Quantum Hall Spin Diode

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Double layer two-dimensional electron systems at high perpendicular magnetic field are used to realize magnetic tunnel junctions in which the electrons at the Fermi level in the two layers have either parallel or antiparallel spin magnetizations. In the antiparallel case the tunnel junction, at low temperatures, behaves as a nearly ideal spin diode. At elevated temperatures the diode character degrades as long-wavelength spin waves are thermally excited. These tunnel junctions provide a demonstration that the spin polarization of the electrons in the $N = 1$ Landau level at filling factors $\nu = 5/2$ and $7/2$ is essentially complete, and, with the aid of an in-plane magnetic field component, that Landau level mixing at these filling factors is weak in the samples studied.

Beginning with the pioneering experiments of Tedrow and Meservey [1,2], electron spin-dependent tunneling has grown into an enormous field of both technological and fundamental scientific importance. For example, today tunnel junctions consisting of two ferromagnetic electrodes separated by a thin insulating barrier are the basic element in magnetic random access memories, and these spintronic devices have become increasingly competitive with conventional memories. On the fundamental physics side, Tedrow and Meservey [1] made elegant use of their observed spin Zeeman splitting of the superconducting energy gap in thin aluminum films [3] to explore spin polarized tunneling currents in junctions having Al and ferromagnetic nickel electrodes. These early experiments opened a new door to the study of the spin structure of magnetic materials.

Here we explore spin-dependent tunneling in magnetic tunnel junctions fabricated from bilayer two-dimensional electron systems (2DESs) in GaAs/AlGaAs heterostructures. In the presence of a large perpendicular magnetic field $B_\perp$, the energy spectrum of a clean and noninteracting 2DES consists of a ladder of discrete Landau levels (LLs), each of which is split into two spin sublevels by the Zeeman effect. In a bilayer 2DES, proper adjustment of the magnetic field (which sets the degeneracy $eB_\perp/h$ of the spin-split LLs) and the individual 2DES densities n_1 and n_2 can realize a magnetic tunnel junction in which the spin polarization of the electrons at the Fermi level in the two 2DES layers are either parallel or antiparallel. For example, if the Landau level filling fraction $\nu = nh/eB_\perp$ in both layers is set to $\nu_1 = \nu_2 = 1/2$, the two 2DESs would be fully spin polarized and have parallel magnetizations. Alternatively, if the densities are adjusted so that $\nu_1 = 1/2$

but $\nu_2 = 3/2$, then the electron spins at the Fermi level in the two layers are oppositely directed. Absent spin-flip tunneling processes, the tunneling conductance at zero bias would be singularly [4] large in the 1/2-1/2 case but zero in the 1/2-3/2 setup. Only at an interlayer voltage equal to the Zeeman splitting would tunneling occur in the latter case.

In real 2DESs at high magnetic fields the above scenario is enriched dramatically by electron-electron interactions. Instead of sharp spin-split Landau levels, the spectral functions of the 2DES are heavily broadened by interactions. This broadening is directly observable in the current-voltage (IV) characteristic for tunneling between two parallel 2DESs [5]. In addition, these same interactions suppress the tunneling conductance dI/dV around zero bias, creating a Coulomb pseudogap at the Fermi level. The pseudogap arises from the inability of a correlated 2DES at high magnetic field to rapidly relax the charge defect created by the injection (or extraction) of a tunneled electron [5–13].

Electron-electron interactions can also profoundly affect the spin configuration of a 2DES, allowing it to deviate qualitatively from that expected via simple Pauli counting rules [14,15]. This is not surprising since in a GaAs-based 2DES the spin Zeeman energy is typically of order $E_Z \sim 1$ K while the mean Coulomb energy E_C between electrons in a partially filled LL is typically 10–100 times larger [16]. As a dramatic example, the spin polarization of the 2DES at $\nu = 1/2$ in the lowest Landau level is known to be incomplete at low density [17–22].

In this Letter we report tunneling measurements on density imbalanced bilayer 2D electron systems, focusing on the case where $\nu_1 = 5/2$, while $\nu_2 = 7/2$. Both of these
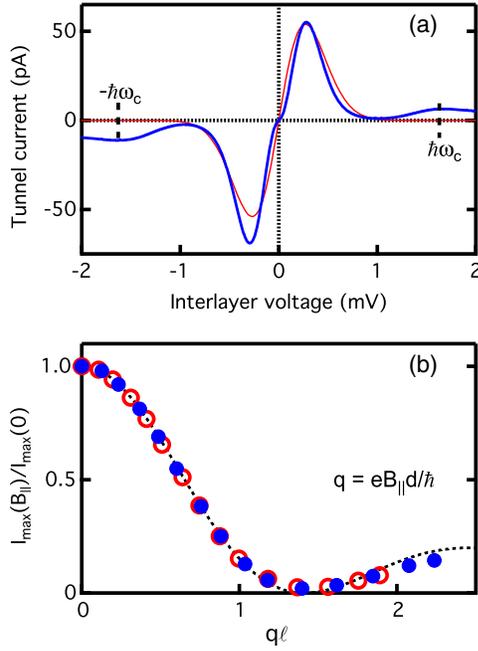
FIG. 1.   (a) Blue curve: Tunneling *IV* characteristic at $B_\perp = 0.94$ T and $T = 50$ mK with both 2DESs at $\nu = 5/2$. Light red curve: Representative theoretical *IV* curve for simple Gaussian spectral functions at zero temperature. (b) Observed effect of an in-plane magnetic field $B_\parallel$ on the normalized maximum tunneling current at $\nu = 5/2$ (solid blue circles, $B_\perp = 0.94$ T) and $\nu = 7/2$ (open red circles, $B_\perp = 0.67$ T). Dashed curve: Matrix element effect described in text.

filling factors are in the first excited, $N = 1$ LL. Our measurements reveal that at low temperature the tunneling *IV* characteristic is extremely asymmetric, behaving as a nearly ideal diode at low voltage. This demonstrates that the spin polarization of the electrons in the partially filled $N = 1$ LL is nearly complete in both 2D layers. Elevated temperatures rapidly degrade this diodelike behavior, with thermal excitation of long-wavelength spin waves being likely responsible.

The samples and methods we employ for measuring tunneling between parallel 2DESs have been described in detail previously [23,24]. Two 18 nm wide GaAs quantum wells are separated by a 10 nm $Al_{0.9}Ga_{0.1}As$ tunnel barrier. Each well contains a 2DES of nominal density 5×10^{10} cm^{-2} and low temperature mobility 10^6 cm^2/V s. Independent control over the electron density in each layer is enabled by electrostatic gates on the top and back side of the sample. The 2DESs are confined to a 250×250 μm square region, with arms extending to Ohmic contacts to the individual 2D layers. These contacts enable direct measurements of the tunneling current I flowing in response to an applied interlayer voltage V.

Figure 1(a) shows a typical high magnetic field tunneling *IV* characteristic for the situation where the two 2DES layers have the same electron density. For these data, taken at $B_\perp = 0.94$ T and $T = 50$ mK, the Landau level filling

factor in each 2DES is $\nu = 5/2$. (The present samples are of insufficient quality for the $\nu = 5/2$ fractional quantized Hall effect to be observed.) The data in Fig. 1(a) exhibit the main consequences of strong electron-electron interactions at high magnetic field discussed above: a broad peak and valley in the tunneling current, roughly [25] antisymmetric in voltage, and a suppression of the tunneling conductance dI/dV very close to zero bias. The width of the main tunneling peaks, $\Gamma \approx 0.3$ mV, is comparable to the mean Coulomb repulsion, $E_{C,v} = e^2 n_v^{1/2}/\epsilon \approx 1$ meV, between the $n_v = eB_\perp/2h$ electrons (or holes) in the partially occupied $N = 1$ LL. The suppression of dI/dV close to $V = 0$ is the Coulomb pseudogap mentioned above. Weak at this low magnetic field, this effect is not part of our present focus. The thin red trace in Fig. 1(a) shows an *IV* curve calculated assuming simple Gaussian spectral functions for the valence $N = 1$ LL in each 2DES.

Before turning to the effects of electron spin on the tunneling *IV* characteristics, we explore the *orbital* character of the energy levels involved. At the magnetic fields studied here, the cyclotron splitting $\hbar\omega_c = \hbar eB_\perp/m^*$ between Landau levels is not much larger than the interaction-induced broadening of those levels. At $\nu = 5/2$, for example, the partially filled valence energy level may be dominated by the $N = 1$ LL but have other LLs mixed in by interactions. This possibility is highlighted by the presence, in Fig. 1(a), of weak additional extrema in the tunnel current around $|V| = \pm 1.6$ mV, close to the cyclotron energy $\hbar\omega_c = 1.63$ meV at this magnetic field. Such inter-LL tunneling events are forbidden [26] in a clean, noninteracting 2DES [27].

To address this question, an in-plane magnetic field $B_\parallel$ is added to the perpendicular field $B_\perp$. Landau level tunneling evolves in a systematic way with the momentum boost $q = eB_\parallel d/\hbar$ created by the in-plane field [28] (d is the center-to-center quantum well separation). For tunneling between states solely within the $N = 1$ Landau level, this effect, taken alone, requires the tunnel current to depend on $B_\parallel$ as $I(B_\parallel) = I(0)(1 - q^2\ell^2/2)^2 e^{-q^2\ell^2/2}$, where $I(0)$ is the tunnel current at $B_\parallel = 0$ and $\ell = (\hbar/eB_\perp)^{1/2}$ is the magnetic length. The factor $(1 - q^2\ell^2/2)^2$ forces the tunnel current to vanish at $q\ell = \sqrt{2}$; this is a direct result of the node in the $N = 1$ Landau level wave function [29].

Figure 1(b) shows the dependence of the maximum tunnel current [30] at $\nu = 5/2$ and $7/2$ on q (and therefore $B_\parallel$), normalized by its value at $B_\parallel = 0$. The close agreement with the momentum boost effect just described (dashed line in the figure) demonstrates that the tunnel current at voltages $|V| \lesssim 1$ mV is dominated by hopping events between states solely within the $N = 1$ Landau level. Landau level mixing is apparently weak.

The results discussed thus far offer little insight into the spin structure of the partially occupied $N = 1$ Landau level. To expose this structure we turn to tunneling measurements
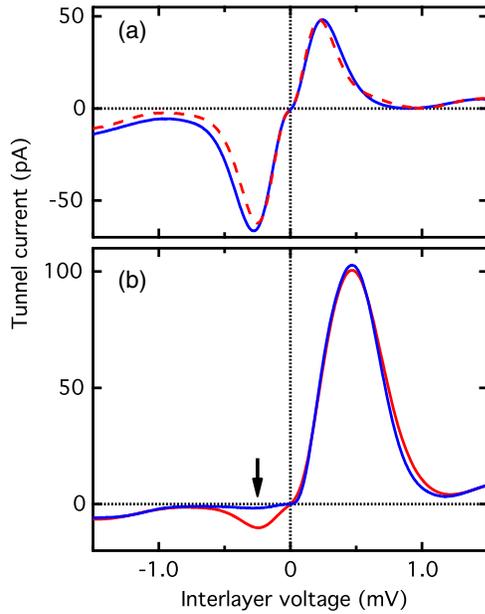
FIG. 2.   (a) Density balanced tunneling IV curves at $\nu = 5/2$ (blue curve) and $\nu = 7/2$ (dashed red curve) at $B_\perp = 0.84$ T and $T = 50$ mK. (b) Diodelike tunneling response observed at $B_\perp = 0.84$ T with one 2D layer at $\nu = 5/2$ and the other at $\nu = 7/2$. $T = 50$ mK (blue curve) and 200 mK (red curve).

in which the layer densities are adjusted to simultaneously produce $\nu = 5/2$ in one layer and $\nu = 7/2$ in the other. If the spin configuration of the 2DES follows simple Pauli counting rules, then the $\nu = 5/2$ layer has only "up" spins at the Fermi level while the $\nu = 7/2$ layer has only "down' spins. In the $5/2$ layer the down-spin branch is completely empty while in the $7/2$ layer the up-spin branch is completely full. If electrons tunneling from one layer to the other preserve their spin, the tunneling IV curve should be highly asymmetric. At zero temperature no electrons can tunnel from the $5/2$ layer into the $7/2$ layer since all up-spin final states are occupied. In contrast, tunneling from the $7/2$ layer to the $5/2$ layer can readily proceed as there are empty states in both spin bands.

Figure 2 compares the tunneling IV curves in the density balanced $5/2$-$5/2$ and $7/2$-$7/2$ configurations with the imbalanced $5/2$-$7/2$ setup. The data in Fig. 2(a) were obtained at $T = 50$ mK and $B_\perp = 0.84$ T, with $B_\| = 0$. The 2DES densities were adjusted to allow examination of these two different filling factors at the same magnetic field. As the figure shows, under these conditions the IV curves for the two filling factors are nearly identical. Since $\nu = 5/2$ and $\nu = 7/2$ are particle-hole conjugate states, the equivalence of their tunneling IV curves suggests that particle-hole symmetry is strong within in the $N = 1$ LL.

In Fig. 2(b) the layer densities were adjusted to produce $\nu = 5/2$ in one layer and $\nu = 7/2$ in the other [31]. The tunnel junction is here configured such that positive interlayer voltage ("forward bias") raises the chemical potential of the $7/2$ layer above that of the $5/2$ layer while

negative interlayer voltage ("reverse bias") does the opposite. Two traces are shown in the figure, the blue is obtained at $T = 50$ mK, the red at 200 mK. At $T = 50$ mK the tunnel current over the range $|V| \lesssim 1$ mV is massively asymmetric; a large peak, centered at $V \approx 0.5$ mV, is seen at forward bias while in reverse bias only a very weak (negative) peak in the current is observed at $V \approx -0.25$ mV. The tunnel junction at this low temperature is a robust quantum Hall spin diode.

The $T = 50$ mK tunneling data in Fig. 2(b) imply that the spin polarization of the electrons (holes) in the $N = 1$ LL is virtually total at $\nu = 5/2$ ($\nu = 7/2$). The tunnel current at the weak minimum near $V \approx -0.25$ mV is less than 1% of that seen at the forward bias peak near $V \approx 0.5$ mV. Moreover, since weak spin-flip tunneling processes (due, for example, to nuclear spin fluctuations) cannot be entirely ruled out, the electron spin polarization might be even more complete than these data suggest.

The spin polarization of the 2DES at $\nu = 5/2$ has long been scrutinized. The present results strongly support the recent Knight shift experiments [32,33] that point to maximal polarization. Although this finding may seem obvious from the perspective of the ordinary Pauli counting rules for spin, it is not. Coulomb interactions within the Landau quantized 2DES are far stronger than the spin Zeeman energy and these interactions can dictate the spin configuration. Indeed, at $\nu = 1/2$, the analog of $\nu = 5/2$ but in the $N = 0$ LL, partial spin polarization persists to magnetic fields considerably higher than those studied here [17–22].

The peak in the tunnel currrent in forward bias occurs at about $V = 0.5$ mV in the $5/2$-$7/2$ data, but at about $V = 0.25$ mV in the $5/2$-$5/2$ and $7/2$-$7/2$ cases. This difference is expected since in the $5/2$-$7/2$ case alignment of same-spin sublevels in the two layers requires an additional voltage bias equal to the spin-flip energy E_{sf}. Owing to exchange interactions, E_{sf} typically greatly exceeds the ordinary Zeeman energy E_Z. For the data in Fig. 2, $E_{sf} \approx 0.25$ meV, whereas $E_Z = 0.021$ meV.

For the balanced $5/2$-$5/2$ and $7/2$-$7/2$ cases, and the $5/2$-$7/2$ setup in forward bias, little temperature dependence is observed for $T \lesssim 0.5$ K ($k_B T \lesssim 0.04$ meV). This is not surprising given the broad resonances in these situations. However, this contrasts sharply with the strong temperature dependence of the $5/2$-$7/2$ spectrum in *reverse* bias. There, as Figs. 2(b) and 3(a) demonstrate, the (negative) peak in the tunnel current at $V \approx -0.25$ mV grows dramatically with temperature.

Figure 3(b) shows the amplitude of the $5/2$-$7/2$ reverse bias peak (with a small background subtracted) in an Arrhenius plot. Two data sets are shown, one at $B_\perp = 0.84$ T and the other at $B_\perp = 1.19$ T. At the lowest temperatures, both data sets saturate. The saturation value may indicate a tiny, but genuine, lack of total spin polarization. However, unknown spin-flip tunneling processes or a small amount of electron heating might also be responsible. Above about $T = 100$ mK, the peak amplitude is roughly thermally
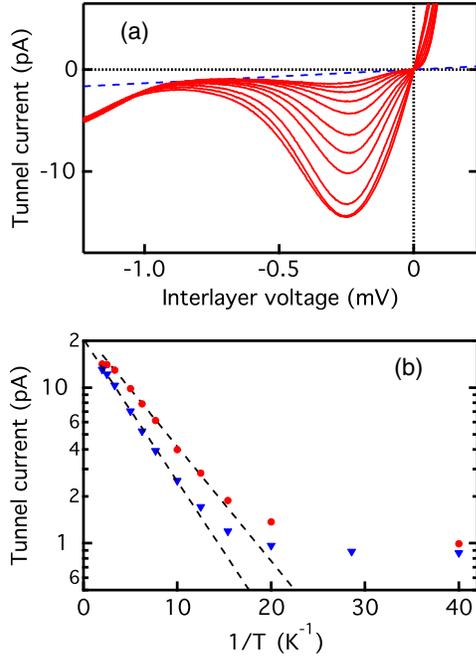
FIG. 3. (a) Temperature dependence of the reverse bias peak in
5/2-7/2 tunneling at $B_\perp = 0.84$ T. Top to bottom: $T = 25$, 50,
65, 80, 100, 130, 160, 200, 300, 400, and 500 mK. Dashed line
is estimated background. (b) Arrhenius plots of reverse bias
peak amplitude. Red circles, $B_\perp = 0.84$ T; blue triangles,
$B_\perp = 1.19$ T. Dashed lines suggest activation energies of
0.17 and 0.21 K, respectively.

activated, with an activation energy of $E_A \approx 0.17$ K (0.21 K)
for the $B_\perp = 0.84$ T (1.19 T) data. These activation energies
are comparable to the bare Zeeman energy at the same
magnetic fields ($E_Z = 0.24$ and 0.35 K, respectively).
Our data therefore suggest that thermal excitation of long-
wavelength spin waves (whose energy $\epsilon_{\text{sw}} \to E_Z$ as $\lambda \to \infty$)
is responsible for the temperature dependence of the reverse
bias tunneling peak in the 5/2-7/2 configuration. Both
spin-wave-assisted tunneling and thermal fluctuations [34]
in the orientation of the spin polarization of the 2DES
provide plausible explanations for the enhanced reverse-bias
tunneling currents our data reveal. Owing to these fluctua-
tions, the spectral function of the 2DES no longer cleanly
separates into spin-up and spin-down components. Similar
arguments have been used previously to understand the
thermal behavior of magnetic tunnel junctions comprising
three-dimensional itinerant ferromagnetic electrodes [35].

In analogy with Tedrow and Meservey's use of thin film
superconductors to explore ferromagnetism [1], the simple
spin structure and robust particle-hole symmetry of the
2DES at $\nu = 5/2$ and 7/2 demonstrated here makes these
states ideal for probing more complex situations. For
example, a strong breakdown of particle-hole symmetry
between $\nu = 1/2$ and 3/2 in the lowest LL has already
been observed in (density balanced) tunneling experiments
[36], and the spin structure of these states is nontrivial.

Tunneling into these states from a second 2DES at $\nu = 5/2$
and 7/2 should shed considerable light on both aspects of
these strongly correlated 2D electron systems.

In conclusion, we have fabricated magnetic tunnel
junctions from density imbalanced double layer 2D
electron systems subjected to strong magnetic fields.
These junctions can behave as almost ideal spin diodes
at low temperature, indicating that the spin polarization of
the valence Landau level in each layer is nearly complete.
Thermally excited spin waves appear to be responsible for
degradation of diode behavior at elevated temperatures.
It should be possible to engineer tunnel junctions in which
one fully spin polarized layer is used to analyze an
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