An Intermediate Phase at the Metal-Insulator Boundary in a Magnetically Doped Two-Dimensional Electron System

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A magnetotransport study in magnetically doped (Cd,Mn)Te 2D quantum wells reveals an apparent metal-insulator transition as well as an anomalous intermediate phase just on its metallic side. This phase is characterized by colossal magnetoresistance-like phenomena, which are assigned to the phase separation of the electron fluid and the associated emergence of ferromagnetic bubbles.

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Despite intensive research efforts, the apparent metal-insulator transition (MIT) in two-dimensional electron systems (2DES) remains one of the most challenging problems of condensed matter physics. Several recent theoretical studies suggest the existence of an intermediate phase near the 2D MIT, where the competition between distinct ground states results in their nanoscale phase separation. A large number of possible configurations of these local regions often have comparable energies, resulting in time-dependent phenomena such as slow relaxation, aging, and other signatures of glassy dynamics. Indeed, such manifestations of glassiness and evidence for an intermediate metallic phase have been found recently in a 2DES in Si metal-oxide-semiconductor field-effect transistors (MOSFETs). There is also growing evidence that phase separation is responsible for several striking effects in bulk transition metal oxides, such as manganites, cuprates, and similar complex magnetic materials. In that context, magnetically doped 2DES (M2DES) in semiconductor heterostructures constitute an ideal system for studying both magnetism and reduced dimensionality effects near the MIT.

M2DES in (Cd,Mn)Te quantum wells (QWs) are particularly appealing, since the 2D electron density \( n_s \) can be changed externally by an electric gate independent of the density of magnetic ions, so that interactions and the amount of disorder can be tuned separately. These M2DES have been well characterized in the studies of quantum Hall ferromagnetism and quantum Hall effect. Furthermore, (Cd,Mn)Te has a simple crystal structure and, most importantly, extensive studies have shown that the distribution of Mn ions in (Cd,Mn)Te is perfectly random, implying an absence of chemical phase separation. Thus the molecular-beam-epitaxy (MBE) grown (Cd,Mn)Te seems to be chemically and structurally the cleanest system for studying a possible electronic phase separation in a magnetic material.

Here we report a magnetotransport study of M2DES in (Cd,Mn)Te QWs, which provides the first experimental evidence of an apparent MIT in M2DES. At sufficiently high temperatures \( T \), the MIT is similar to that observed in low-mobility (high disorder) Si MOSFETs. However, when \( T \) is low enough, a qualitatively new transport regime emerges just on the metallic side of the MIT. In this intermediate phase, the resistivity \( \rho \) increases dramatically by several orders of magnitude with decreasing \( T \). A magnetic field \( B \) applied parallel to the 2D plane gives rise to an enormous negative magnetoresistance (MR), which drives the system back to metallic conductivity. This is exactly the opposite of the behavior observed in nonmagnetic 2DES near the MIT, but it resembles the phenomena found in manganites and other colossal magnetoresistance (CMR) materials. We propose that they share essentially the same origin: a nanoscale coexistence of competing phases which, in our case, corresponds to the formation of ferromagnetic (FM) metallic bubbles embedded within a carrier-poor, magnetically disordered host. This picture is further supported by the observed strongly nonlinear current-voltage (I-V) characteristics in this novel regime, where sufficiently high excitation voltages \( V_{exc} \) destroy the heterogeneous state and, hence, drive the system back to metallic conductivity.

Our MBE grown samples contain a 10 nm wide Cd\(_{1-x}\)Mn\(_{x}\)Te QW, in which the 2DES is confined by Cd\(_{0.8}\)Mg\(_{0.2}\)Te barriers. A 10 nm thick layer of the front barrier residing 20 nm away from the QW is doped with iodine donors up to \( n_f \approx 10^{18} \text{ cm}^{-3} \). In Structures A and B, Mn contents \( x \) are 0.015 and 0.005, the peak 4.2 K mobilities 3.0 and 6 \( \times 10^4 \text{ cm}^2/\text{Vs} \), 1.4 \( \leq n_s \leq 4.2 \) and 4.9 \( \leq n_s \leq 6.2 \times 10^{11} \text{ cm}^{-2} \) (controlled by a metal front gate), respectively. The experiments are performed in parallel \( B \) up to 9 T, and down to either 0.24 K in a pumped \(^3\)He system or 0.03 K in a \(^3\)He/\(^4\)He dilution refrigerator. \( \rho(B,T) \) is measured em-
FIG. 1: (color online) Resistivity as a function of $T$ for different electron densities at $B = 0$ (a) and $B = 3$ T (b). The same data as a function of $n_s$ at selected $T$ (c, d). Except for the lowest trace in (a) all the data are from Structure A.

ploying a standard low-frequency lock-in technique.

Figures 1(ab) show $\rho(T)$ of Structure A at $B = 0$ and $B = 3$ T for different $n_s$. The data were obtained with low $V_{exc} \sim 10$ $\mu$V. At elevated $T$ and high $n_s$, $\rho(T)$ is weakly metallic, i.e. $d\rho/dT \gtrsim 0$, which is seen better in the scale of Fig. 1(b). At $n_s^* \approx 2.4 \times 10^{11}$ cm$^{-2}$, $d\rho/dT$ changes sign, which is sometimes attributed to an apparent 2D MIT. In our case, this occurs at a relatively low $\rho \sim 0.2$ $h/e^2$. The 2D metallic behavior in a (Cd,Mn)Te QW is similar to that observed in n-GaAs [17] as well as in low-mobility Si MOSFETs [3], where the $\rho(T)$ dependence in the metallic phase is also weak. These are in contrast to a rather strong $\rho(T)$ found in high-mobility Si MOSFETs [18]. However, the critical density $n_c$ for the MIT obtained from the extrapolation of the hopping activation energy, as well as from the saturation of the $I$-$V$ characteristics [19] is substantially lower: $n_c \approx 1.7 \times 10^{11}$ cm$^{-2}$, corresponding to $\rho_c \sim 2h/e^2$, similar to other 2D systems. At $B = 3$ T, we find $n_s(B=3$ T$) = 2.1 \times 10^{11}$ cm$^{-2}$, indicating that, for high enough $T$, $B$ shifts the system towards an insulating phase just as in standard non-magnetic materials.

However, below some $T^*(n_s)$, a dramatic upturn of $\rho(T)$ by almost three orders of magnitude is observed for moderate $n_s$ at $B = 0$ [Fig. 1(a)]. Here, $\rho(T)$ increases down to $T_C \approx 0.3$ K, goes through a maximum, and either continues to grow or decreases as $T$ is lowered. Around $T_C$, a strong resistance noise is observed (not shown), while below $T \lesssim T_C$, $\rho$ becomes hysteretic with respect to both $T$ and $B$. Moreover, in the range of $T_C < T < T^*$, $\rho(T)$ for a wide range of densities $1.6 \lesssim n_s \lesssim 3.5 \times 10^{11}$ cm$^{-2}$ collapse onto almost the same curve. This striking behavior is further highlighted in Fig. 1(c), which shows clearly that $\rho$ does not depend on $n_s$ at a fixed $T$. Importantly, these densities $n_s \gtrsim n_c = 1.7 \times 10^{11}$ cm$^{-2}$, i.e. they belong to the metallic side of the MIT. The same dramatic upturn of $\rho$, as well as a lack of $\rho(n_s)$ dependence, are also clearly seen at $B = 3$ T [Figs. 1(bd)] at a slightly lower $T^*$ and a narrower range of densities $2.1 \lesssim n_s \lesssim 3.0 \times 10^{11}$ cm$^{-2}$. Again, these $n_s \gtrsim n_c(B = 3$ T$) = 2.1 \times 10^{11}$ cm$^{-2}$.

Figure 2 depicts the MR of our devices. At high $T$, and at low $T$ for either high or low $n_s$, a relatively weak positive MR is visible. In the weakly localized regime, where $k_F \ell > 1$ ($k_F$ - Fermi wave vector, $\ell$ - mean free path), this positive MR is ubiquitous in diluted magnetic semiconductors (DMS), such as (Cd,Mn)Te, in the paramagnetic phase [21, 22, 23]. It originates from
the giant spin-splitting $\Delta_s$ of the electron states, which considerably affects quantum corrections to the conductivity brought about by the effect of disorder modified electron-electron interactions [24]. The same mechanism is believed to be responsible for positive MR in Si MOSFETs [25] and other nonmagnetic 2DES, in which $\Delta_s$ is appropriately large. Since in DMS $\Delta_s$ is proportional to the magnetization $M$ of the Mn spins, this positive MR scales with $B$ and $T$ like the Brillouin function $B_{3/2}/|T + T_{AF}|$ [15]. Here $T_{AF}$($x$) > 0 describes a reduction of $M$ by intrinsic antiferromagnetic (AF) couplings between the Mn ions, and its value is well known from extensive magnetooptical and magnetic studies in (Cd,Mn)Te layers [13]. In particular, $T_{AF} = 0.5$ K for $x = 0.015$. Figure 2(c) shows the results of the MR calculations carried out according to this model [21, 21, 22] and without any fitting parameters, together with the experimental results for Structure B in which $kp\ell \gg 1$, so that the theory should apply quantitatively. Indeed, there is a good agreement between measured and calculated positive MR at low $B$.

However, the overall MR is dominated by a strong negative component. Importantly, this CMR shows up exclusively in the range of $T$ and $n_s$, where the lowering of $T$ results in a strong increase of $\rho(T)$. The effect is not observed on the insulating side of the MIT, where localization is driven by non-magnetic disorder and visible already at high $T$. A sizable negative MR shows up only if magnetic effects lead to $T$-dependent localization, so that $B$ can drive the system back to the metallic phase. Remarkably, this negative MR does not scale with $M(T, B)$; a relatively weak field is sufficient to destroy the magnetism-related localization. As a result, a colossal negative MR is observed.

Similar effects, in particular, a dramatic upturn of $\rho(T)$ and the associated negative MR, have been observed in bulk DMS [20, 22, 24] below a characteristic temperature $T^*$ ($T^* \approx 1.5$ - 2.0 K in n-Cd$_{1-x}$Mn$_x$Te [24]). They were attributed [20, 24] to the formation of bound magnetic polarons (BMP), even though the region where those effects are observed spreads from the vicinity of the MIT deep into the metallic phase, in remarkable analogy to the 2D system. In addition, in a modulation-doped n-(Cd,Mn)/Te QW, Mn are neutral, while the ionized donors are far from the conducting channel, so that the BMP effects are expected to be virtually absent or, at least, considerably less important than in 3D. On the other hand, the tendency towards phase separation should be more pronounced in 2D than in 3D [28]. We propose, therefore, that similarly to the case of manganites [3], the novel intermediate phase in M2DES contains bubbles of different electronic phases, which account for the CMR-like behavior.

In order to identify the nature of the phases in question, we note that, according to the Zener theory of carrier-mediated FM, a ferromagnetic transition is expected to occur at low $T$ in bulk zinc-blende DMS [29], such as (Cd,Mn)Te. Recent Monte Carlo simulations [30-31] indicate a formation of isolated ferromagnetic bubbles and the CMR-like behavior at $T^* \gg T_C$ ($T_C$ – Curie temperature) even in the absence of attractive impurity potentials, provided that AF couplings are strong enough. At $B = 0$, the FM bubbles are oriented randomly, which diminishes percolation and thus enhances resistance. Since the magnetic field aligns the bubbles, a strong negative MR follows. These effects are expected to exist in both 3D and 2D cases but should be stronger in 2D, in agreement with our results. The lack of $\rho(n_s)$ dependence in the intermediate phase [Fig. 1(c)], where magnetic effects take control over charge transport, is also consistent with the Zener theory of ferromagnetism [29, 32], which predicts that FM ordering temperature depends merely on the carrier density of states (DOS) and magnetic susceptibility of the Mn ions. However, DOS does not depend on $n_s$ in 2D, resulting in this striking behavior. At the lowest $n_s$, where carriers become localized, the local FM order is destroyed, and the intrinsic AF interactions between the Mn ions dominate [32].

In general, a heterogeneous state may be expected to exhibit glassy behavior and nonlinearities [10]. Indeed, signs of glassiness, such as $\rho$ noise and hysteretic behavior [Fig. 1(a)] are present in our system. We have established that the $I$-$V$ characteristics are strongly nonlinear [Fig. 3(a)]. In particular, while the Ohmic regime is observed for all values of $n_s$ for $V_{exc}$ below $\approx 10$ $\mu$V, a strong nonlinear behavior is clearly seen for higher $V_{exc}$. For low $n_s$, the nonlinear characteristics obeys $I \propto V^2$, but in the intermediate, heterogeneous state, a much steeper dependence is first observed, which is then followed by $I \propto V^{0.7}$. This striking behavior resembles depinning of colloids [32], Wigner glass to liquid transitions modeled for disordered 2DES [34], as well as Wigner crystal depinning in quantum Hall systems [35]. In particular, the exponents 2 and 0.7 were found [33] in the $I$-$V$ characteristics of colloidal dynamics and correspond to plastic and elastic depinning, respectively. It is also possible that the observed nonlinearity stems from the current-induced rotation of FM domains, though the
FIG. 4: (color online) Different transport regimes in the $n_s$–$T$ plane determined from the measurements in Structure A. FM ordering is expected in the metallic phase at low enough $T$ based on the studies of 2D p-(Cd,Mn)Te QW [32, 37] and 3D p-(Zn,Mn)Te [24, 38], although other states might be possible. For $n_s < n_c$, we expect AF correlations to dominate.

current density used here is 3 orders of magnitude lower than that employed for domain rotation in (Ga,Mn)As. A sufficiently high $V_{exc}$ destroys the heterogeneous state and drives the system back to metallicity, as expected: for $V_{exc} > 100 \mu V \gtrsim T^*$, the metallic behavior ($d\rho/dT > 0$) is clearly seen down to the lowest $T$ for $n_s \gtrsim 2.2 \times 10^{11} \text{cm}^{-2}$ [Fig. 3(b)].

The different transport regimes observed in our M2DES are shown in Fig. 4. We note that, even if the BMP model could apply for $n_s < n_1 < n_2^*$, one would expect a decrease of $T^*$ with the increasing $n_s$, resulting from a dramatic increase or a divergence of the localization length as $n_s \rightarrow n_1^*$. This is exactly the opposite of what is observed in the experiment. On the other hand, it is expected in general [1] that a heterogenous state may exist in the metallic phase just above the MIT: as the density of carriers $n_s$ and their Fermi energy $E_F$ are reduced, any tendency towards magnetic ordering will be revealed just prior to the MIT. Since FM correlations are mediated by mobile carriers, the local magnetic ordering and the heterogeneous phase will disappear as the number of mobile carriers is further reduced to zero as $n_s \rightarrow n_c$ from above, in agreement with our results. In contrast, BMPs are most stable within the localized phase. It is interesting that the phase diagram (Fig. 4) reveals a striking qualitative similarity to that proposed for CMR materials [3], cuprates [39] and, in general, for model systems that form heterogeneous phases [40].

In summary, we have observed the emergence of an anomalous intermediate phase exhibiting CMR-like phenomena in a M2DES just on the metallic side of the MIT. We attribute our findings to the competition between AF exchange characterizing the insulating phase and the FM correlations induced by itinerant electrons, resulting in the formation of FM metallic bubbles embedded within a carrier-poor, magnetically disordered matrix. Similarities to other systems, including nonmagnetic 2DES

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