Critical Resistance of the Quantum Hall Ferromagnet in AlAs 2D Electrons

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Magnetic transitions in AlAs two-dimensional electrons give rise to sharp resistance spikes within the quantum Hall effect. Such spikes are likely caused by carrier scattering at magnetic domain walls below the Curie temperature. We report a critical behavior in the temperature dependence of the spike width and amplitude, from which we deduce the Curie temperature of the quantum Hall ferromagnet. Our data also reveal that the Curie temperature increases monotonically with carrier density.

Various forms of order have been shown to derive from or compete with the quantum Hall (QH) state in two-dimensional (2D) electron systems, including charge density waves, the Wigner crystal, stripe and bubble phases, and liquid crystal states. Recent experimental evidence, often in the form of magnetic hysteresis, also points to the existence of a ferromagnetic phase within the integer and fractional QH states [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11]. The analogy with spontaneous polarization in conventional Ising ferromagnets exists when two Landau levels (LL’s) with opposite spin quantum numbers and different orbital indices are degenerate [Fig. 1(b), inset]. Experimentally, this LL coincidence is obtained by tilting the magnetic field. Exchange energy ensures that at temperature $T = 0$, one of the two crossing levels is fully occupied and the other empty. Magnetic domains form as the temperature is raised, and the electronic state within each domain is described as an Ising-like QH ferromagnet with either one of two possible spin orientations. In materials such as AlAs, (Cd,Mn)Te, InGaAs, InSb, and wide GaAs quantum wells, LL crossings and the associated magnetic domains lead to resistance maxima within the integer QH or Shubnikov-de Haas minima of the magnetoresistance ($R_{xx}$) [Fig. 1], while in GaAs 2D electrons, sharp resistance peaks are observed in the fractional QH $R_{xx}$ minima. In the latter case, the spikes are caused by crossing LL’s of composite fermions [5].

Theorists have begun to address the nature of domain boundaries in Ising QH ferromagnets [12, 13, 14], though no calculation of the domain wall resistance in these systems exists at present. Estimates for the domain wall resistance spikes can be separated fairly easily from the background resistance of the 2D system, so that they provide a direct measure of the domain wall magnetoresistance. Measurements of the resistance spike dimensions, namely its amplitude ($\Delta R_{sp}$) and width in magnetic field ($\Delta B_{sp}$) [see Fig. 2(a)], therefore supply an experimental basis against which future models of the domain walls can be tested, and provide a second motivation for our study.

In this Letter, we report temperature- and density-dependence measurements of the resistance spikes in AlAs 2D electrons. Our results reveal that: (1) $\Delta R_{sp}$ increases with $T$ up to a characteristic temperature, $T_M$, beyond which it decreases with $T$; (2) below the same temperature, $\Delta B_{sp}$ is relatively constant, while above $T_M$, $\Delta B_{sp}$ increases significantly with temperature; (3) $T_M$ increases with the 2D electron density $(n)$. Comparing the temperature dependence of the spike width with that expected from a mean-field 2D Ising model, we are able to identify $T_M$ with the Curie temperature of the QH ferromagnet.

AlAs offers several advantages for the study of QH ferromagnets: first, the band $g$-factor of 2D electrons in AlAs is approximately 2 [12], while the effective electron masses (at the $X$ points of the Brillouin zone) are 1.1 and 0.19 in the longitudinal and transverse directions, respectively [12]. The latter properties ensure that the Zeeman ($E_Z$) and cyclotron ($E_c$) energies are comparable in magnitude for low values of $\theta$, a regime in which the orbital effect of the tilted field can be neglected [12]. Second, the high quality of our AlAs quantum wells (QW’s), in which we have observed developing fractional QH states at high-order fillings [17], implies that the interparticle Coulomb interaction, rather than disorder, dominates the ground state of the 2D system.

The sample studied here is a 150 Å-wide AlAs QW surrounded by Al$_{0.4}$Ga$_{0.6}$As barriers, modulation-doped on the front side with Si, and grown by molecular beam epitaxy on a GaAs (411)B substrate. For magnetotransport measurements, a 100 × 325$\mu$m Hall bar was lithographically etched on the sample surface, and 1500 Å-thick Au-GeNi contacts were deposited and alloyed at 440 °C for 10 minutes in forming gas. Front and back gates were fitted to the sample. Experiments were performed in pumped $^3$He and dilution refrigerators in magnetic fields up to 18 T. Prior to measurements, the sample was illuminated with a red LED at $T \approx 4$ K, while a positive bias was applied between the back gate and the 2D system. This procedure is required to make Ohmic contact to the 2D system in our sample, and is detailed in [15].

Figure 2(a) gives an overview of the sample magnetoresistance for $n = 2.5 \times 10^{11}$ cm$^{-2}$ and $\theta = 38^\circ$, showing...
FIG. 1: (a) Magnetoresistance of AlAs 2D electrons for a density \( n = 2.5 \times 10^{11} \text{ cm}^{-2} \). Resistance spikes occur at Landau level crossings near \( \nu = 3 \) and 5. (b) Magnetoresistance of AlAs 2D electrons near \( \nu = 3 \), showing the resistance spike for different \( n \) and temperatures \( (300 \lesssim T \lesssim 700 \text{ mK}) \). From left to right, tilt angles are \( \theta = 16^\circ, 25^\circ, 30^\circ, 34^\circ, \) and \( 37^\circ \). Note the strong suppression of the spike amplitude as \( n \) increases. For clarity, only data for downward \( B \) sweeps are shown. Inset schematically shows the crossing of opposite spin Landau levels at \( \nu = 3 \). (c) Resistance spike near \( \nu = 4 \) for \( n = 1.86 \times 10^{11} \text{ cm}^{-2} \).

FIG. 2: (a) Definition of the spike amplitude \( (\Delta R_{sp}) \) and linewidth \( (\Delta B_{sp}) \). (b) Plots of the resistance spike amplitude \( (\Delta R_{sp}) \) vs. \( n \), for several carrier densities. (c) Temperatures of the \( \Delta R_{sp} \) maxima as a function of \( n \) (full squares: from this figure; hollow square: data from a separate cooldown).

The resistance spikes near \( \nu = 3 \) and 5. The \( T \) and \( n \) dependence of the \( \nu = 3 \) spike are given in Fig. 1(b). From these data we first plot, in Fig. 2(b), the spike amplitudes as a function of \( T \). We see that \( \Delta R_{sp} \) reaches a maximum at a temperature \( T_M \), and that \( T_M \) increases monotonically with \( n \) [Fig. 2(c)]. Furthermore, \( \Delta R_{sp} \) decreases quickly as the density increases; for \( n \gtrsim 2.7 \times 10^{11} \text{ cm}^{-2} \) in this sample, the spike amplitude is too small to be measured. On the other hand, at the lowest measured density, the maximum \( \Delta R_{sp} \) is about 700 \( \Omega \), comparable to the \( R_{xx} \) maxima at half-integer \( \nu \), when the Fermi level lies close to the energies of extended states. We note that an even stronger resistance spike is seen near \( \nu = 4 \) in this sample; its \( \Delta R_{sp} \) is more than twice the magnitude of the neighboring \( R_{xx} \) maxima at or near half-integral fillings [Fig. 1(c)]. The large magnitude of \( \Delta R_{sp} \) at low \( n \) and near \( \nu = 4 \) indicates that the scattering process at the resistance spike is fundamentally different from that present in the sample when the Fermi level nearly coincides with that of an extended state. In the following paragraphs, we concentrate on the resistance spike near \( \nu = 3 \).

The \( T \) dependence of the spike width, \( \Delta B_{sp} \), is plotted for two different densities in Figs. 3(a) and (b). Both graphs show that \( \Delta B_{sp} \) decreases as the 2D electrons cool down, and tends to saturate below a given temperature that depends on the density. Although \( \Delta B_{sp} \) depends smoothly on \( T \), the onset of its rise with \( T \) appears to occur near \( T_M \), the temperature at which \( \Delta R_{sp} \) is maximum. More quantitatively, a “threshold” temperature can be defined for the \( \Delta B_{sp}(T) \) data in Figs. 3(a) and (b), by first fitting straight lines to the low- and high-\( T \) ranges, and taking the intersection of these lines. In Fig. 3(a), the resulting \( T \) is 500 mK, a value close to \( T_M \). This correspondence suggests a common physical process for
the $T$ dependencies of both $\Delta R_{sp}$ and $\Delta B_{sp}$.

In order to better understand our data, we use a Bragg-Williams model applied to a system composed of two energy levels with respective relative fillings $f_1$ and $f_2$, corresponding to the highest occupied level and the lowest unoccupied level at $\nu = 3$. We define the magnetization ($m_z$) as $m_z = f_1 - f_2$, so that $m_z = 1$ ($-1$) if the first (second) level is fully occupied. The electron energy can then be written as $E(m_z) = bm_z - \frac{1}{2}Jm_z^2$, where $b$ is a reduced magnetic field ($b = 0$ at the transition) that includes contributions from single-particle energies ($E_Z$ and $E_c$) and from interactions, and $J$ is an effective interaction strength. The free energy of the 2D system is given by

$$F(b, m_z) = -TS(m_z) + E(b, m_z), \quad (1)$$

where $S(m_z)$ is the mixing entropy of the two phases. For every $b$ and $T$, we minimize $F$ with respect to $m_z$, and thus obtain the equilibrium magnetization. The model predicts that for $T < T_C = J$ (the Curie temperature), two different $m_z$’s minimize $F$, and that the system divides into magnetic domains.

Above the Curie point, the transition in field becomes increasingly gradual as $T$ increases. The width of the transition can be quantified by the reduced field ($b_+)$ at which $m_z = -1/2$, halfway between the transition ($m_z = 0$) and full polarization ($m_z = -1$). By symmetry, the field width of the transition, defined between $m_z = +1/2$ and $-1/2$, is thus $\Delta b = 2b_+$. From Eq. (1) we derive:

$$\Delta b = 2b_+(T) = -T_C + 1.1T \quad (T > T_C). \quad (2)$$

We see that $\Delta b$, plotted in the inset of Fig. (b) as a function of $T$, vanishes at $T$ close to $T_C$ (i.e., at $T = 0.91T_C$), and increases for larger $T$. This behavior is similar to that of the measured $\Delta B_{sp}$, suggesting that the “threshold” temperatures in Figs. (a) and (b) are close to the Curie temperatures of the QH ferromagnet at the respective carrier densities. An implication of our analysis is that $T_M \approx T_C$, since the peak in $\Delta R_{sp}(T)$ agrees with the temperature threshold of $\Delta B_{sp}(T)$.

The fact that the $\Delta R_{sp}$ maximum occurs near $T_C$ is qualitatively consistent with calculations of the critical resistance in ferromagnetic semiconductors with recent experiments in (Ga,Mn)As. According to those calculations, the diverging correlation length of spin fluctuations as $T \to T_C$ causes a peak resistance at a temperature $T_M$ close to $T_C$, with $|T_M - T_C|/T_C \sim 10^{-5}$ in typical semiconductors. Although the origin of the scattering at the spike in our system is unclear at present, in typical semiconductors, the origin of the scattering at the spike in our system is unclear at present, data in Fig. (b) confirm qualitatively the predicted peak resistance near $T_C$. We also note that we obtain similar empirical correspondences between the $T$ dependencies of $\Delta R_{sp}$ and $\Delta B_{sp}$ for $n = 2.35$ and $2.47 \times 10^{11}$ cm$^{-2}$, two other densities for which the data ranges are large enough for comparison to be possible.

In Fig. (c), we plot the density dependence of $T_M$ deduced from the $\Delta R_{sp}$ peaks in Fig. (b). Within the small density range allowed by our experiment, we observe that $T_M$ increases with $n$. This is consistent with our expectation that $T_C \approx T_M$, through the exchange interaction, should scale with the Coulomb energy, $V^2/4\pi\epsilon t_B \sim 10\epsilon_0$ is the dielectric constant of AlAs and $t_B = (h/eB_1)^{1/2}$ is the magnetic length; the latter increases with $B_1$, which in turn increases with $n$ at a fixed $\nu = 3$. The values we obtain for $T_C$ also agree with the estimate ($\sim 500$ mK) calculated by Jungwirth and MacDonald for the Curie temperature of AlAs 2D electrons at $n = 2.5 \times 10^{11}$ cm$^{-2}$.

Plotted in Fig. (a) are the $\Delta R_{sp}$ and $\Delta B_{sp}$ data for both upward and downward $B$ sweeps. These values, which depend on the sweep direction at sufficiently low $T$, reflect the observed $R_{xx}$ hysteresis (which mainly occurs in amplitude rather than in field). Figure (a) shows that the temperature corresponding to the onset of hysteresis is lower than the Curie temperature derived from the $\Delta R_{sp}(T)$ and $\Delta B_{sp}(T)$ dependencies. This implies that magnetic domains present (below $T_C$) at the LL crossing do not necessarily give rise to hysteretic $R_{xx}$. Furthermore, the strength of hysteresis depends on sample cooldown, while $T_C$ as defined above does not show such sensitivity, suggesting that hysteresis is controlled by cooldown-dependent parameters such as the precise nature of impurity disorder.

While the $T$ and $n$ dependencies described in our work apply to resistance spikes at $\nu = 3$, we have obtained similar data for LL crossings at other filling factors, though in a less complete manner. The $T$ dependencies of $\Delta R_{sp}$ and $\Delta B_{sp}$ for the spike near $\nu = 5$, e.g., are analogous to our $\nu = 3$ spike data; the amplitude of the spike at $\nu = 4$ (at $T = 30$ and $300$ mK) also decreases monotonically as $n$ increases. Spike measurements at $\nu = 4$ and $5$ are thus qualitatively consistent with results obtained from the $\nu = 3$ spike.

We now outline the main differences between our work and that of Jaroszyński et al., who recently performed a detailed study of resistance spikes in (Cd,Mn)Te quantum wells. First, authors in Ref. (a) determine $T_C$ from the temperature at which the total value of the resistance at the spike ($R_{tot}$) reaches a maximum, whereas we treat the spike amplitude $\Delta R_{sp}$ as the physical parameter reflecting the contribution of the domains (or, near $T_C$, of the spin fluctuations) to the total resistance. Second, the onset of hysteresis in Ref. matches the peak in $R_{tot}(T)$ (for one of the measured densities). In our samples, as can be seen in Fig. (b), $R_{tot}$ increases monotonically with $T$, so that the peak in $R_{tot}(T)$, if it exists, occurs at $T > 700$ mK, i.e., at a much higher $T$ than the onset of spike hysteresis. Third, $T_C$ determined in Ref. decreases with increasing $n$, a trend that is contrary to our experimental results and unexpected based on theoretical grounds. While we do not understand the
can be understood by a mean-field analysis of the Ising semiconductors, and the measured $\Delta$ by calculations of the critical resistance in ferromagnetic temperatures, and increasing with $T$.

In conclusion, we have observed critical behaviors (at 90°C). Upward- and downward-pointing triangles represent data from up and down field sweeps respectively, and show that the onset of hysteresis (vertical mark at $T = 350$ mK) is significantly lower than $T_C$.

Inset: spike width predicted by Bragg-Williams theory, displaying a behavior qualitatively similar to the Curie temperature of the QH ferromagnet.

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