Spin Transport and Localization in a Magnetic Two-Dimensional Electron Gas

I. P. Smorchkova and N. Samarth
Department of Physics, The Pennsylvania State University, University Park, Pennsylvania 16802

J. M. Kikkawa and D. D. Awschalom
Department of Physics, University of California, Santa Barbara, California 93106
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Magnetotransport is investigated in a new class of heterostructures wherein a two-dimensional electron gas (2DEG) is exchange coupled to a 2D distribution of local moments. Quantum transport in these "magnetic" 2DEGs is strongly influenced by the s-d exchange-enhanced spin splitting, resulting in a highly spin polarized gas beginning at large Landau level filling factors. Diffusive transport in low magnetic fields is dominated by modifications of the Hartree corrections to the conductivity arising from the giant spin splitting. An anomalous negative magnetoresistance at higher magnetic fields suggests the suppression of spin-disorder scattering. [S0031-9007(97)03095-0]

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The interplay between spin-dependent electronic transport and localization is central to the behavior of many artificially tailored materials, and has given rise to phenomena such as giant magnetoresistance in metallic multilayers, spin polarons in high-T_c superconductors, and skyrmions in two-dimensional electron gases (2DEGs) within semiconductors [1]. To explore the detailed dynamics of such coupled electron-spin systems, it is desirable to develop model structures with well-characterized spin interactions in which one may *independently* tune the electronic and magnetic degrees of freedom. Studies of undoped (insulating) magnetic semiconductor (MS) quantum structures have played an important role in this context, with spatially and temporally resolved spin spectroscopies providing detailed insights into the dynamical interactions between optically excited carriers and local moments [2].

Here we introduce a new *doped* MS heterostructure wherein a 2DEG is exchange coupled to a 2D distribution of local moments, hence complementing magneto-optical probes of spin interactions in quantum structures with transport measurements [3,4]. The ferromagnetic kinetic s-d exchange ($J_{s-d} \sim 10^3$ K) in these "magnetic 2DEGs" yields spin splittings ΔE_S which exceed both the Landau level splitting $\hbar\omega_C$ and the thermal energy $k_B T$ [5]. The conduction electron spins are entirely polarized at low magnetic fields, providing a flexible template for studies of mesoscopic spin-polarized transport and tunneling [6]. Transport measurements indicate remarkable modifications of the quantum corrections to the 2D magnetoconductivity in the weakly localized regime [7], and a negative magnetoresistance (MR) at high fields suggesting a field-induced suppression of spin-disorder scattering.

Magnetic 2DEG structures are obtained by modulation doping a MS quantum well that is designed with a strong wave function overlap between confined electronic states and magnetic ions—in this case Mn^{2+}. In order to vary the local moment distribution systematically, a "digital" scheme is used [Fig. 1(a)], in which the local moments are restricted to 2D planes with limited interdiffusion, approximating a randomly diluted square lattice of antiferromagnetically interacting $S = \frac{5}{2}$ spins with a nearest-neighbor interaction $J_{dd} \sim -10$ K. The 2D arrangement of spins inhibits transitions to antiferromagnetic and spin glass phases, allowing a paramagnetic response from large local concentrations of magnetic ions.

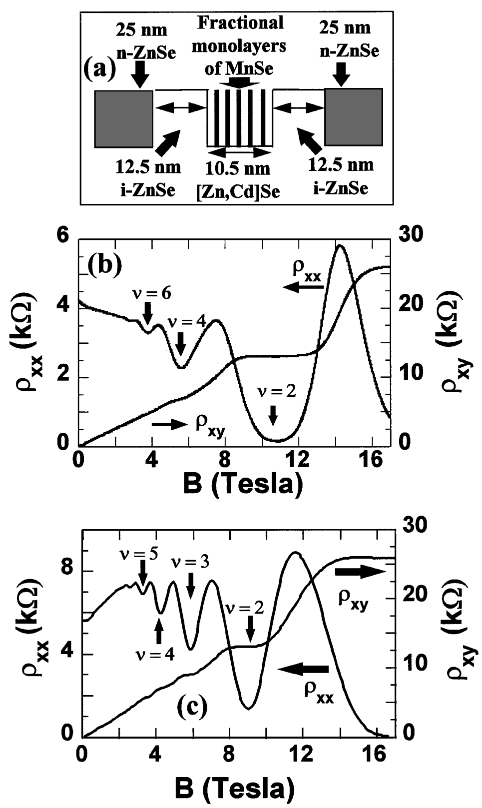

FIG. 1. (a) Sample structure. The n-type dopant in all cases is chlorine. (b),(c) Longitudinal and transverse sheet resistances (ρ_{xx} and ρ_{xy}, respectively) at 4.2 K in (b) sample A and (c) sample B, demonstrating the observation of an IQHE in each case. The figures also indicate the filling factors ν.

Samples consist of a modulation doped single quantum well (10.5 nm) in which the symmetrically placed n-type ZnSe doping layers (25 nm) are spaced 12.5 nm from the well region by intrinsic ZnSe barriers. The well is a digital alloy of $(\mathrm{Zn}_{0.80}\mathrm{Cd}_{0.20}\mathrm{Se})_{m-f}$ $(\mathrm{MnSe})_f$, with $m = 5$ and the 2D spin concentration $f = 0$, 0.125, 0.25, and 0.5 (samples A, B, C, and D, respectively). Details of sample fabrication and routine characterization are given elsewhere [3,4]. Magnetotransport measurements are carried out on mesa-etched Hall bars using dc techniques in magnetic fields ranging up to 17 T and temperatures down to 360 mK. Except where explicitly mentioned, the magnetic field is applied perpendicular to the 2DEG plane. Polarization-resolved photoluminescence (PL) and absorption is measured in the Faraday geometry in a magnetooptical cryostat in fields up to 7 T.

Table I summarizes the sheet resistance ρ_{XX}, as well as Hall effect measurements of the sheet concentration N_S and the mobility μ_H for all the samples. The two latter quantities are deduced assuming the absence of parallel conduction in the doped barriers. While this assumption is confirmed from quantum oscillation data in samples A and B, its validity is unclear for samples C and D in which quantum oscillations are too weak for detailed analysis. The large values of ρ_{XX} in the two latter samples accompanied by a significantly reduced mobility indicate the onset of a strong localization mechanism with increasing magnetic ion concentration.

Figure 1 shows a developing integer quantum Hall effect (IQHE) at 4.2 K in the higher mobility samples A and B when the quantum limit is reached ($\omega_C \tau_S \gg 1$, where τ_S is the single particle scattering time) and when the Landau level separation $\hbar\omega_C$ overcomes the overlap between disorder-broadened Landau levels. (A more detailed study of the well-developed IQHE at lower temperatures will be discussed in future work.) In both samples, standard analysis [4] of the temperature and field dependence of the quantum oscillations yields $\tau_S \sim 0.35$ ps, consistent with the onset of quantum oscillations at $\sim$2 T. The simultaneously deduced sheet concentrations agree with low-field Hall measurements, confirming the absence of parallel conduction in the barriers. Since the effective mass of the carriers is not yet accurately known from experiment [8], we use a value of $m^* = 0.16 m_0$, obtained by linearly interpolating between the effective masses of ZnSe ($0.17 m_0$) and CdSe ($0.12 m_0$).

TABLE I. Summary of sample characteristics at 4.2 K, as determined from low-field Hall effect measurements. As explained in the text, f is the 2D Mn concentration.

Sample	f	ρ_{XX} (kΩ)	N_S (cm^{-2})	μ_H (cm^2/V s)
A	0	4.3	5.3×10^{11}	2700
B	0.125	5.6	4.2×10^{11}	2700
C	0.25	12.0	6.5×10^{11}	800
D	0.50	21.5	4.8×10^{11}	600

The filling factors labeled in Fig. 1(b) indicate that the Landau level spin splitting $\Delta E_S = g\mu_B B$ in the nonmagnetic 2DEG cannot be resolved at 4.2 K; the spin splitting is only noticeable beyond a field of 6 T at lower temperatures [Fig. 2(a)]. In contrast, Fig. 1(c) shows that ΔE_S in the magnetic 2DEG is large enough to completely spin resolve the Landau levels right from the onset of quantum oscillations even at 4.2 K. Here, the spin splitting is proportional to the sample magnetization and is readily estimated from Zeeman shifts in magneto-optical spectra [4,9]. Specifically, $\Delta E_S = (\Delta E)_{\max} B_{5/2}(5\mu_B B/k_B T_{\mathrm{eff}})$, where $B_{5/2}(x)$ is the Brillouin function for $S = \frac{5}{2}$, empirically modified by using a rescaled temperature ($T_{\mathrm{eff}} = T + T_0$) to account for antiferromagnetic spin-spin interactions [5]. By combining the Landau level splitting $\hbar\omega_C$ with the spin splitting ΔE_S, Landau level fan diagrams are constructed for samples A and B [Figs. 2(c) and 2(d)]. The magnetic field variation of the Fermi level in these figures shows that the transport which occurs in states near the Fermi level involves spin-resolved states at low temperatures. Furthermore, Fig. 2(d) demonstrates the creation of a highly spin-polarized 2DEG even in modest magnetic fields ($\sim$2 T).

Another striking difference between the nonmagnetic and magnetic 2DEGs is the opposite sign of the low-field longitudinal MR. This is seen more clearly in Figs. 3(a) and 3(c) which compare the low-field magneto*conductivity* (MC) in samples A and B, respectively. The contrasting behavior in these two weakly localized samples can be attributed to quantum corrections to the conductivity in

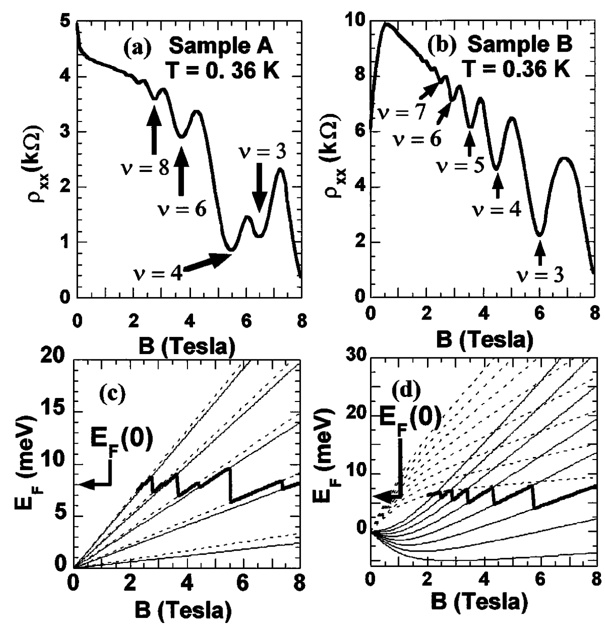

FIG. 2. (a),(b) Behavior of ρ_{xx} at $T = 0.36$ K in samples A and B, respectively. (c),(d) Landau level fan diagrams in samples A and B, respectively, with the dark, solid line indicating the position of the Fermi level in each case. Dashed (thin solid) lines belong to Landau levels with spin up (spin down).

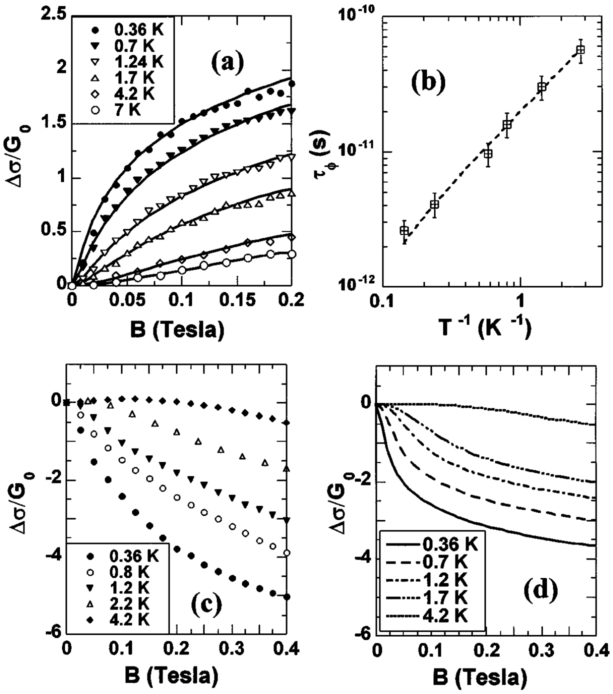

FIG. 3. (a) Low-field MC in sample A obtained by inverting the magnetoresistance tensor. Solid lines are weak localization fits to the data, with τ_ϕ as the principal fitting parameter and $\alpha = 0.7$. The classical MC is negligible over this range of magnetic field. (b) Temperature dependence of τ_ϕ determined from the fits in (a). The linear variation with inverse temperature is in qualitative agreement with expectations that take into account electron-electron interactions [18]. (c) Low-field MC in sample B at various temperatures. (d) Theoretical behavior of the low-field MC in sample B given by $\Delta\sigma(B) = \Delta\sigma_L(B) + \Delta\sigma_D(B)$.

disordered 2D systems [10], bearing in mind that the relevant perturbative parameter within this theoretical framework, $(k_F l_e)^{-1}$, is ~ 0.25. Three distinct contributions arise within this interpretation: (a) a positive MC ($\Delta\sigma_L$) from the destructive effect of a magnetic field on weak localization, (b) a negative MC ($\Delta\sigma_D$) from the modification of electron-electron interactions by a carrier spin splitting ("particle-hole" contributions), and (c) a negative MC ($\Delta\sigma_C$) from the modification of electron-electron interactions by the orbital effect of a magnetic field ("particle-particle" contributions). Our analysis ignores $\Delta\sigma_C$ in the nonmagnetic sample since it is small over the range of magnetic field studied; these particle-particle terms are also rendered negligible in the magnetic samples by the large spin splitting and by spin-disorder scattering [11]. Spin-orbit effects can also produce a negative MC in magnetic systems but are insignificant here because of the *S*-state nature of the magnetic ions; further, band-structure related spin-orbit terms appear to be unimportant since we do not observe negative MC in the nonmagnetic 2DEG.

The positive MC in the nonmagnetic 2DEG sample A arises from the first type of contribution: Fig. 3(a) shows weak localization fits to the low field MC given by $\Delta\sigma_L(B) = \sigma(B,T) - \sigma(0,T) = G_0 \alpha f_2(x_L)$ where $G_0 = (e^2/\pi h)$, f_2 is a well known function, and α is a prefactor of the order of unity [12]. The argument of the function f_2 is $x_L = (2L_\Phi/L_B)^2$, where L_Φ is the phase breaking length and L_B the magnetic length. Figure 3(b) shows the temperature variation of the phase breaking time τ_ϕ employed in the fits. Both figures confirm a standard weak localization interpretation of the data.

In contrast, the presence of local moments in sample B produces a more complex behavior [Fig. 3(c)] with competing contributions from $\Delta\sigma_L$ and $\Delta\sigma_D$. The essential effect of the giant spin splitting on the latter is a drastic reduction in the Hartree contributions to the particle-hole diffusion channel [10]. The resulting MC follows a field dependence given by $\Delta\sigma_D(B) = -(G_0/2)F_\sigma(F)g_2(\Delta E_S/k_BT)$. The function F_σ depends on the angular average F of the statically screened Coulomb interaction over the Fermi sphere; $g_2(\Delta E_S/k_BT)$ is a function that can be evaluated numerically [13]. Detailed attempts to fit the MC in this sample using the parameters τ_ϕ and F_σ are not meaningful since the presence of magnetic ions may lead to other contributions to the MC unaccounted for in the standard theory for quantum corrections to the conductivity. Rather, we generate a theoretical plot for one set of reasonable parameters so as to examine the plausibility of the above framework. This is shown in Fig. 3(d) with $F_\sigma = 2$ and $\alpha = 0.2$; the values of τ_ϕ at different temperatures are taken from the weak-localization fits to sample A. The small value of α chosen in these calculations is consistent with theoretical expectations for magnetic samples [12]. Comparison with the experimental data shows that the low field MC in sample B can be attributed at least partially to the mechanism discussed above.

This picture is further substantiated by measuring the longitudinal MR with the magnetic field applied in the plane of the 2DEG [Fig. 4(a)]: this removes all "orbital" contributions to the quantum corrections (i.e., $\Delta\sigma_L$ and $\Delta\sigma_C$) while keeping the isotropic spin-splitting dependent contributions unaffected. In this geometry, the nonmagnetic sample A exhibits negligible MR while all three

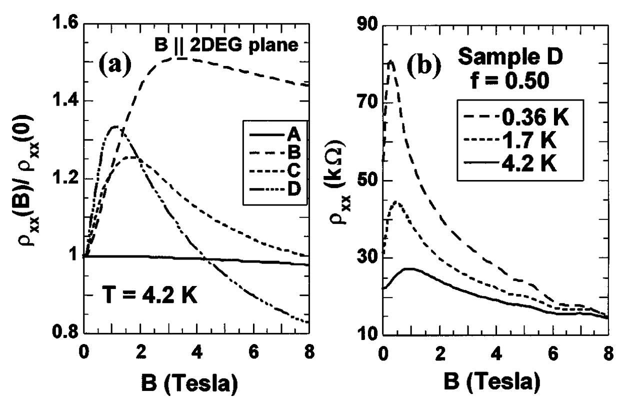

FIG. 4. (a) Longitudinal MR in all the samples at $T = 4.2$ K with the magnetic field applied in the plane of the 2DEG. (b) Longitudinal MR in sample D ($f = 0.5$) at three different temperatures—the magnetic field here is applied perpendicular to the plane of the 2DEG.

magnetic samples retain the characteristic low field positive MR observed in a perpendicular field. In addition, however, these measurements reveal an anomalous negative MR in the high field regime where $\Delta E_S \geq E_F(0)$ (the Fermi energy at zero field). This effect is also observable with the field perpendicular to the sample plane and is strongly temperature dependent [Fig. 4(b)]. In the absence of any rigorous models that can account for the anomalous MR in magnetic 2DEGs, we qualitatively attribute the observed behavior to the quenching of spin-disorder scattering by a magnetic field [14]. A relevant question that needs to be addressed in this context is the nature of the scattering source.

In contrast to the situation in metals, the Fermi vector k_F is small ($\sim$0.2 nm^{-1}); hence, spin scattering via a short-ranged exchange interaction with individual magnetic ions is relatively inefficient [14]. However, spin-disorder scattering can play an important role in the conductivity when large collections of magnetic ions are involved. In uniformly doped bulk MS crystals and in magnetic quantum wells containing impurities, bound magnetic polarons of $\sim$10 nm diameter are created by the ferromagnetic interaction between impurity-bound electrons and local moments [15]. The unbinding of such magnetic polarons by a magnetic field is believed responsible for the negative MR observed both in the weakly and strongly localized regimes [7,16]. In both cases, the temperature variation of the zero-field conductivity $\sigma(0,T)$ shows distinct departures from the effects of disorder alone.

However, in the magnetic 2DEG samples, we find that $\sigma(0,T) = A + B\ln(T)$ over a temperature range 0.36–4.2 K, as anticipated for any disordered 2DEG. Further, time-resolved Faraday rotation measurements do not show any evidence for the existence of bound magnetic polarons in the magnetic 2DEG samples [9]. This raises the intriguing possibility of spin-dressed free carrier states (free magnetic polarons) that undergo an unbinding in a magnetic field. Although energetically unfavorable in 3D, such conduction electron-local moment complexes could be marginally stable in 2D systems [17]. Time-resolved magnetooptical experiments are currently underway in order to examine this possibility in more detail.

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