Possible Evidence of a Spontaneous Spin Polarization in Mesoscopic Two-Dimensional Electron Systems

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We have experimentally studied the nonequilibrium transport in low-density clean two-dimensional (2D) electron systems at mesoscopic length scales. At zero magnetic field (B), a double-peak structure in the nonlinear conductance was observed close to the Fermi energy in the localized regime. From the behavior of these peaks at nonzero B, we could associate them with the opposite spin states of the system, indicating a spontaneous spin polarization at $B = 0$. Detailed temperature and disorder dependence of the structure shows that such a splitting is a ground-state property of low-density 2D systems.

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Spin polarization of electrons in low dimensional systems at $B = 0$ has recently attracted extensive theoretical and experimental attention. In the metallic regime, the spin-orbit (SO) effect may result in energy separation of several millivolts between the spin bands through the bulk (the k^3 term) and the interface inversion asymmetry (the Rashba term) effects [1]. At low electron densities, however, the electron-electron interaction dominates over the kinetic energy, and a homogeneous 2D system becomes unstable to spontaneous spin polarization (SSP) due to exchange [2,3]. Since the influence of interaction is strong at lower dimensions, several recent experimental investigations on the spin state of 0D [4,5] and 1D systems [6] have indicated the possibility of a SSP, even though the origin and nature of such a phase is controversial. In low-density 2D electron systems (2DES's), however, a direct observation of a "spin gap" has remained experimentally elusive, even though evidence of an enhanced g factor and anomalous spin susceptibility have been reported when the disorder is low [7–10].

An unpaired spin in weakly isolated systems has been shown to be screened by Kondo-like singlet formation with the electrons in the leads [11]. This results in a resonance in the tunneling density of states (DOS), and an enhancement in the differential conductance (dI/dV) through the system when the chemical potential of the leads are aligned. When studied as a function of source-drain bias (V_{SD}), the zero-bias peak (ZBP) splits linearly in finite B by $\Delta_Z = g^*\mu_B B$, where g^* and μ_B are the effective g factor and the Bohr magneton, respectively. Recent nonlinear studies in ballistic quantum point contacts (QPC's) have also shown the evidence of a ZBP [12], which was attributed to a Kondo-like correlation resulting from a dynamic SSP in 1D. In this Letter, we report nonequilibrium transport measurements in high-quality 2DES's of mesoscopic dimensions. In the low-density regime, clear evidence of a split ZBP was observed at $B = 0$. The magnitude of the split (Δ) evolved continuously with B, implying its origin to be related to the underlying spin structure of the 2DES. Simultaneous measurement of the Fermi energy (E_F) showed that such a structure is an intrinsic ground-state property of 2D systems, depending critically on the impurity scattering, as well as the temperature (T) and magnetic field (B).

We have used 2DES's in Si δ-doped GaAs/AlGaAs heterostructures, formed ≈ 300 nm below the surface. Disorder was varied by changing the spacer thickness δ_{sp} separating the dopant layer from the GaAs/AlGaAs interface. Data from two samples with $\delta_{sp} = 40$ and 60 nm (referred to as A78 and A79, respectively) are reported in this work, even though all the samples show qualitatively similar results. In both samples, a source-drain voltage V_{SD} was applied on a 5 μm $\times$ 5 μm region of the wafer, defined by an etched mesa and a metallic surface gate. At zero gate voltage ($V_g = 0$) and $T = 0.3$ K, the mobility of both samples were $\gtrsim 2 \times 10^6$ cm^2/V s. By varying V_g, electron density (n_s) as low as $\sim 5 \times 10^9$ cm^{-2} could be attained in sample A79 (corresponding to an interaction parameter $r_s = 1/a_B^*\sqrt{\pi n_s} \sim 7.6$, where a_B^* is the effective Bohr radius). In all the magnetic field measurements, B was applied in the plane of the 2DES and parallel to the direction of the current. The differential conductance dI/dV was measured with a standard two-probe mixed ac + dc method, where the ac excitation bias was kept at $< k_BT/e$. For all samples, the gate was trained several hundred times to obtain an excellent run-to-run reproducibility (better than 0.1%).

The dependence of the linear response conductance (G) on V_g is shown in Fig. 1 at various values of B, recorded at $T \approx 35$ mK in sample A79. We focus on the localized regime (metal-insulator transition in A79 occurs at $G \sim 3 \times e^2/h$), where the electron density is low, and the interaction effects are most pronounced. For all V_g, G was found to decrease rapidly with increasing B. The functional dependence of the in-plane magnetoconductance (MC) on B has been shown to change from $\sim e^{-B^2}$ to $\sim e^{-B}$ at a critical field B_c, when the electron

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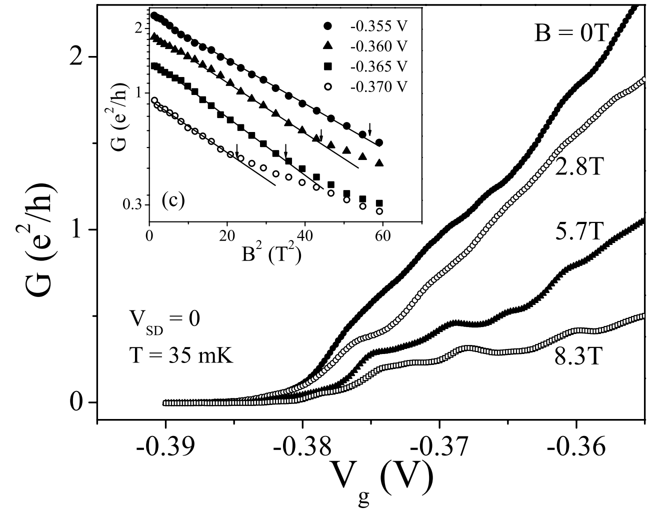

FIG. 1. Typical gate voltage V_g dependence of the linear response conductance G at various magnetic fields. Inset: G, as a function of B^2 at four V_g's. Arrows indicate the deviation from linear dependence and the onset of complete polarization.

gas becomes completely spin polarized, and the splitting of the majority and minority spin bands is equal to the Fermi energy [7,10]. In the inset of Fig. 1 we have shown the zero-bias MC as a function of B^2 at four representative gate voltages. The values of B_c at each V_g, shown by the arrows, indicate a deviation from the linear behavior at low fields. This enables us to evaluate the spin-polarized Fermi energy E_F^* as $E_F^* = g^* \mu_B B_c$. The dependence of E_F^* on V_g is shown in Fig. 2(c). We have used $g^* = 3.4|g_b|$ for evaluating E_F^*, where $|g_b| = 0.44$ is the band g factor in bulk GaAs. This value of g^* is obtained from V_{SD} measurements and will be discussed later. Note that above $V_g \approx -0.376$ V, corresponding to $n_s \approx 5 \times 10^9$ cm^{-2}, the transport is essentially 2D in nature with E_F^* varying

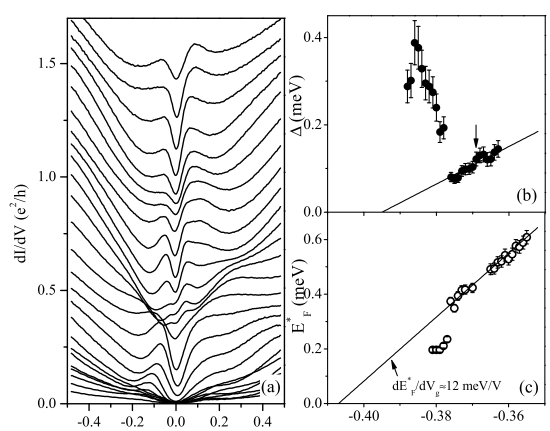

FIG. 2. (a) The differential conductance dI/dV vs source-drain bias V_{SD} at various V_g. V_g differs by 1 mV for successive sweeps. (b) The peak separation Δ as a function of V_g. (c) V_g dependence of the spin nondegenerate Fermi energy E_F^*, obtained from the magnetic field scale of complete field polarization (see text).

approximately linearly with V_g. The slope dE_F^*/dV_g was found to be ≈ 12 meV/V, agreeing roughly with the effective free-electron spin nondegenerate 2D density of states, $(dE_F^*/dV_g)_{\rm free} = (h^2/2\pi m^*)dn_s/dV_g \approx \epsilon_0\epsilon_r h^2/2\pi e m^* d_s \approx 16$ meV/V, where $d_s = 310$ nm is the depth of the 2DES from the surface, and $m^* \approx 0.067 m_e$ is the band effective mass of the electron. The discrepancy could be due to a weak density dependence of g^* [7]. Below $V_g \approx -0.376$ V ($G \approx 0.3 - 0.4 \times e^2/h$), E_F^* drops abruptly, possibly due to the onset of inhomogeneity in the charge distribution as screening becomes weak.

The V_{SD} dependence of dI/dV at various values of V_g (i.e., n_s) is shown in Fig. 2(a). V_g differs by 1 mV in successive offset-corrected traces. The striking feature of these traces is the double-peak structure of dI/dV with a local minimum at $V_{SD} = 0$. This was found to be a generic feature observed in all the low-disorder samples of similar dimensions. The detection of the double-peak structure was difficult in the strongly localized regime ($V_g \lesssim -0.385$ V), as well as in the metallic regime ($V_g \gtrsim -0.35$ V), indicating a disorder-dependent window of n_s where the effect becomes clearly visible. In most cases the peaks are dissimilar in magnitude and width, both of which vary when V_g is changed. The separation (Δ) of the peaks shows a nonmonotonic dependence on V_g, as shown in Fig. 2(b). At low V_g (~ -0.385 V), Δ is largest, but decreases rapidly with increasing V_g, reaching a minimum at $V_g \approx -0.375$ V. Comparing to the V_g dependence of E_F^* [Fig. 2(c)] we find the onset of linear dependence of E_F^* at the same V_g. When $V_g \gtrsim -0.375$ V, Δ increases roughly linearly with increasing V_g. Since this regime can be directly associated with a 2D ground state, we shall restrict further discussions on Δ to this range of V_g. Extrapolating the linear dependence of Δ, we find the V_g (≈ -0.395 V) at which $\Delta = 0$ agrees within the experimental uncertainty with the V_g (≈ -0.408 V) at which the extrapolated $E_F^* = 0$, establishing a direct correspondence between Δ and n_s.

In order to investigate the nature of this effect, we then studied the double-peak structure in a parallel magnetic field. The behavior is illustrated with the trace measured at $V_g \approx -0.37$ V, indicated by the arrow in Fig. 2(b). This is shown in Fig. 3, where the traces with increasing B are offset vertically for clarity. The peak positions (V_p) change nonmonotonically as a function of B (see the arrows). We find that the peaks close in over the field scale of $B \lesssim 0.5$ T, but eventually separate at higher fields (see the inset of Fig. 3). The evolution of the peaks with B strongly suggests a spin-related effect, where Δ is the energy difference between the opposite spins. Note that the B field does not split each peak individually, differentiating our case from a disorder-induced quantum molecule. An asymmetrical suppression of the peaks with increasing B sets the maximum field scale (≈ 2.8 T) of our experiments, beyond which the left peak becomes undetectable.

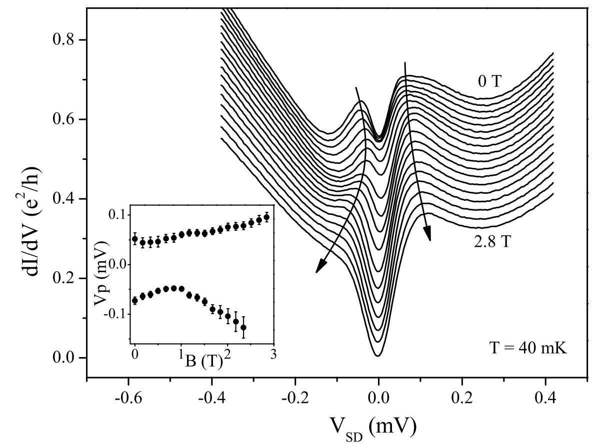

FIG. 3. Evolution of the differential conductance with magnetic field B. We have illustrated this with the trace obtained at $V_g \approx -0.37$ V [indicated by the arrow in Fig. 2(b)]. Traces are shifted vertically for clarity. Inset: Positions (V_p) of the peaks as a function of B.

The observability and characteristics of the peaks were found to depend critically on disorder and T. We have changed the local disorder profile over the sample region by controlled thermal cycles from room temperature to 4.2 K. The result for three successive thermal cycles carried out for A78 are shown in Fig. 4(a). All traces were recorded at a similar E_F and $B = 0$ (C_2 and C_1 are shifted vertically for clarity). While the general behavior of dI/dV is similar and agrees with that of A79, we find the overall magnitude and width of the peaks to differ markedly, even from one cooldown to the other. In general, when the cooling was done at a slow rate (trace C_3, over a few hours) we found the peaks to be more pronounced than when the cooling was done rapidly (trace C_1, over a few tens of minutes). Greater disorder in C_1 is also observable in terms of the linear response conductance, $G \approx 0.1e^2/h$, which for C_3 is $\approx 0.3e^2/h$. Disorder broadening also affects the observability of the effect as the sample dimensions are increased. Typically, no double peaks were observed in 10 μm $\times$ 10 μm samples.

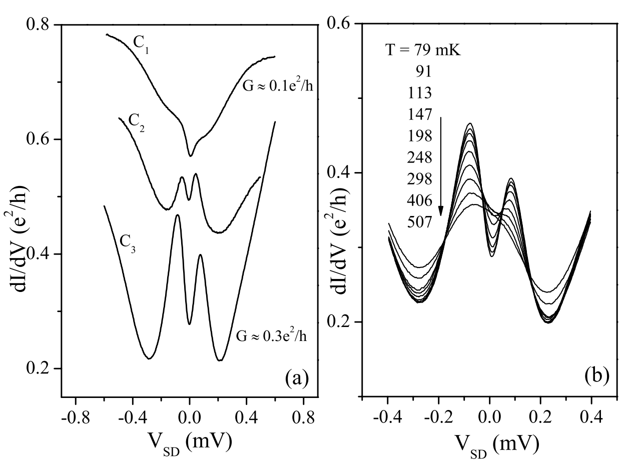

FIG. 4. (a) Double-peak structure in dI/dV in the same sample for various cooldowns. Traces are shifted vertically for easy comparison. The linear response conductance is minimum for C_1 and maximum for C_3. (b) Temperature dependence of the double peak structure. Note the smearing of each peak results in the increase of the zero-bias conductance with increasing T.

Thermal broadening of the peaks, associated with a strong suppression of the peak height, from $T \sim 70$ mK to $\sim$0.5 K are shown in Fig. 4(b). Note that even though G at $V_{\rm SD} = 0$ rises with increasing T, as expected in a localized system, it is essentially a result of the overlap of the broadening peaks. This also confirms that, as a function of $V_{\rm SD}$, we indeed observe a nonlinear effect, and the double-peak structure is a ground-state property of the 2D electron system in the low-density regime.

We now discuss possible mechanisms that may give rise to such a structure in nonequilibrium measurements. Assuming a weak tunnel barrier that physically splits the 2D region into two parts, the conservation of transverse momentum would allow maximum tunneling at $V_{\rm SD} = 0$. This would result in a disorder-broadened ZBP in the tunneling dI/dV. Then, an interaction-induced suppression of states at E_F, e.g., $\sim \ln(|\epsilon|\tau)$ in the diffusive regime [13] or Efros-Shklovskii-type soft gap $\sim|\epsilon|$ in the hopping regime [14], might split the ZBP to give rise to the double-peak structure [15]. The main arguments against such a scenario are (a) that the separation of the peaks are B independent, hence inconsistent with Fig. 3, and (b) that the separation decreases with increasing E_F, contrary to the result of Fig. 2(b) [15].

To investigate whether the peak separation Δ is, indeed, spin related, we have plotted Δ as a function of B for the data shown in Fig. 3. As shown in Fig. 5, at low fields Δ decreases with increasing field, while at high B ($\gtrsim 1$ T), Δ shows a monotonic increase as B increases. In this high-B regime, Δ appears asymptotic to a linear B dependence (the solid line), which when extrapolated, passes through the origin. We identify this as Zeeman spin splitting. From the asymptote, $\Delta_Z = g^* \mu_B B$, we find g^* to be $\approx 1.5 \pm 0.1 \approx 3.4|g_b|$, which can be attributed to the interaction-induced enhancement, suggested by several quantum Monte Carlo studies when $r_s \gg 1$ [2,16]. Note that the observed value of g^* also agrees closely with the values reported in recent measurements over a similar range of n_s [7].

From the critical role of spin, and also the behavior of dI/dV near $V_{\rm SD} = 0$, a Kondo-like many-body correlation, as discussed extensively in the context of quantum dots [11], can be envisaged. There are, however, important differences. In our system, as in the case of QPC's, there are no obvious singly occupied quasibound electronic states. Unlike the suggested ferromagnetic states in QPC's [17], however, the magnetic moment of a frozen spin-polarized state in 2D would be much higher than that of a single electron, and hence Kondo-type screening would be difficult. Furthermore, a dynamic spin polarization, along with optimal band hybridization, would

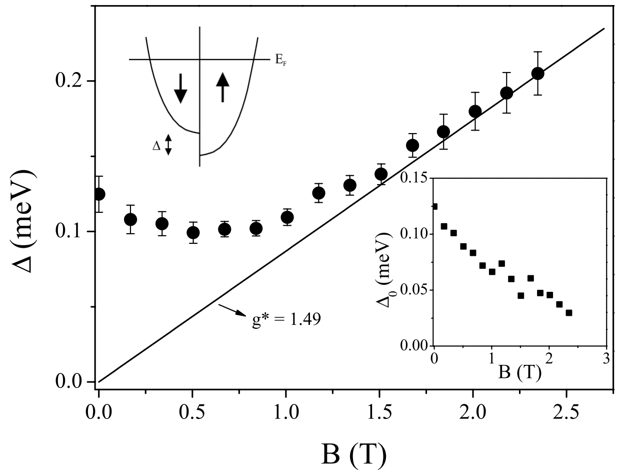

FIG. 5. Dependence of the peak separation Δ on the magnetic field B. We have used the Δ shown in Fig. 3. The high-field asymptote extrapolates through the origin. Inset: B dependence of the Δ_0.

give rise to only a ZBP in dI/dV for QPC's [18]. Our case is further complicated by the splitting of the ZBP at $B = 0$, resembling the behavior of ZBP in dots and QPC's at a finite B [11,12]. Although the Kondo effect in coupled dot systems has a similar nonequilibrium behavior as a function of V_{SD} at $B = 0$, such a case would appear only over a restricted parameter range of interdot and lead couplings, and hence should be rather rare in open systems with no intentional confinement [19].

Finally, in parallel B, it has been shown that in sufficiently smooth disorder, both SO and exchange-induced spin splitting could result in satellite peaks in the tunneling DOS at finite bias $\approx \pm\sqrt{\Delta_0^2 + \Delta_Z^2}$, where Δ_0 is the magnitude of SSP [20]. The tunneling DOS could be obtained in a nonlinear dI/dV measurement if we assume a quasiballistic transport in our clean mesoscopic samples, i.e., electrons mainly lose their energies at the leads. As well as explaining the double-peak structure in dI/dV, this also justifies (a) the broadening of the peaks with disorder and (b) the linear B dependence of Δ at high B, where $\Delta \rightarrow \Delta_Z$. If Δ_0 arises from a strong SO coupling, one expects negative magnetoconductance at low perpendicular B field, arising from weak antilocalization. No evidence of antilocalization was observed in our mesoscopic 2D systems. The SO origin of Δ_0 seems to be unlikely on two more grounds. First, calculation of the magnitude of splitting in GaAs/AlGaAs heterostructures, taking into account both bulk and Rashba terms, shows that Δ_0 would be $\ll 0.05$ meV below $n_s \sim 10^{11}$ cm^{-2} [21]. Second, if the absence of antilocalization is attributed to a B-dependent Δ_0, as in large open quantum dots, Δ_0 should increase with B at low fields [5,22]. However, as shown in the inset of Fig. 5, $\Delta_0 \sim \sqrt{\Delta^2 - \Delta_Z^2}$ decreases with increasing B in our samples. Alternatively, assuming an exchange origin, and the Fermi liquid limit, Δ_0 represents the shift of one spin state with respect to the other (see the inset of Fig. 5). An estimate of the polarization ζ could then be obtained as $\zeta = (n_{s\uparrow} - n_{s\downarrow})/n_s \sim \Delta/E_F^*$. In the regime of 2D conduction, $V_g \gtrsim -0.375$ V, we find $\zeta \sim 0.2$, implying only a partial spin polarization. This is probably not surprising considering the low $r_s \sim$ 6–7 in our system, and finite T [3]. The exchange origin of Δ_0 is also supported by the decrease of Δ_0 with increasing B, as the additional confinement ($\sim B^2$) imposed by B tends to counteract the formation of parallel spins [17].

In conclusion, nonlinear conductance measurements in low-density mesoscopic 2D electron systems show an unexpected double-peak structure close to the Fermi energy at $B = 0$. The structure appears to be universal to all 2DES's, appearing within a window of disorder, temperature, and electron density. The evolution of the peak separation with parallel magnetic field indicates the peaks to be spin related, with the finite separation signifying an exchange-driven spontaneous spin polarization at $B = 0$.

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