}As$ double wells with 14.2% of Al composition in the left and 8.2% of Al in the right wells separated by 5 nm AlAs barrier. The thick AlAs barrier does not allow the hybridization of the subband energies and, consequently, mixing g-factors in two wells. Therefore the electronic g-factor is +0.081 in the left well and −0.13 for the right well as shown in Fig. 1 (penetration to the AlAs barrier is taken into account for g-factor calculations). The width of each $Al_xGa_{1-x}As$ well is 14 nm. Sample has high total electron density $9 \times 10^{11}\,\mathrm{cm}^{-2}$ ($4.5 \times 10^{11}\,\mathrm{cm}^{-2}$ in each layer), and average mobility $\mu = 50 \times 10^3\,\mathrm{cm}^2/\mathrm{V\,s}$. We have measured longitudinal and Hall resistances at $T =$ 50 mK up to 15 T. Both layers are shunted by ohmic contacts. Because of the different Al content in the wells, our system is weakly asymmetric. We compensate such asymmetry by introduction of the thinner spacer layer from the right side of the double well structure. It is confirmed from the measurements of the low field SdH oscillations ($B < 0.2$ T), which show no beating effects, as is expected for balanced bilayer system with thick barrier. The relative densities in the wells are adjusted by the top gate which comprised the gold film. The voltage of the top gate raises or lowers the density of only the well closest to the sample surface (topmost well), with carrier density in the bottom well being almost constant.

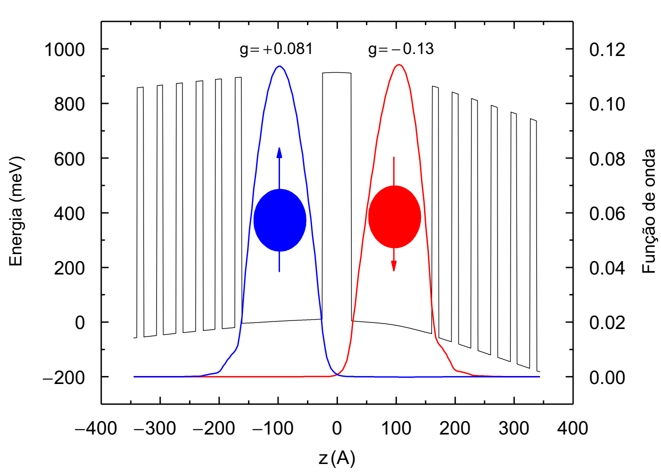

Fig. 1. The well profile and wavefunctions of the symmetrically doped $Al_xGa_{1-x}As$ double wells with different Al compositions in each well ($x = 8.2\%$ in the right and $x = 14.2\%$ in the left well).

Fig. 2 shows the typical trace for the longitudinal resistance R_{xx} as a function of the perpendicular magnetic field. Arrows indicate the peaks which become spin splitted. The amplitude of these peaks decrease in comparison with peak when spin splitting is completely absent. Such peak is often referred to as critical peaks, where the disorder potential has the same magnitude as the sum of the exchange potential and bare Zeeman energy [4]. Surprisingly, the spin splitting is not developed with an increase in the magnetic field, but collapses again. One can see that the critical peak reappears several times. We may argue that such repeated reentrance of the spin splitting

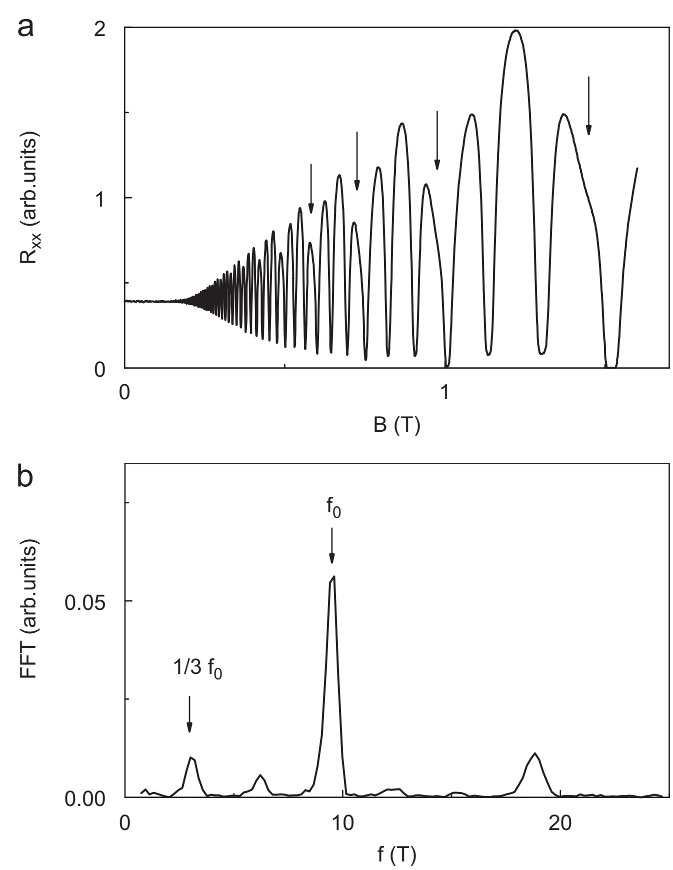

Fig. 2. (a) SdH oscillations for bilayer with opposite sign of g-factor, $T = 50$ mK. Arrows indicates the critical peaks, when the splitting appears. (b) FFT power spectrum, harmonics for $\frac{1}{3}$ and $\frac{2}{3}$ of the main frequency are seen.

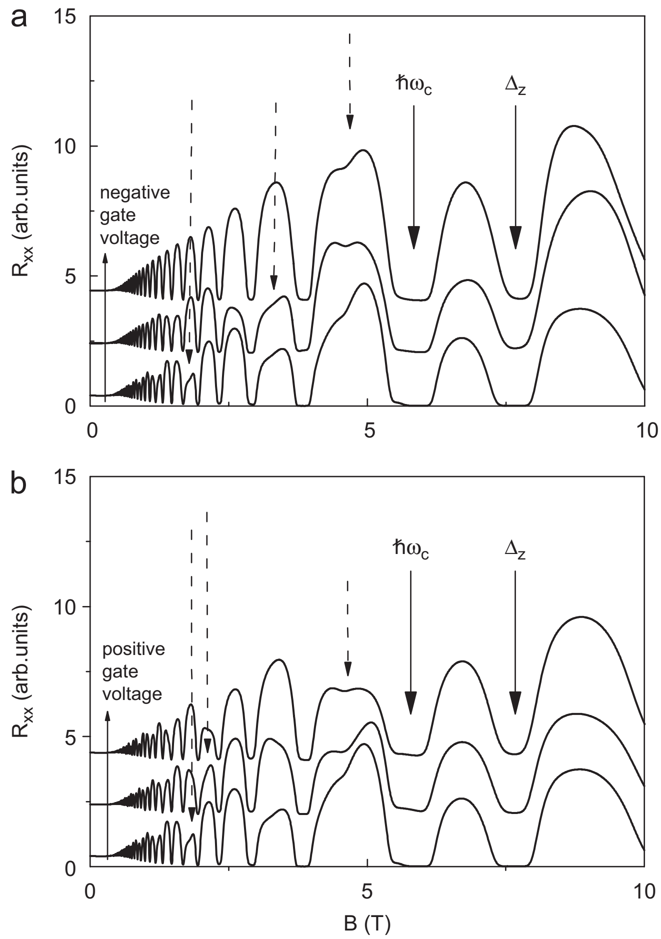

Fig. 3. (a) SdH oscillations for bilayer with opposite sign of g-factor for different negative V_g (V): 0, 0.2, 0.4. (b) SdH oscillations for bilayer with opposite sign of g-factor for different positive V_g (V): 0, 0.2, 0.6. Minima with corresponding gaps are indicated, $T = 1.6\,\text{K}$. $\hbar\omega_c$ is the cyclotron energy, Δ_z is the Zeeman energy. Dashed arrows indicate the critical peaks, when the splitting appears.

occurs due to oscillations of the exchange-correlation energy, which is probably periodic in the inverse field. To quantify this results we perform fast Fourier transform (FFT) on the resistance data, shown in Fig. 2b. Such analysis has uncovered two frequencies, one corresponds to the main period f_0 and second corresponds to $f_0/3$. Therefore, we may argue that exchange correlation energy oscillates in $1/B$ with frequency 3 times smaller than the frequency of the SdH oscillations.

In our double well structure the interplay between the interlayer and intralayer Coloumb interaction determines the ground state, since the tunneling gap is very small ($\sim$0.045 meV). We estimate intralayer Coloumb interaction $E_c^{\text{intra}} = e^2/4\pi\varepsilon d = 5.7\,\text{meV}$ which becomes smaller than interlayer Coloumb interaction $E_c^{\text{inter}} = e^2/4\pi\varepsilon l_B$ (ε is the dielectric constant, $l_B = \sqrt{\hbar c/eB}$ is magnetic length), at $B > 1.8\,\text{T}$.

Fig. 3 shows the magnetoresistance traces in the quantum Hall effect regime for different gate voltages. We may see that the Zeeman gap becomes open at lower filling factors or higher magnetic field. The spin splitting occurs at magnetic field, when E_c^{inter} is larger than E_c^{intra}, and two quantum wells behaves independently. At lower magnetic field $E_c^{\text{inter}} < E_c^{\text{intra}}$, therefore the correlations between layers may suppress the intralayer exchange energy, and the spin splitting collapses again. We cannot explain why such competitions between E_c^{inter} and E_c^{intra} leads to the periodic spin splitting collapse, it requires detailed theoretical calculations.

Fig. 3 also shows that application of the negative voltage and depletion of the upper layer destroys the periodic spin splitting collapse effect. In contrast the application of the positive voltage shifts the position of the critical peaks.

In conclusion we fabricated the new system double quantum wells with opposite signs of the electronic g-factor in each layer. Interplay between the interlayer and intralayer Coloumb interaction results to the reentrant spin collapse at low magnetic field.

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References

[1] S. Das Sarma, A. Pinzuk (Eds.), Perspectives in Quantum Hall Effects, Wiley, New York, 1997.
[2] D.-W. Wang, et al., Phys. Rev. B 68 (2003) 165303.
[3] T. Jungwirth, A.H. MacDonald, Phys. Rev. B 63 (2000) 035305.
[4] D.R. Leadley, et al., Phys. Rev. B 58 (1998) 13036.