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Evidence for an electric-field-induced phase transition in a spin-polarized two-dimensional electron gas

B. E. Kane, L. N. Pfeiffer, and K. W. West
AT&T Bell Laboratories, Murray Hill, New Jersey 07974
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A junction between two coplanar two-dimensional electron gases in a $Al_xGa_{1-x}As/GaAs$ heterostructure at which the Fermi level crosses between adjacent spin-split Landau levels has remarkable current-voltage characteristics: current is time dependent, a consequence of dynamic nuclear polarization at the junction. Also, when biased so as to increase the junction electric field, the junction exhibits a series of abrupt transitions between distinct states, an effect that we attributed to an electric-field-induced phase transition of the spin-polarized electrons at the junction.

The two-dimensional electron gas (2DEG) is characterized by a sequence of magnetic-field-induced metal-insulator transitions, with distinct insulating phases appearing at integral and fractional filling factors (ν). While the integral and fractional quantum Hall effects and, at low ν, the Wigner crystal, may be an exhaustive list of phases of the 2DEG in the absence of an applied electric field (**E**), it is possible that entirely new phases of the 2DEG can exist when a sufficiently strong **E** is applied to a 2DEG in an insulating state.[1] If the 2DEG insulating phase has low-lying neutral excitations that possess an electric dipole moment, then, in an applied E, the energy of these excitations could become negative, and the 2DEG would undergo a phase transition. Such a phenomenon can only occur when electron-electron (e-e) interactions are strong enough to prevent the excitation from immediately being ionized by **E**.

A particularly attractive system in which to search for **E**-induced phases is a spin-polarized (SP) 2DEG ($\nu=1$) in $GaAs/Al_xGa_{1-x}As$ heterostructures. The elementary excitations of a SP2DEG are spin excitons: bound states of an electron in the higher-energy spin level and a vacancy or hole in the lower spin level. Kallin and Halperin[2] have calculated the energies of these excitations as a function of wave vector **k**. At $\mathbf{k}=0$, corresponding to an electron-hole (e-h) pair in close proximity, the exciton energy is identical to the Zeeman energy: $\Delta U = g\mu_B B$, where g is the bare g factor in GaAs, and can be determined from electron-spin resonance (ESR) measurements.[3] At large **k**, corresponding to well-separated e-h pairs, exciton energies are enhanced by the effects of exchange interactions.[4] The enhanced spin splitting, $\Delta U = g^*\mu_B B$, has been estimated using transport,[5] optical,[6] and activation energy[7] measurements. The large values of $\Delta U(\mathbf{k}\rightarrow\infty)/\Delta U(\mathbf{k}=\mathbf{0})\equiv\eta$ determined from these experiments ($10\lesssim\eta\lesssim 20$) attest to the importance of e-e interactions in the SP2DEG.

The measurements that we report in this paper were performed on "spin diodes:" junctions between two coplanar 2DEG's in which $\nu<1$ on one side and $\nu>1$ on the other, and the Fermi level E_F crosses between spin levels at the junction.[8] In such a device the 2DEG is highly conducting except in a narrow region (with width of order several hundred angstroms) where $\nu=1$. Current-voltage (I-V) measurements of a spin diode are thus a probe of the properties of a narrow SP2DEG. In analogy to a semiconductor diode, an electric field **E** must exist at the junction when it is in thermal equilibrium, and **E** increases when the junction is reverse biased. Because E_F is in different spin levels on opposite sides of the junction, any crossing electrons must flip spin.

Our experiments have shown that spin diodes have the following properties: at temperature (T) low enough (~ 1 K) that the I-V characteristics are strongly nonlinear, I, measured after V is switched on, is time dependent, often taking upwards of 1000 sec to reach a steady state. We have established that this behavior is a consequence of dynamic nuclear polarization that occurs when I flows across the junction. At still lower T (<300 mK), slowly swept I-V measurements in reverse bias (when the externally applied bias is augmenting **E** at the junction) display a complex structure: a succession of nearly linear regions in the I-V are punctuated by discontinuous shifts in I. We propose that these effects are a signature of a new phase of the SP2DEG that is stabilized by the presence of **E**.

A schematic drawing of a spin diode junction is shown in Fig. 1(a). To fabricate such a device a gate is evaporated on part of the top surface of a $GaAs/Al_xGa_{1-x}As$ single interface heterostructure, and a potential V_g is applied to the gate to regulate the 2DEG density n_{2D} beneath it [Fig. 1(b)]. In the actual device used to make measurements [Fig. 1(c)], and interior Ohmic contact is encircled by a 2DEG mesa region whose outer edge is composed of 30 paths, each radiating outward and making separate contact to an exterior Ohmic contact. The annular gate is positioned so that its interior edge lies entirely above the 2DEG, while its exterior edge passes over the separate paths leading to the outer Ohmic contact. By biasing the gate so that $\nu_{\text{ungated}}>1$ and $\nu_{\text{gated}}<1$, channels with $\nu<1$ along the edges[9] of the outer paths can transmit electrons in the lowest-energy spin level directly from beneath the gate to the exterior Ohmic contact [Fig. 1(c)]. Thus, electrons traveling from the inner to the outer contact must scatter between spin levels only near the interior gate edge, which alone produces a junction that contributes to the measured I-V characteristic. Using structures in which the potential in the region between the interior and exterior gate edge could be directly measured, we

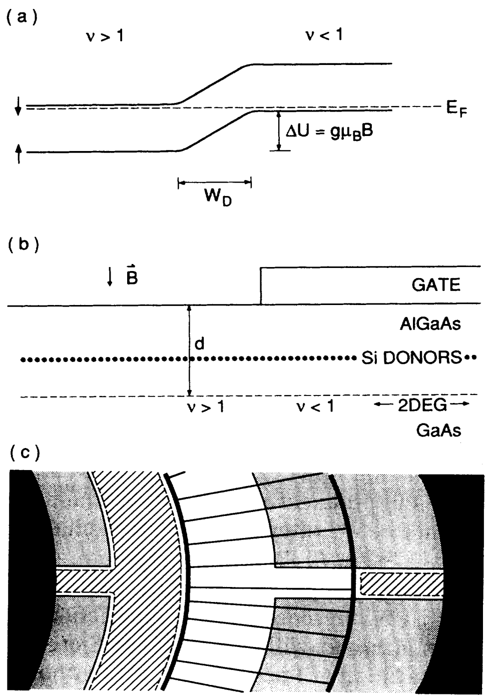

FIG. 1. (a) Schematic diagram of a "spin diode." An electron density discontinuity is introduced in a 2DEG such that $\nu > 1$ on one side of the discontinuity and $\nu < 1$ on the other. (b) Such a device is realized by evaporating a gate on top of part of a $Al_xGa_{1-x}/GaAs$ heterostructure. (c) Top view of a portion of the device: black regions represent Ohmic contacts; the shaded region is where 2DEG is etched away; the white region is 2DEG where $\nu < 1$; the hatched region is 2DEG where $\nu > 1$. The region with radiating lines designates the gated area. Because of the presence of edge channels along the outer paths where $\nu < 1$, electrons traversing between the inner and outer contacts must scatter between spin states only at the interior gate edge.

have established that interrupting the outer gate edge with separate current paths always nullifies its contribution to the measured I-V.

Although we have observed similar behavior in several samples, the measurements reported here were all made on a single sample with an ungated n_{2D} of $1\times10^{11}/\mathrm{cm}^2$ and a mobility in excess of $10^6\ \mathrm{cm}^2/\mathrm{V\,sec}$. The distance d between the top gate and the 2DEG is 6100 Å. The magnitude of the voltage applied to the gate is typically a few tenths of a volt, so gate leakage is negligible. We present data for two conditions: in Fig. 2, $B=3.5$ T, $\nu_{\mathrm{ungated}}=\frac{5}{4}$, and $\nu_{\mathrm{gated}}=\frac{3}{4}$. In Fig. 3, $B=5.95$ T, $\nu_{\mathrm{ungated}}=\frac{3}{4}$, and $\nu_{\mathrm{gated}}=\frac{5}{4}$. At these filling factors, σ_{xx} in the 2DEG's away from the junction is large, and consequently the resistance in series with the junction ($\cong 20\ \mathrm{k}\Omega$) does not contribute to the I-V characteristics. The width W_d of the depletion region of a spin diode (the region where $\nu=1$) may be approximated using formulas that Chklovskii, Shklovskii, and Glazman[10] derived for the edges of a 2DEG in the quantized Hall regime. Assuming that the enhanced spin splitting is the appropriate energy gap for a spin diode, we estimate that $W_d \cong 700$ Å in our

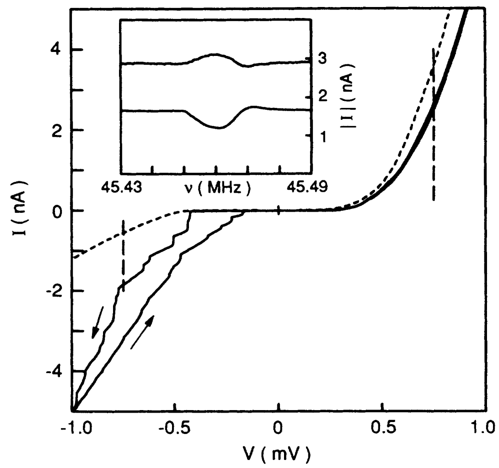

FIG. 2. I-V characteristics of a spin diode at 45 mK and $B=3.5$ T, with forward bias corresponding to positive V. The solid lines are slowly ramped data. The dashed line is data taken by briefly pulsing V away from $V=0$ to make each measurement. Inset: I, measured at a constant V, as an applied rf B is slowly swept across the NMR frequency of ^{71}Ga. Top and bottom traces are taken when V corresponds respectively to the right and left dashed vertical lines in the main figure.

device at 3.5 T and $\cong 1000$ Å at 5.95 T. As in a semiconductor diode, W_d will widen when a reverse bias voltage is applied.

Because the I-V measurements are time dependent, two experimental procedures were used to obtain the data presented in Fig. 2: The solid-line data were taken by sweeping V extremely slowly (~ 72 h) so that the plotted I is the final steady-state value at each V. The measure-

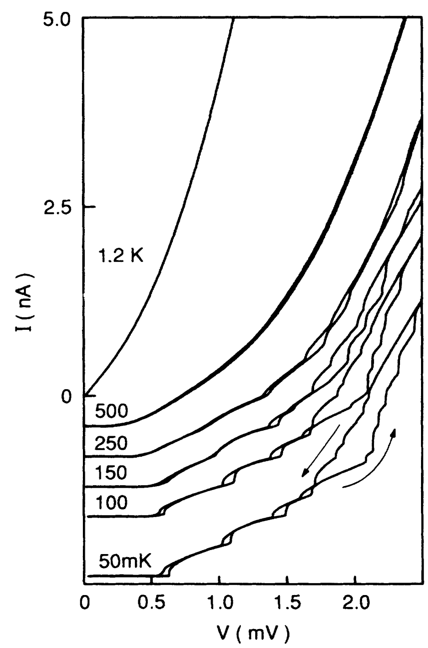

FIG. 3. Slowly swept I-V characteristics of a spin diode in reverse bias at various values of T when $B=5.95$ T. The curves are offset vertically for clarity.

ments represented by the dashed line were made by pulsing V away from $V=0$ for 50 msec at 20 sec intervals. The time dependence in I can be interpreted in light of the observations by Dobers *et al.*[11] of dynamic nuclear polarization (DNP) in ESR experiments on a SP2DEG. In those experiments, electrons whose spin is flipped by a photon can return to their ground state by flipping a nuclear spin. At $T<10$ K the relaxation times of nuclear spins can be extremely long, and the nuclear spins become polarized. DNP results in the Overhauser shift in the ESR line: A new effective B, arising from the hyperfine interaction and proportional to the nuclear polarization, contributes to the bare electron-spin splitting, $\Delta U = g\mu_B(B+B_N)$. In GaAs, B_N can in principle be as large as 5 T.[12] The authors of Ref. 11 were able to prove the nuclear origin of the observed ESR lineshifts by applying an rf B tuned to the NMR frequency of one of the nuclear species in GaAs. The applied rf B depolarized the nuclei, and the ESR frequency was observed to shift abruptly.

In a spin diode DNP can occur when I passes across the junction and the electrons transfer their spin to neighboring nuclei. As the nuclei become polarized, B_N becomes large enough to significantly change the electron-spin splitting, and hence the properties of the junction. Because nuclear spins are constantly diffusing away from the junction, the small duty cycle pulsed I-V data reflects the properties of the junction in the absence of DNP effects. To prove that the time-dependent effects observed in spin diodes are of nuclear origin, the junction was biased at a constant V and allowed to reach its steady-state I. The frequency of an applied rf B ($\cong 10^{-7}$ T) was then slowly swept across the resonance of ^{71}Ga at $B=3.5$ T (Fig. 2, inset). Both in forward and reverse bias, when the rf B is at resonance, I shifts towards the value of I measured using the pulsed technique. The direction of the shift differs, however, because B_N increases the electron-spin splitting when I is flowing in forward bias but decreases the spin splitting in reverse bias.

The remarkable structure seen in Fig. 2 when the spin diode is reverse biased appears only when V is slowly swept. When V is ramped away from $V=0$, the diode passes through a sequence of regions where I is nearly linear in V. Even when V is ramped extremely slowly, the junction is hysteretic: The device passes through a different sequence of linear regions when V is ramped back to $V=0$. The positions of the shifts are irregular in all the samples we have studied and, although repeatable in a given run, are not the same if the sample is cycled to room temperature. These observations suggest that the properties of the junctions are sensitive to small perturbations of the junction environment. In Fig. 3 the reverse bias slowly swept (24 h) I-V are plotted for different T when $B=5.95$ T. As T is raised, the shifts become less pronounced, and they are entirely absent at $T=0.5$ K, even though the junction I-V is still strongly nonlinear.

While we emphasize that the structure we observe in reverse bias occurs when nuclei near the junction are polarized, it is unlikely that nuclear effects along can account for these observations, since the T dependence is characteristic of an electronic, and not a nuclear, energy scale. The simplest possible model for a spin diode in reverse bias is a 2DEG at $\nu=1$ in a uniform $\mathbf{E}$. Electrons in the lowest Landau level, confined to the x-y plane and experiencing $\mathbf{E}=E_x\hat{\mathbf{x}}$, will have wave functions:

$$\Psi(x,y)=e^{ik_y y}\exp\left[\frac{-(x-k_y l_B^2)^2}{2l_B^2}\right],$$

where $l_B \equiv (\hbar c/eB)^{1/2}$. Two such wave functions are drawn schematically in Fig. 4(a). Any given wave function may be equivalently characterized by the x coordinate of its guiding center or by the wave number k_y determining its periodicity in the y direction.

The elementary neutral excitations of a SP2DEG, shown in Fig. 4(b), consist of a flipped spin in the higher spin level and a vacancy in the lower level. These excitations may be pictured as an e-h pair with the wave functions drawn in Fig. 4(a), separated from each other by a distance Δx and propagating with wave vector $k_y=\Delta x/l_B^2$. In the absence of e-e interactions these excitations will all have energy $U=g\mu_B B$. By Kohn's theorem, the energy of the $k_y=0$ state (or equivalently, the $\Delta x=0$ state) will be the same in the presence of e-e interactions; however, states with nonzero k_y will have a higher energy, reflecting the finite separation of the e-h pair. The authors of Ref. 2 have calculated the energies of these excitations, neglecting the effects of disorder and the finite z extent of the electrons. In Fig. 4(c) the results of their calculations are plotted and scaled so that $\eta=20$, which is appropriate for

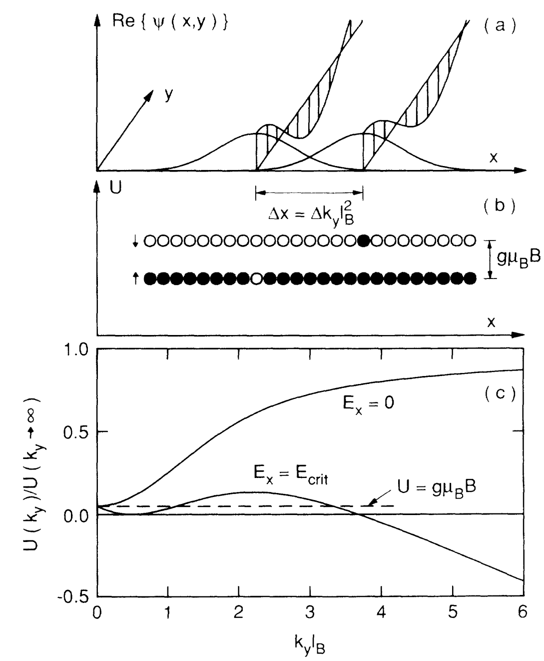

FIG. 4. (a) Lowest Landau-level wave functions for electrons confined in the x-y plane in an applied perpendicular B. (b) Elementary excitations of a SP2DEG consist of a single electron in a higher spin level and a vacancy in the lower level. (c) Energy of spin excitons as a function of k_y. When $E_x \neq 0$, a new term in the energy appears, proportional to the electric dipole moment of the excitation. When $E_x=E_{crit}$, bound excitons have zero energy and the spin-polarized ground state is unstable.

GaAs heterostructures of high quality.[7] Because the excitons have an electric dipole moment $e\Delta x = el_B^2 k_y$, a nonzero E_x will introduce an energy linear in k_y to the exciton dispersion curve. Notice that when $\mathbf{E}=\mathbf{0}$, all possible exciton states are bound (i.e., they cannot be ionized by small Δk inelastic scattering), since a global minimum in $U(\mathbf{k})$ is located at $\mathbf{k}=\mathbf{0}$. However, both bound and unbound states can exist when $\mathbf{E}\neq\mathbf{0}$, separated from each other by a point where $U(k_y)$ is a local maximum. For E_x exceeding some critical field E_{crit}, bound excitonic states have $U<0$. e-h pairs will then scatter into and accumulate in these states; consequently, the SP2DEG ground state must be unstable when $E_x > E_{\text{crit}}$. Using the equations of Ref. 2, it is possible to show that bound excitonic states with $U<0$ can occur when $\eta \gtrsim 7$ and are thus relevant to the interpretation of our experiment.

SP2DEG excitons are spin waves: The spin of the excitation lies in the x-y plane and rotates around the z axis with period $\lambda = 2\pi/|\mathbf{k}|$. If the **E**-induced ground state is a coherent superposition of these excitations, then the new state will be a spin-density wave,[13] and will have an antiferromagnetic order parameter **k**. For the conditions pertaining to a spin diode at 3.5 T ($l_B = 140$ Å, $g^*\mu_B B \cong 1.5$ meV, and $\eta \cong 20$), we estimate $\lambda \cong 1800$ Å and $E_{\text{crit}} \cong 2$ mV/1000 Å. Since the width of the depletion region is approximately 700 Å, E_{crit} is comparable to the field that would be expected at the junction when the unusual behavior in reverse bias is observed.

We believe that a distinct ground state with an order parameter **k** at the spin diode junction would have significant effects on its I-V characteristic. Of primary importance is that because of irregularities at the junction, **k** will not change continuously as junction parameters are varied, but will be pinned at energetically favorable values. It is this "stickiness" of an antiferromagnetic phase that we propose is an explanation for the irregular structure and hysteresis observed in spin diodes in reverse bias. It is also probable that the presence of a nuclear polarization field B_N at the junction will help stabilize states with a particular **k**. A thorough understanding of these devices, however, will have to await a more elaborate theory of electric-field-induced phases in a SP2DEG.

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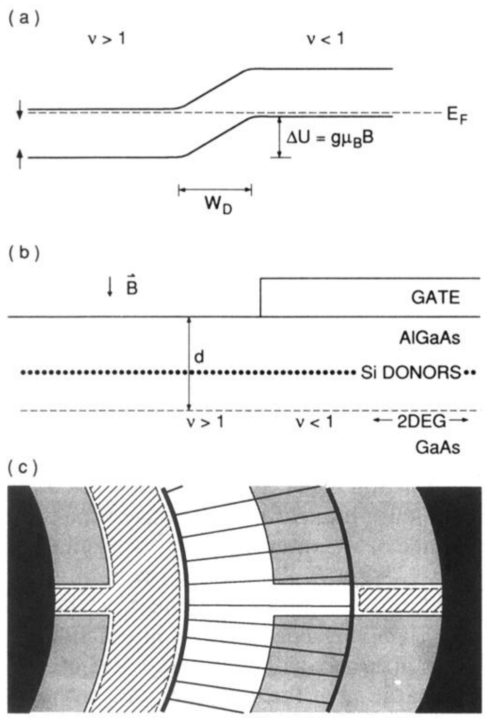

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