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CONDUCTANCE FLUCTUATIONS IN QUANTUM WIRES OF n-CdTe AND n-$Cd_{1-x}Mn_xTe$*

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We present millikelvin studies of magnetoconductance in submicron wires of In-doped n^+-CdTe and n^+-$Cd_{0.99}Mn_{0.01}Te$ epilayers. Weak-field magnetoresistance which arises from quantum localization as well as universal conductance fluctuations have been observed. The exchange coupling to magnetic impurities is shown to decrease the correlation field of the fluctuations. This novel effect is 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 spin-splitting of the electronic states.

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In mesoscopic regime, where the linear size of a conductor L, becomes comparable to the phase breaking length L_φ and/or thermal diffusion length L_T, quantum interference of transition amplitudes corresponding to various possible electron trajectories leads to random but reproducible fluctuations of the conductance as a function of external parameters such as a magnetic field [1]. This phenomenon is known as the universal conductance fluctuations (UCF) as their mean amplitude is remarkably insensitive to system properties. The fluctuation pattern, on the other hand, is extremely sensitive to the actual distribution of scattering potential in a given sample. Thus, the presence of magnetic impurities, because of their exchange coupling to the carriers, can considerably affect quantum transport phenomena. In particular, a perturbing potential associated with frozen spins leads to violation of the Onsager–Büttiker symmetry relations in mesoscopic samples [2, 3]. The fluctuating spins, on the other hand, are an efficient source of the conductance noise [1, 4] which, after time-averaging, results in a damping of the fluctuation amplitude [5, 6].

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We report here on a study of millikelvin magnetoconductance in submicron wires of a diluted magnetic semiconductor (DMS) [7] $Cd_{0.99}Mn_{0.01}Te$ doped with In donors to the electron concentration $\approx 8 \times 10^{17}$ cm^{-3}. For comparison, similar measurements were carried out for quantum wires made of nonmagnetic CdTe:In.

The $Cd_{1-x}Mn_xTe$:In films with thickness of 0.3 μm and electron concentrations $\approx 8 \times 10^{17}$ cm^{-3} were grown by MBE on semi-insulating (001) GaAs epiready substrates with 10 Å ZnTe and 3 μm CdTe buffer layers. SIMS (secondary ion mass spectroscopy), high resolution TEM (transmission electron microscopy), X-ray diffraction, photoluminescence, conductivity, and Hall effect studies showed a homogeneous impurity distribution and good structural properties of the epilayers.

The studied wires had the form of six-terminal Hall bars with a square cross-section with a side of 0.3 ± 0.05 μm, and with the distance between the voltage probes 4 and 5 μm. They were fabricated by means of high-energy 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 indium. Low-frequency a.c. currents down to 100 pA were employed for the resistance measurements in a dilution refrigerator.

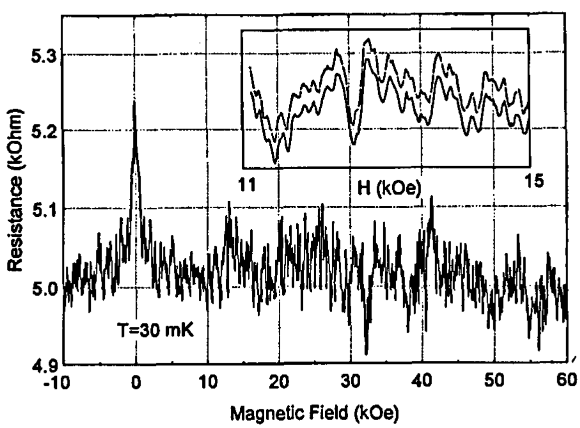

Fig. 1. Resistance as a function of the magnetic field perpendicular to the n^+-CdTe wire. Reproducibility of the fluctuations is clearly visible in the inset.

Figures 1 and 2 present the resistance as a function of the magnetic field for CdTe:In and $Cd_{1-x}Mn_xTe$:In wires with the electron concentration 1.0×10^{18} and 8×10^{17} cm^{-3}, respectively, and $x = 1 \pm 0.1\%$, as determined by SIMS. Weak-field magnetoresistance and irregular reproducible resistance fluctuations are detected in both materials. As shown by dashed lines in Fig. 2 (computed following a procedure presented in detail elsewhere [8]) the magnetoresistance can quantitatively be described in terms of weak-localization theory [9]. The opposite sign of the

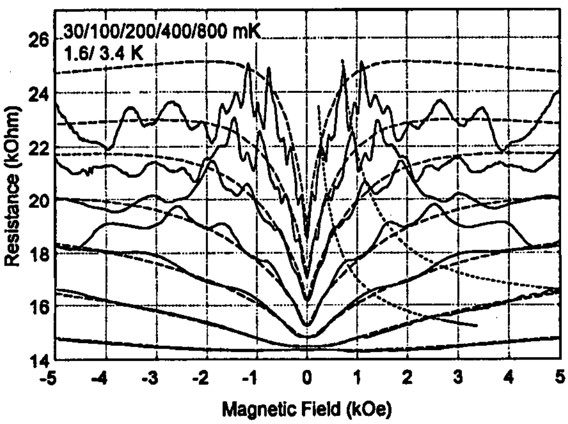

Fig. 2. Resistance changes as a function of the magnetic field perpendicular to the wire of $Cd_{0.99}Mn_{0.01}Te$ (curves are vertically shifted). Dashed lines represent magnetoresistance calculated in the framework of 3D weak-localization theory [8, 9] and with parameters given in the main text. Dotted lines are guides for the eye, and visualize a strong temperature dependence of resistance features.

magnetoresistance in the studied materials is due to the giant spin-splitting in DMS [8],

$$\hbar\omega_{\mathrm{s}} = g^{*}\mu_{\mathrm{B}}H + \alpha M(T,H)/g\mu_{\mathrm{B}}. \tag{1}$$

In our computations we used the values of the electron effective mass and the band Landé factor ($m^{*}/m_{0} = 0.099$, $g^{*} = -1.7$) together with the $s-d$ exchange integral $\alpha N_{0} = 0.22$ eV [11] and the magnetization of the Mn spins given by a modified Brillouin function, $M(T,H) = xN_{0}g\mu_{\mathrm{B}}SB_{S}(T+T_{0},H)$, where $N_{0} = 1.48\times10^{22}$ cm^{-3}, $g = 2.0$, $S = 5/2$, and $T_{0} \approx 80$ mK [10, 11]. Thus, the Coulomb amplitude $g_{3}+g_{4}$ was the only adjusted parameter, and its value was found to be equal to 1.3.

Turning to the resistance fluctuations in $Cd_{0.99}Mn_{0.01}Te$ we note that their root mean square amplitude is independent of the magnetic field. It increases with the temperature according to $\mathrm{rms}(R)/R^{2} \approx (C/T)^{r}e^{2}/h$, where $C = 0.1$ mK and $r = 0.5$. Such behavior is typical of nonmagnetic 1D wires, in which the distance between voltage probes is greater than both the thermal L_{T} and phase breaking length L_{φ} [1], and its occurrence in $Cd_{0.99}Mn_{0.01}Te$ demonstrates clearly a weak influence of spin–disorder scattering on UCF in semiconductors.

Another important aspect of the data depicted in Fig. 2 concerns with an unusual behavior of the correlation field H_{c} of the resistance fluctuations. As shown by the dotted lines, the field differences ΔH between characteristic points of the fluctuation pattern tend to increase with either the temperature or the magnetic field, a behavior not observed in nonmagnetic wires, including those of n^{+}-CdTe. This new effect is visible for the magnetic field either perpendicular or parallel 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 [3]. We suggest the existence of another spin effect that can operate also in the paramagnetic phase considered here. This effect stems from 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-up and spin-down subbands, result in a gradual change of energy levels of the system which contribute to the conductance. If $\varepsilon_F \gg \hbar\omega_s > \mu_c$, where μ_c is the energy correlation range of the chemical potential, the correlation field for the spin effect assumes a simple form,

$$H_{\text{spin}} = \sqrt{2}\hbar\mu_c \left(\frac{\partial\omega_s}{\partial H}\right)^{-1}, \tag{2}$$

with $\mu_c \approx \min(k_B T, h/\tau_\varphi)$ and τ_φ equal to the phase breaking time. Since the correlation field for the orbital effects [1]

$$H_{\text{orb}} \approx \frac{h/e}{L_{\min}^{(x)} L_{\min}^{(y)}}, \tag{3}$$

where $L_{\min}^{(i)} = \min(L_\varphi, L^{(i)})$ and $L^{(x)}L^{(y)}$ is the sample area projected perpendicularly to H, we get when L_φ is the relevant length scale,

$$\frac{H_{\text{orb}}}{H_{\text{spin}}} \approx \left| g^* + \frac{\alpha N_0 \chi(T,H)}{g\mu_B^2} \right| \frac{m^*}{m_0 k_F l}. \tag{4}$$

We see that for appropriately large magnetic susceptibility $\chi(T,H) = \partial M(T,H)/\partial H$ and small diffusion constant $D \approx \hbar k_F l/3m^*$ the spin effect will dominate. According to the material parameters quoted above this is the case of n^+-$Cd_{0.99}Mn_{0.01}Te$ at $T \leq 1$ K.

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, as could their magnetic properties. We were able to quantitatively describe the weak-localization magnetoresistance. Our results demonstrate the importance of the spin-splitting-induced redistribution of the carriers between the spin subbands in quantum transport phenomena.

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