Influence of *s-d* Exchange Interaction on Universal Conductance Fluctuations in $Cd_{1-x}Mn_xTe$: In

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We present millikelvin studies of diffusive charge transport in submicron wires of n^+-CdTe and n^+-$Cd_{0.99}Mn_{0.01}Te$ epilayers. In contrast to expectations, the paramagnetic Mn impurities leave a mean amplitude of reproducible magnetoconductance fluctuations unchanged but *decrease* the fluctuation correlation field. These findings are interpreted by invoking a new driving mechanism of the magnetoconductance fluctuations—the redistribution of the electrons between energy levels of the system, induced by the giant *s-d* exchange spin splitting.

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Soon after the discovery that the Anderson-Mott localization in disordered metals and the universal conductance fluctuations (UCF) in mesoscopic conductors are controlled by diffusion poles in particle-particle and particle-hole correlation functions, it became clear [1–3] that the exchange coupling between the carriers and the subsystem of magnetic impurities would play an important role in the physics of quantum transport. Indeed, it is well established by now that the localized spins, apart from introducing an additional temperature and magnetic-field dependent contribution to the momentum relaxation rate, $1/\tau_s(T,H)$, can affect quantum transport phenomena in many other ways, depending on their dynamics, ordering, and relevant degrees of freedom [1–14]. In particular, the perturbing potential associated with the frozen spins leads to the violation of the Onsager-Büttiker symmetry relations in mesoscopic samples [6–8]. The fluctuating spins, on the other hand, because of an extreme sensitivity of the conductance to potential realizations, are an efficient source of conductance noise [2,9]. If, therefore, the integration time of the resistance meter is longer than the correlation time of spin fluctuations and τ_s is shorter than characteristic times of coherence breaking, the exchange interaction results in damping of the UCF amplitude [10–12]. In addition, electron scattering by disordered Heisenberg spins introduces a cutoff $1/\tau_s$ to all diffusion poles except for the particle-hole channel with total spin $j = 0$ [3–5]. Similarly, the coupling of electrons to spins aligned by an external or molecular field along one direction gives rise to a cutoff in the particle-particle channels with $j_z = 0$ and the particle-hole channels with $j_z = \pm 1$ [13,14]. This alters the universality class of the metal-to-insulator transition (MIT) [4] and the scaling factor of the UCF amplitude [3]. It leads also to a giant positive magnetoresistance in the neighborhood of the MIT [14,15].

We report here on a study of millikelvin magnetoconductance in submicron wires of a diluted magnetic semiconductor (DMS) [16] $Cd_{0.99}Mn_{0.01}Te$:In with the electron concentration greater by a factor of 5 than that corresponding to the MIT. For a comparison, similar measurements were carried out on quantum wires of nonmagnetic CdTe:In. The carrier and Mn concentrations are low enough to preclude the appearance of either spin-glass freezing or the Kondo effect, even at the lowest temperature studied here, $T = 30$ mK [17]. Our results confirm [14–16] a dramatic influence of the *s-d* coupling on the magnetoresistance at the localization boundary. Surprisingly, no effect of the localized spins upon the mean *amplitude* of UCF is observed. At the same time, however, we find a striking behavior of the *correlation field* H_c of the magnetoconductance fluctuations in the wires with Mn. Prompted by the data, we argue that a new driving mechanism of magnetoconductance fluctuations exists in quantum structures that contain magnetic impurities. This mechanism is associated with a redistribution of the electrons between energy levels, induced by the giant *s-d* exchange spin splitting. Our model is supported by the fact that H_c scales with the *d*-spin magnetization. Furthermore, the results we present here have important implications for the interpretation of recent studies of UCF in semiconductor [11] and spin-glass [8] systems.

$Cd_{1-x}Mn_xTe$:In films with $x = 0$ or $x = 1 \pm 0.1\%$, typical thickness of 0.3 μm, and electron concentrations around 10^{18} cm^{-3} were grown by MBE onto (001) oriented SI GaAs epiready substrates with 10 Å ZnTe and 3 μm CdTe undoped buffer layers. Secondary-ion mass spectroscopy (SIMS), high-resolution TEM, x-ray diffraction, photoluminescence, deep-level transient spectroscopy (DLTS), conductivity, and Hall effect studies showed homogeneous impurity distribution and good structural properties of the epilayers [18]. In addition, SIMS and the room temperature Hall data provided the values of Mn molar fraction and electron concentration, respectively, and their combination the activation of the In donors. The studied wires had the form of

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six-terminal Hall bars with a square cross section of side $W = 0.3 \pm 0.05$ μm, and the distance between the voltage probes being 5 μm, as shown in the inset to Fig. 1. They were fabricated by means of 30 keV electron-beam lithography, followed by wet etching in 0.5% solution of Br_2 in ethylene glycol. No degradation in the carrier concentration or mobility was noted after nanostructuring by this process. Ohmic contacts were formed by alloying of indium. Low-frequency ac currents down to 100 pA were employed for the resistance measurements in a dilution refrigerator, carefully protected against electromagnetic noise.

Figures 1 and 2 present resistance as a function of the magnetic field perpendicular to wires of CdTe:In and $Cd_{0.99}Mn_{0.01}$Te:In with the electron concentrations 1.0×10^{18} and 8×10^{17} cm^{-3}, respectively. Weak-field magnetoresistance and irregular reproducible resistance fluctuations are detected in both materials. Starting from the magnetoresistance, we note that, because down to 100 mK W is greater than the thermal diffusion length $L_T = \sqrt{\hbar D/k_B T}$, the studied wires are three dimensional (3D) with respect to phenomena that are sensitive to thermal broadening of the distribution function, such as electron-electron interactions. Since, however, in nonmagnetic wires $L_\varphi = \sqrt{D\tau_\varphi} > L_T$ [14], we may expect a dimensional crossover in the negative magnetoresistance as it is controlled by phase breaking effects. That this is the case is shown in Fig. 2(a), which displays the temperature dependence of the magnetoresistance $\Delta\rho$ in n^+-CdTe. The theoretical curves were calculated for the 3D case from weak-localization theory [4], taking $m^*/m_0 = 0.099$ and assuming $L_\varphi = A/T^{3/4}$, where A was a fitting parameter determined to be 0.9 μm $K^{3/4}$.

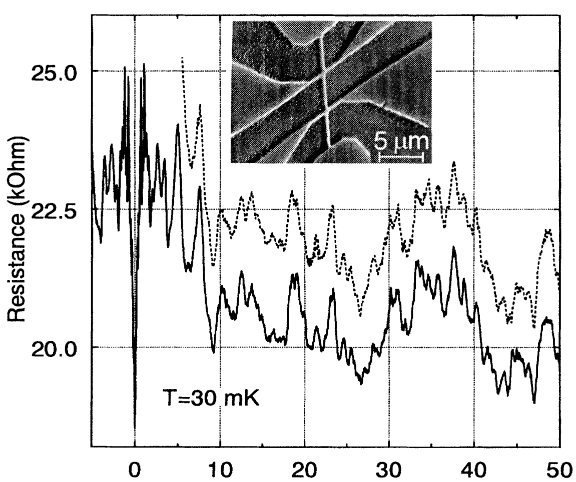

FIG. 1. Two measurements of the resistance as a function of the magnetic field for the wire of n^+-$Cd_{0.99}Mn_{0.01}$Te at 30 mK. Inset shows a scanning electron micrograph of the sample.

Since in 3D $\Delta\rho \sim H^{-1/2}$, while in 1D $\Delta\rho \sim H^{-1}$, we take the discrepancies between the experimental and calculated $\Delta\rho$, appearing at $L_\varphi(T) > W$, as evidence for the presence of the temperature-induced crossover from 3D to 1D at ~ 3 K in the studied wire.

A striking influence of the magnetic impurities upon the magnetoresistance and UCF is shown in Fig. 2(b), where data for n^+-$Cd_{0.99}Mn_{0.01}$Te are shown together with the results of a theoretical computation [4,14]. As demonstrated previously [14], the positive magnetoresistance is caused by the effect of the giant exchange spin splitting upon the electron-electron interaction. This spin splitting depends on the temperature and the magnetic field according to [16,19]

$$\hbar\omega_s \equiv \tilde{g}\mu_B H = g^*\mu_B H + \alpha M(T,H)/(g\mu_B), \quad (1)$$

where $\alpha N_0 = 0.22$ eV is the s-d exchange energy, $M(T,H)$ is the magnetization of the Mn spins given by a modified Brillouin function, $M(T,H) = \bar{x}N_0 g\mu_B S B_S(T + T_0, H)$, where $N_0 = 1.48 \times 10^{22}$ cm^{-3}, $g = 2.0$, $S = 5/2$, and, for $\bar{x} = 1\%$, $T_0 \approx 80$ mK

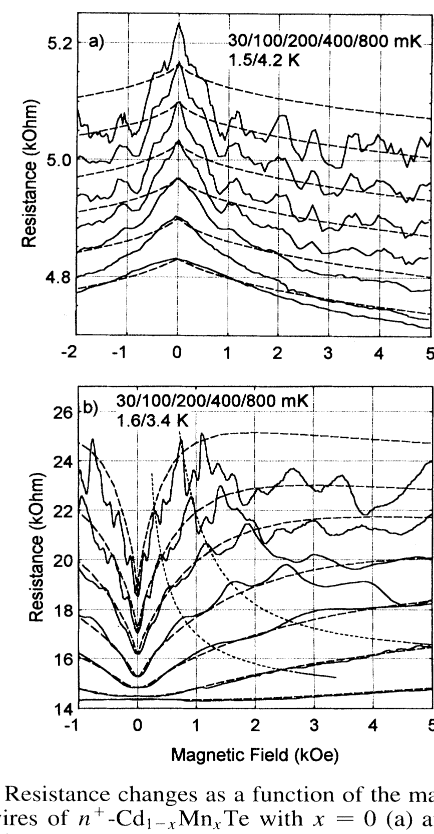

FIG. 2. Resistance changes as a function of the magnetic field for the wires of n^+-$Cd_{1-x}Mn_xTe$ with $x = 0$ (a) and $x = 1\%$ (b) at various temperatures between 30 mK and 4.2 K (traces for the lowest temperatures are shifted upward). Dashed lines represent magnetoresistance calculated in the framework of 3D weak-localization theory [4,14]. Dotted lines are guides for the eye, and visualize a strong temperature dependence of the resistance features in $Cd_{0.99}Mn_{0.01}$Te (b).

[17,19]. These parameters imply $\tilde{g}\mu_B H = 5.5$ meV for $Sg\mu_B H \gg k_B(T + T_0)$ and $\tilde{g} = 150$ K$/(T + T_0)$ in the opposite limit. In that way, the Coulomb amplitude was the only adjustable parameter and its fitting yielded $g_3 + g_4 = 1.3$. As expected, no dimensional crossover to 1D is observed in the positive magnetoresistance as it is controlled by a short length scale L_T.

Turning to the resistance fluctuations in the studied samples, we note that their root mean square amplitude is independent of the magnetic field. On the other hand, it increases with decreasing temperature according to $\mathrm{rms}(\Delta R)/R^2 \approx (C/T)^r e^2/h$ where, above 100 mK, $C = 0.1$ mK and $r = 0.5$. While such a behavior is typical for nonmagnetic 1D wires, in which the distance between the voltage probes is greater than both L_T and L_φ [3,5], it comes as a surprise in the case of $Cd_{0.99}Mn_{0.01}Te$. Indeed, in the latter rms (ΔR) is expected to be controlled by τ_s, which for $T > T_0$ is independent of temperature but increases with the magnetic field [10–12]. However, because of the low density of states specific to semiconductors, we obtain $\hbar/(k_B\tau_s) = \alpha^2 m^* k_F \bar{x} N_0 S(S + 1)/(4\pi\hbar^2 k_B)$ to be as low as 100 mK at $H = 0$. This estimate explains the minor importance of spin-disorder scattering in the studied system. At the same time our data put into question the suggestion [11] that spin-disorder scattering by etching-induced defects can account for the absence of the resistance fluctuations in the region of weak magnetic fields in n^+-GaAs wires at $T \geq 1.3$ K [20].

Another important aspect of the data depicted in Fig. 2 concerns the unusual behavior of the correlation field H_c of the resistance fluctuations in $Cd_{0.99}Mn_{0.01}Te$. As shown by dotted lines, the fields H_i corresponding to characteristic points of the fluctuation pattern tend to increase with either temperature or magnetic field, a behavior not observed in nonmagnetic wires, including those of n^+-CdTe. This new effect is visible not only for the perpendicular but also for the parallel orientation of the magnetic field with respect to the wires.

We note that field-induced changes of spin configurations have been proposed as the mechanism driving magnetoconductance fluctuations in spin-glass Cu:Mn wires [8]. We suggest the existence of another spin effect that can also operate in the paramagnetic phase considered here. This effect has its origin in the spin-splitting-induced redistribution of carriers between the spin subbands. The redistribution, and the corresponding shift of the Fermi energy ε_F with respect to the bottom of the spin-down and spin-up subbands, result in a gradual change of energy levels of the system that contribute to the conductance. Since, according to Eq. (1), the spin splitting is proportional to the magnetization, the positions of the characteristic points of the fluctuation pattern should be temperature independent if the resistance would be plotted as a function of the magnetization M, not of the magnetic field H. That this is indeed the case is shown in Fig. 3.

In order to evaluate the correlation field related to the spin splitting H_c^{spin} we observe that, if $\varepsilon_F \gg \hbar\omega_s$, an increase of the magnetic field by ΔH leads to the shift of the Fermi energy $\Delta\varepsilon_F = \pm\frac{1}{2}\Delta H \partial\hbar\omega_s/\partial H$. Hence, for $\hbar\omega_s > \mu_c$, where [3] $\mu_c \approx \max(k_B T, h/\tau_\varphi)$ is the energy correlation range, we obtain H_c^{spin} in the form

$$H_c^{\mathrm{spin}} = \sqrt{2}\mu_c(\partial\hbar\omega_s/\partial H)^{-1}, \qquad (2)$$

where the factor $1/\sqrt{2}$ appears because the fluctuations result from a superposition of two independent contributions associated with two different spin subbands. We presume that in magnetic materials $\tau_\varphi \equiv h/\mu_c$ is equivalent to spin-relaxation time T_2 of the itinerant electrons. According to detailed experimental and theoretical studies of T_2 in paramagnetic n-$Cd_{0.95}Mn_{0.05}Se$ near the MIT [21], we then have in the limit of weak magnetic fields

$$H_c^{\mathrm{spin}} = \frac{2\sqrt{2}k_B T \alpha m^* k_F}{\hbar^2 g \mu_B}\left[1 + \frac{3\sqrt{3}}{\pi(k_F\ell)^2}\right]\left(1 + \frac{F}{2}\right). \qquad (3)$$

The terms in the square bracket and the parentheses represent enhancement factors of the s-d scattering caused by nonmagnetic impurities and electron-electron interactions, respectively. By putting parameters suitable for our CdMnTe wire ($k_F\ell = 1.5$ and $F = 2$), we obtain $H_c^{\mathrm{spin}} = 410 \times [T(\mathrm{K})]$ Oe. Except for the lowest temperatures, where the effect of bound magnetic polarons may appear [14,21], this agrees with the experimental values, $H_c^{\mathrm{exp}} = 360 \times [T(\mathrm{K})] + 36$ Oe, determined in the range $0.03\ \mathrm{K} \leq T \leq 0.8$ K and $0 \leq H \leq k_B(T + T_0)/(g\mu_B)$.

It is interesting to find out whether the spin-splitting effect invoked here could account for the finite value of H_c^{spin} observed in Cu:Mn [8]. By taking parameters suitable for 1000-atomic-ppm Cu:Mn [8], i.e., $\ell = 200$ Å, $L_\varphi = 0.35$ μm, $m^* = m_0$, $\chi = \chi_C(T_g) = 3.8 \times$

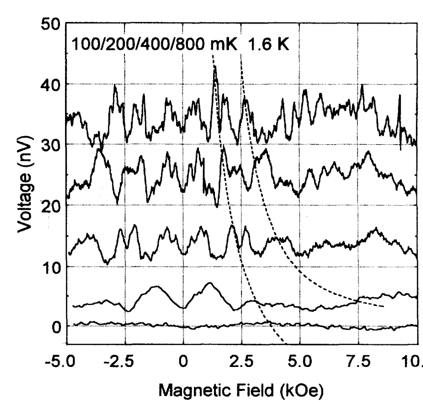

FIG. 3. Magnetoresistance data of Fig. 2(b) plotted as a function of magnetization in the units of $M_s = g\mu_B S N_0 \bar{x}$ [magnetization parameters are given below Eq. (1)].

10^{-4} emu, and $|\alpha N_0| = 0.5$ eV, we obtain from Eqs. (1) and (2), $H_c^{\rm spin} = 4.1$ kOe, a value quite close to the experimental finding, $H_c^{\rm spin} = 4.2-6.4$ kOe [8].

In summary, we have performed a low-temperature magnetoresistance study on nanostructures, for which the incorporation of magnetic impurities could be controlled during the growth process, while the details of magnetic properties and the value of the exchange coupling between the spins and the electrons could be monitored by means of a quantitative study of magneto-optical effects and weak-localization magnetoresistance. Our results reemphasize the relatively small importance of spin-disorder scattering in semiconductors. At the same time, they demonstrate the significance of the spin-splitting-induced redistribution of the carriers between the spin subbands in quantum transport phenomena. It was so far noted that the redistribution may affect the conductivity in two ways: first, by its influence on the mean free path that appears for $\hbar\omega_s \gtrsim \varepsilon_F$ [22]; and second, by changing the distance of ε_F to the mobility edge ε_m [23], an effect operating if $\hbar\omega_s \gtrsim |\varepsilon_F - \varepsilon_m|$. Our findings show that yet another, third, mechanism can play a role, namely, that in mesoscopic systems the redistribution between the nanostructure energy levels is relevant, resulting in the fact that the scales of characteristic energy and the field are rather small, $\hbar\omega_s \gtrsim \max(k_B T, h/\tau_\varphi)$.

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[20] The high-field fluctuations observed in Ref. [11] show, unexpected by the authors, periodicity in the *inverse* magnetic field. This may suggest that it is more appropriate to interpret them rather as Shubnikov–de Haas oscillations than UCF. Actually, their period gives an expected value of the electron concentration. Of course, 1D character of electron transport may perturb their properties such as a temperature dependence and a magnitude of the spin splitting.

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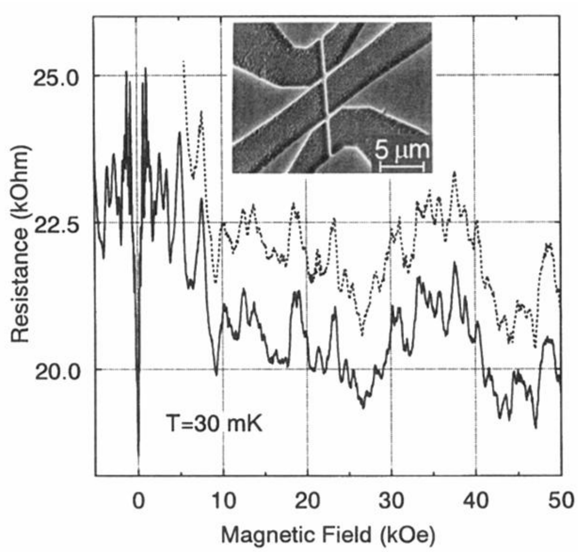

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