Activation studies of pseudospin quantum Hall ferromagnets in double quantum wells

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Abstract

We study pseudospin quantum Hall ferromagnets realized in a strongly coupled double-quantum-well structure. The pseudospin dependence of the Coulomb interactions leads to magnetic anisotropy. Activation energies measured as a function of the single-particle gap, i.e. the pseudospin Zeeman energy, reveal a striking difference between the easy-axis and easy-plane ferromagnets. In the limit of zero single-particle gap, we observe a novel low-energy excitation, reminiscent of Skyrmions, for the \( v = 4 \) easy-axis ferromagnet. We discuss the reduced gap in terms of topological charge excitations in the domain walls. © 2002 Elsevier Science B.V. All rights reserved.

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Quantum Hall (QH) ferromagnets provide a unique situation where ferromagnetism and charge incompressibility of a system are linked by the density commensurability between the electrons and the flux quanta. The ferromagnetic order in the ground state imposes a large exchange energy penalty for a spin reversal, thereby producing a gap for charged excitations. When the Landau-level (LL) filling factor \( v \) is slightly detuned, the density mismatch is accommodated by locally introducing charged quasiparticles, and so the commensurability and the incompressibility of the bulk regions are preserved. Hence, the quantization of the Hall conductance and the vanishing of the longitudinal resistance can be explained coherently in terms of localization of quasiparticles at disorder. A further unique feature of QH ferromagnets is the possibility for topological excitations, in which the quasiparticle is transformed into an extended object whose stability is guaranteed by the boundary conditions. Around these defects, the spin degree of freedom is restored, so the system can enjoy charge degree of freedom as well. It is now well established that the Skyrmion [1,2], a topological soliton in the isotropic Heisenberg spin system, governs dissipative transport around \( v = 1 \) for a sufficiently small Zeeman energy [3,4].

In this paper, we study pseudospin QH ferromagnets realized in a strongly coupled double-quantum-well (DQW) structure. LLs with different subband and Landau orbital indices act as up- and down-pseudospin levels when they cross at the Fermi level. The pseudospin dependence of the Coulomb interactions leads to magnetic anisotropy. The system can therefore...
exhibit easy-axis or easy-plane anisotropy, and accordingly behaves like an Ising or XY ferromagnet depending on the orbital states and spins of the LLs involved [5,6]. We show that easy-plane and easy-axis ferromagnetism occurs for \( v = 3 \) and 4, respectively, for which the crossing LLs have the same and opposite spins. Activation energy measurements reveal a novel low-energy excitation for the \( v = 4 \) easy-axis ferromagnet in the limit of zero single-particle gap, which we discuss in terms of topological charge excitations in domain walls.

The system we study is a bilayer electron system in a strongly coupled DQW, which consists of two identical 20-nm thick GaAs quantum wells (QWs) coupled through a thin (1 nm) \( \text{Al}_{0.3}\text{Ga}_{0.7}\text{As} \) tunnel barrier. Using the front and back gates, we are able to tune the electron density \( n_s \) from 0.5 to \( 3.5 \times 10^{15} \text{ m}^{-2} \) while keeping the DQW potential symmetric [7,8]. Our DQW structure has a symmetric–antisymmetric gap, \( \Delta_{\text{SAS}} = 29 \text{ K} \), and a mobility of 64 m\(^2\)/V s for \( n_s = 1.22 \times 10^{15} \text{ m}^{-2} \). Magneto-transport measurements are carried out using an AC lock-in technique with a current of 10–20 nA.

Fig. 1(a) shows the calculated wave functions of the symmetric (S) and antisymmetric (A) states for the DQW. When a perpendicular magnetic field \( B \) is applied, two sets of Landau fans originate from the S and A subbands, which then give rise to crossings between LLs with different Landau orbital indices. We label the single-particle levels \( (i, N, \sigma) \), where \( i = (\text{S, A}) \), \( N \), and \( \sigma = (\uparrow, \downarrow) \) are the subband, Landau orbital, and spin indices, respectively. For LLs with \( N \) and \( N' = (N + \Delta N) \), the crossing occurs when

\[
|\Delta N| \frac{e}{m^*} + \Delta \sigma |g| \mu_B B = \Delta_{\text{SAS}}.
\]

Here, \( \hbar = h/2\pi \), \( e \), \( \mu_B \), \( m^* \), and \( g \) are the Planck constant divided by \( 2\pi \), electronic charge, Bohr magneton, effective mass and \( g \)-factor of electrons, respectively. \( \Delta \sigma = 0 (\pm 1) \) corresponds to crossings between parallel (antiparallel) spins. When the Fermi level lies between two adjacent LLs, we take these LLs as up and down pseudospin states irrespective of their real spins. It can easily be seen that \( \Delta \sigma = \pm 1 \) and 0 hold for crossings at even and odd \( v \), respectively. When a crossing occurs at \( B = B_c \), the energy difference between the single-particle levels at \( B = B_c + \Delta B \) is

\[
\Delta_{\text{SP}} = \left[ \frac{|\Delta N| \hbar e}{m^*} + \Delta \sigma |g| \mu_B - \frac{\partial \Delta_{\text{SAS}}}{\partial n_s} v e \right] \frac{1}{\hbar} \Delta B,
\]

and this acts as an effective Zeeman energy for the pseudospins. The third term is a correction due to the \( n_s \) dependence of \( \Delta_{\text{SAS}} \).

Fig. 1(c) shows the magnetoresistance \( R_{xx} \), at \( T = 50 \text{ mK} \) as a function of \( B \) and \( n_s \). The data are obtained by simultaneously scanning the front- and back-gate biases so as to keep the DQW potential symmetric throughout. The white regions at higher fields represent the QH regions. LL crossings in these regions give rise to a finite \( R_{xx} \), and lead to features running vertically across the QH regions (see white arrows). The surprise here is the striking even/odd asymmetry in the widths of these features. Those at even \( v \) are found to be extremely sharp, in marked contrast to the broad features at odd \( v \). This is confirmed by Fig. 2(a), in which we show \( R_{xx} \) for \( n_s = 1.22 \times 10^{15} \text{ m}^{-2} \). The peak at \( B = 1.22 \text{ T} (v = 4) \), which is due to the crossing between (S, 1, \( \uparrow \)) and (A, 0, \( \uparrow \)), has a full-width at half-maximum of only 1.5 mT at \( T = 55 \text{ mK} \). As shown in Fig. 2(b), the peak grows and broadens with increasing temperature, indicating the existence of a finite activation energy for the dissipative transport.
Similar results are obtained for another crossing for \( v = 4 \) at \( B = 1.52 \) T.

As we have reported previously [9], such sharp peaks take place only when the DQW potential is symmetric, i.e. when the Hartree energy is not important. As a result, the exchange energy, which is highly pseudospin dependent for \( \Delta \sigma = \pm 1 \), dominates the magnetic anisotropy and leads to easy-axis ferromagnetism. Recently, similar resistance spikes have been reported by Poortere et al. for tilted-field experiments on AlAs QWs [10]. They explained the resistance spikes in terms of electron scattering at domain walls separating regions with opposite magnetization. The domain structure reflects the discrete symmetry and the long-range spin order in easy-axis ferromagnets, and is absent in isotropic or easy-plane systems with continuous symmetry. Hence, domain formation is also likely in our system.

Taking advantage of our DQW structure, in which \( n_s \) can be varied without changing the QW potential, we measure the activation energy for a fixed \( v \) at different values of \( B \), i.e. as a function of \( A_{SP} \) [Fig. 2(c)]. The activation energy, \( A_v \), is determined by fitting the data to \( R_{xx} \propto \exp(-A_v/2T) \). The data summarized in Fig. 3(a) reveal a striking difference between \( v = 3 \) and 4. At the crossing, \( A_4 \) decreases abruptly, which explains the observed sharp resistance peak. By contrast, \( A_3 \) varies smoothly around the minimum. The solid lines in the figure represent the slopes of \( |A_{SP}| \) calculated using \( m^* = 0.07m_e, |g| = 0.4 \), and the measured \( n_s \) dependence of \( A_{SAS} \). The excellent agreement with the data indicates that electron–hole excitations between the up and down pseudospin levels, shown as vertical arrows in Fig. 3(b), are responsible for the measured gaps in these regions.

In Fig. 4(a), we plot \( A_4 \) vs. \( A_{SP} \), both normalized by the characteristic Coulomb energy \( e^2/4\pi\varepsilon_0B \). Interestingly, the data are reminiscent of the \( v = 1 \) data for \( \gamma \to 0 \) [3,4]. \( A_4 \) is reduced to about 25% of the extrapolated value for \( A_{SP} \to 0 \). Different from isotropic systems in which the magnetization has no particular directions for \( A_{SP} = 0 \), the magnetization favors either up or down alignment in the easy-axis system. In other words, \( A_{SP} = 0 \) implies that the two phases with opposite magnetizations have equal energies. Hartree–Fock calculations for a similar easy-axis system show that the lowest-energy charged excitation is not a Skyrmion but a single pseudospin flip [11]. To account for the resistance spikes observed in AlAs QWs, Jungwirth and MacDonald [12] have calculated the energy of a Hartree–Fock quasiparticle, or a pseudospin flip, inside domain walls. They find that the energy is reduced to about half that of the bulk [see I and III in Fig. 4(b)]. We speculate that the energy may be reduced further by allowing the pseudospin to rotate
Fig. 4. (a) $\Delta_v$ vs $\Delta_{SP}$, both normalized by $e^2/4\pi\varepsilon_0/\hbar$. (b) Possible excitation processes in the presence of domain structure. The regions where the pseudospin has a negative (positive) $z$ component are shown as gray (white). (I) single pseudospin flip in the bulk, (II) Skyrmion in the bulk, (III) pseudospin flip inside the domain wall, (IV) kink in the domain wall.

smoothly around the quasiparticle in the domain wall. Interestingly, the resultant structure resembles the topological defect discussed in Ref. [13] for a domain structure at $v = 1$ defined by an inhomogeneous $g$-factor. As pointed out in Ref. [13], such a structure can be regarded as a Skyrmion trapped at the domain wall [see II and IV in Fig. 4(b)]. While these carriers are confined in domain walls, their motions parallel to the Hall electric field will dissipate energy and contribute to the finite resistance. We also note that our system does not show clear hysteretic behavior, which suggests that the domain walls can move rather easily.

Finally, we point out that $v = 3$ also has a finite gap at $\Delta_{SP} = 0$. The smooth variation of the gap around the minimum indicates the continuous evolution of the ground state and the absence of domain structure. These observations suggest that $v = 3$ is an easy-plane ferromagnet, and this will be discussed in more detail elsewhere.

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References