Ising Ferromagnetism and Domain Morphology in the Fractional Quantum Hall Regime

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(Received 23 August 2000)

The density driven quantum phase transition between the unpolarized and fully spin polarized $\nu = 2/3$ fractional quantum Hall state is accompanied by hysteresis in accord with 2D Ising ferromagnetism and domain formation. The temporal behavior is reminiscent of the Barkhausen and time-logarithmic magnetic after-effects ubiquitous in familiar ferromagnets. It too suggests domain morphology and, in conjunction with NMR, intricate domain dynamics, which is partly mediated by the contact hyperfine interaction with nuclear spins of the host semiconductor.

DOI: 10.1103/PhysRevLett.86.2412 PACS numbers: 73.43.–f, 73.21.–b, 73.23.Ad, 73.61.–r

The two-dimensional electron system (2DES) with density n_s in a strong perpendicular magnetic field $B_\perp$ condenses by virtue of the Coulomb interaction at particular rational values of the filling factor, $\nu = n_s h/(eB_\perp)$, into the incompressible fractional quantum Hall (FQH) states with their quantized Hall and vanishing longitudinal conductance [1]. At very strong fields, all electron spins are aligned and the spin degree of freedom is effectively frozen out, since the Coulomb interaction scales with $\sqrt{B_\perp}$, whereas the Zeeman splitting rises linearly. However, in GaAs-based 2DESs the Zeeman splitting is so small that by lowering n_s the FQH regime can be shifted to fields, where spin is turned into an important extra dynamical internal degree of freedom [2]. Spin reversal then occurs at little or no energetic cost and rich phase transition physics ensues, since multiple FQH ground states that differ mainly in their spin configuration compete. Signatures for phase transitions at, for example, $\nu = 2/3$ and $2/5$ between distinct spin-unpolarized and fully spin-polarized FQH states that occupy the same filling factor were uncovered in transport experiments [3]. A photoluminescence study even gained direct access to the degree of spin polarization [4].

In the integer quantum Hall (IQH) regime, the correlation between two macroscopically degenerate Landau levels, which are brought energetically close to alignment, frequently contrives a transition of the electronic system to ordered many-particle ground states similar to those of familiar low-dimensional ferromagnets [5–7]. To benefit from this analogy, the Landau level degree of freedom is assigned a pseudospin and the problem is analyzed in terms of the anisotropy energy for a particular pseudospin orientation. The competition between exchange and Coulomb interaction energies controls the most favorable orientation. In cases where electrostatic energy contributions are negligible, exchange energy costs dictate that the pseudospin points either upwards or downwards characteristic of a ferromagnet with easy axis anisotropy [5]. IQH states at even integer filling near the coincidence of two spin-resolved Landau levels with different index and opposite spin constitute examples. In the FQH regime a rigorous physical description of ferromagnetism has not been put forward. Because the ground state spin transition physics at filling factors $2/3$ and $2/5$ can be rephrased in the composite fermion (CF) [1] language as occurring at even CF filling factor $\nu_{\text{CF}} = 2$ from the coincidence of the spin-down state of the lowest CF Landau level with the spin-up state of the second Landau level, it is natural to pursue whether these phase transitions, too, fall within the realm of ferromagnetism. In such ferromagnets disorder should introduce a random component into the effective field strength that aligns the pseudospin [5]. Moreover, it may pin and nucleate domains of opposite pseudospin orientation. Large energy barriers between adjacent domains then are bound to promote hysteresis in physical properties. From its observation Ising ferromagnetism has been inferred [6,8]. The domain morphology, dynamics, and microscopic mechanisms for transport through such a ferromagnet have not been addressed to date.

Here, we trace the location of the ground state spin transition near $\nu = 2/3$ in the full (ν, n_s) plane as a function of a wide set of parameters such as field sweep rate and direction, in-plane magnetic field, rf irradiation, and the excitation current. We find that the spin transition following the line $\nu = 2/3$ occurs at different values of the carrier density depending on whether n_s is gradually lowered or raised, as one would anticipate for a ferromagnet with easy axis anisotropy broken up in domains. To improve our comprehension of the physical mechanisms responsible for hysteresis, the time behavior of the resistance is examined. It exhibits sudden jumps akin to the Barkhausen effect in the magnetization of conventional ferromagnets [9], where it is ultimately assigned to the energy landscape in which the system evolves with a huge number of local minima and saddle points that reflect the unavoidable presence of structural disorder in a macroscopic magnetic system. Scrutinizing the resistance on longer time scales reveals that equilibrium is progressively approached in a logarithmic fashion, typical for systems characterized by a wide distribution of energy barriers or time constants [9].

0031-9007/01/86(11)/2412(4)$15.00

Finally, a response to rf irradiation in the resistance is reported. Its correlation with the sign and size of the hysteresis supports the conjecture that the nuclear spin system affects transport through this peculiar ferromagnet. All these observations are intimately connected with domain morphology.

Two devices, which impart identical information, have served our study: a modulation doped GaAs/AlGaAs heterostructure with a backgate tunable carrier density between 4×10^{10} and 11×10^{10} cm^{-2} and a field effect transistor (FET), which exploits the virtues of cleaved edge overgrowth. A cross section of the FET, recently developed at the Walter Schottky Institute, is depicted in Fig. 1. The absence of modulation doping and the contact scheme with n^+-GaAs permit continuous tuning from nearly fully depleted to 3×10^{11} cm^{-2}. The incorporated ultrashort period superlattice (SL) is not crucial for our observations. It mainly improves the sample quality of the FET [10]. In this geometry, the condensation in a quantized Hall state is heralded by a plateau in the source-drain resistance R, quantized in units of h/e^2, or a maximum in case it is not fully developed [11].

Figure 2(a) displays R in the $(1/\nu, n_s)$ plane for $\nu < 1$. Following the line of constant filling $\nu = 2/3$ as n_s (equivalently $B_\perp$) is lowered, the resistance maximum collapses and subsequently reemerges at a slightly offset filling factor. This reentrant behavior is the signature in transport for the transition between the spin-unpolarized (↑↓) to the spin-polarized (↑↑) ground states [3]. This interpretation is also borne out in tilted field experiments on this sample. Inverting the field sweep direction for recording the resistance in the $(1/\nu, n_s)$ plane unveils hitherto undisclosed aspects of this 2/3 phase transition. When acquiring the data during upward sweeps in Fig. 2(b), the spin transition is postponed to higher n_s and $B_\perp$ in comparison with data collected during downward sweeps. Accordingly, the electronic spin polarization γ along the lines of constant filling factor $\nu = 2/3$ will exhibit hysteretic behavior. These observations are congruous with an Ising ferromagnetic phase transition, if the unpolarized and fully polarized ground states are mapped onto states of opposite pseudospin orientation. The drop in the resistance in the vicinity of the phase transition may then reflect the dissipative current, which originates from the eventual backscattering of charge-carrying quasiparticles that suffer reflections off energy barriers separating disorder-induced domains of distinct pseudospin.

The introduction of time as a parameter indirectly confirms the ferromagnetic nature. It allows one to corroborate on the importance of domains and their boundaries and sheds light on their dynamics. The resistance in the hysteretic region manifests a strong dependence on both the field sweep rate and the time following a change in applied $B_\perp$. One example is depicted in Fig. 3. Phenomenologically, the behavior invariably reminds one of the Barkhausen and magnetic after-effects in familiar ferromagnetic materials [9,12]. Their hallmarks are abrupt, mostly irreproducible jumps in the magnetization and the time lag on the scale of minutes, hours, or even days between the sudden change in applied field and the equilibrium of the magnetization in a specimen. Here, in an analogous fashion, impediments to free domain wall motion, caused by any imperfections or irregularities that render the wall energy position dependent, may make wall motion in our system proceed by a series of thermal agitation or external field driven, Barkhausen jumps between energy minima. Surges in R proclaim these prompt rearrangements of domains, which reshape the potential

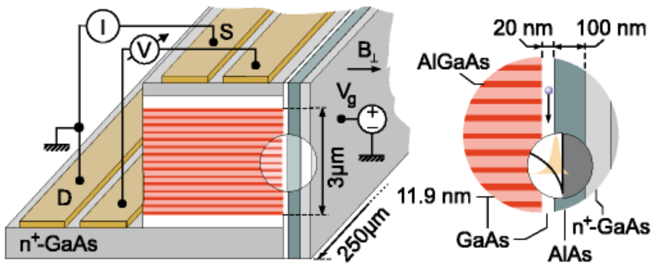

FIG. 1 (color). Schematic cross section of the FET with a 3 μm long and 250 μm wide channel. Its fabrication entails a conventional MBE growth sequence on an (001)-GaAs substrate followed by an *in situ* cleave and cleaved edge overgrowth. During the first growth an undoped, 3 μm thick and 15 nm period GaAs/Al$_{0.32}$Ga$_{0.68}$As is sandwiched between highly doped n^+-GaAs source (S) and drain (D) contact layers. During the postcleave growth the 20 nm undoped GaAs layer, which will later host the 2DES, is deposited on the freshly exposed (110)-oriented surface. It is covered by a 100 nm AlAs barrier. An n^+-GaAs cap layer serves as a gate. A positive bias with respect to source and drain induces the 2DES at the GaAs/AlAs boundary.

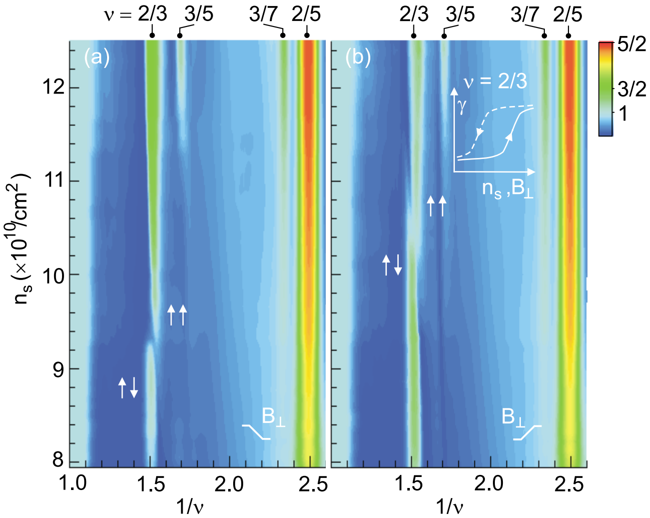

FIG. 2 (color). Color map of the source-drain resistance R in units of h/e^2 in the $(1/\nu, n_s)$ plane when the field or carrier density is swept (a) downwards or (b) upwards at $T = 50$ mK. The inset schematically indicates the degree of electron spin polarization γ along the line $\nu = 2/3$ when the carrier density or field is increased (solid line) or lowered (dashed line).

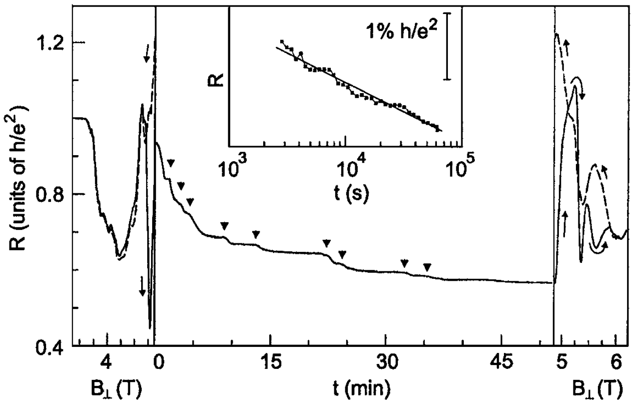

FIG. 3. Time dependence of R when the field sweep is interrupted. Arrows mark the location of sudden resistance jumps. The longer time scale behavior is illustrated in the inset. The data (solid circles) are collected in a logarithmic fashion. The noise level is approximately 0.02% h/e^2.

landscape for backscattering of the mobile charge-carrying quasiparticles near domain walls held responsible for the dissipative current. When monitoring R over longer time frames (>10 h) it does not settle and its overall trend follows a time-logarithmic function (Fig. 3 inset). In common ferromagnetic materials, described by a wide spread of time constants because of the heterogeneous domain shapes and barriers, the thermal relaxation and magnetic viscosity indeed accomplish only a logarithmic approach of the magnetization to the equilibrium state [9,12]. Keeping in mind that here R is measured, the analogies are extraordinary. Even though only one specific example is shown, the time-logarithmic relaxation and the "resistive Barkhausen jumps" are pervasive in the entire phase transition region. We interpret them as additional evidence for domain morphology. Selected repeat experiments on the conventional single heterojunction with backgate reproduced qualitatively all key elements: hysteresis, Barkhausen jumps and a time-logarithmic resistance change. Some are illustrated in Fig. 4. The SL embedded in the FET is thus not essential and mainly serves to obtain high quality [10], even though it likely intensifies the role of domains by offering periodic pinning centers.

For a system partitioned in domains, domain growth, or transport across domains with different spin configuration demands electron spin flips. Besides spin-orbit coupling and acoustic phonon emission, the contact hyperfine interaction is a possible candidate to mediate electron spin reversal via flip-flop scattering events, the simultaneous flip of an electron and nuclear spin [13]. As a consequence, the nuclear spin polarization of the host semiconductor is modified. This process, referred to as dynamic nuclear spin polarization (DNP), conversely will affect the electron transport in the following ways if the net nuclear spin polarization is substantial: (i) The altered number of nuclear partners with the appropriate spin modulates the flip-flop scattering rate. (ii) A net nuclear spin polarization represents an effective nuclear field to be considered for the electronic Zeeman splitting. Depending on whether at the domain wall the transition occurs from an unpolarized to a spin polarized domain or vice versa, the nuclear field will either enhance or lower the Zeeman splitting as the net nuclear spin polarization grows and subsequently in turn suppresses or promotes additional spin flips. This effective field lays out modified energy barriers between domains of opposite electronic spin configuration. (iii) Because of nuclear spin diffusion, the net nuclear spin polarization is not localized to the domain walls and "crosstalk" will further complicate the picture. The standard approach in transport to highlight the influence of the nuclear spin system consists of irradiating the sample with narrow-band rf, while simultaneously monitoring the resistance of the 2DES [13,14]. rf in resonance with a transition between the Zeeman split nuclear energy levels impairs the net nuclear spin polarization and reverses the effects of the DNP. NMR spectra for As^{75} are plotted in Fig. 5. They buttress the importance of DNP for transport across this ferromagnetic phase, since magnitude and sign of the rf response correlate with the difference in R between up and down sweeps. Quadrupole splitting accounts for the resonance substructure. It is difficult to unravel in this NMR setup whether the nuclear spin polarization is the sole consequence of current flow. However, other potential sources are difficult to reconcile with the large number of nuclear spin flips required to have an observable impact in comparison with the insignificant number of electrons involved. DNP and nuclear spin diffusion will bring in a slow time dependence and should themselves be—besides the very presence of domains due to the exchange interaction and disorder—an *additional* source for hysteresis. Granting that current flow is responsible for the nuclear spin polarization, this assertion is supported by systematically lowering the excitation current over 3 orders of

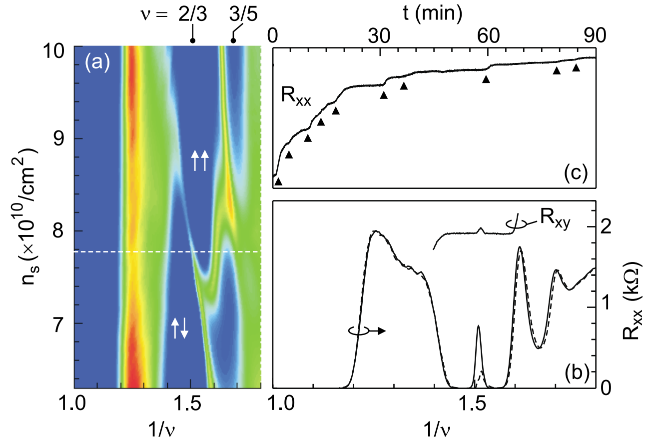

FIG. 4 (color). (a) Color map of R_{xx} in the conventional heterostructure with backgate when the field is swept down (blue = 0 Ω; red = 2.5 kΩ). (b) Hysteresis in R_{xx} at $n_s \approx 7.8 \times 10^{10}$ cm^{-2} (dashed line sweep up; solid line sweep down). R_{xy} is shown for sweep down only. (c) Time dependence of R_{xx} after interrupting the field sweep.

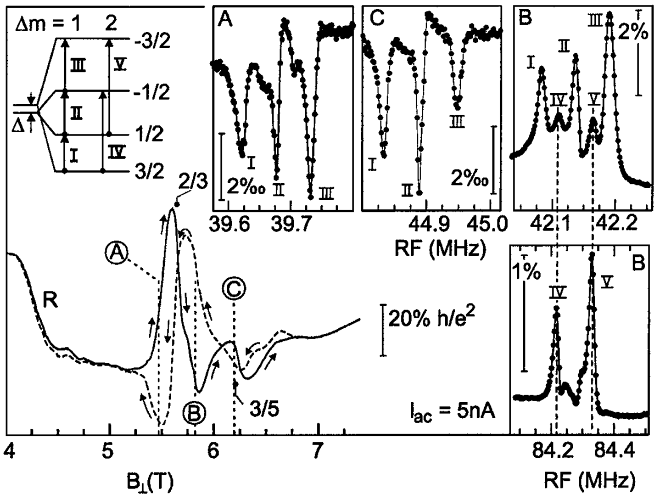

FIG. 5. Resistively detected NMR for As^{75} on the cleaved edge overgrown FET at different fields (A, B, C) indicated on the R vs $B_\perp$ curves. The transitions between the nuclear energy levels are depicted in the inset. The resonance lines show a threefold splitting, ascribed to the interaction of the quadrupole moment of these $I = 3/2$ nuclei with intrinsic electric field gradients induced by stress and/or the broken cubic symmetry near the interface of the slightly lattice-mismatched GaAs and AlAs layers. Two additional peaks, also seen in Ref. [15], in between the dominant triplet, are identified as $\Delta m = 2$ transitions triggered by the unintentionally generated second harmonic of the incident rf frequency [16]. By virtue of the quadrupole interaction, these transitions are no longer forbidden and saturable because of the long $T1$-relaxation time. Data taken at double the frequency (bottom right panel) confirm this assertion.

magnitude (5 nA down to 5 pA), while keeping the sweep rate constant, and studying the hysteresis along $\nu = 2/3$. The contribution of DNP should dwindle. Indeed, at 5 pA dramatic hysteresis remains. It is altered only in shape for currents above 0.5 nA, and the transitions shift to different densities with increasing excitation current.

The intricate, time-dependent interplay of the disorder-induced domain structure, thermal relaxation, and the role of nuclear spins turns the microscopic description of transport through this ferromagnet in the FQH regime into a tremendous challenge. The study of samples with an artificially created boundary between both phases of opposite pseudospin is promising to isolate the various mechanisms pointed out here, since local probes may then be put to work. The unrivalled controllability, through patterning and gating among others, inherent to the GaAs-based 2DES is then likely to render it into a profitable test vehicle for the general study of low-dimensional magnetism, macroscopic quantum tunneling, and nonequilibrium thermodynamics.

We thank G. Denninger, A. MacDonald, Y. Meir, and A. Stern for discussions and U. Wilhelm for software. This work was supported by the BMBF (01BM919/5, 01BM912) and the DFG (SFB348 B8).

Note added.—After submission of this Letter, Ref. [17] was published covering similar ground at a different fractional filling.

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[11] R is a mixture of the different tensor components. Between two QH states, the nonzero longitudinal conductance short circuits the Hall voltage, due to the large channel width to length ratio of the sample. Consequently, R drops in between two QH states, *opposite* to the behavior of the longitudinal resistance in a Hall bar geometry. In this regime the sample topology thus resembles more closely the corbino geometry.

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