Metal-Insulator Transition in Semimagnetic Semiconductors

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A rare insulator-to-metal transition on increasing magnetic field has been observed in *n*-$Cd_{0.95}Mn_{0.05}Se$ and *p*-$Hg_{0.915}Mn_{0.085}Te$. The two systems belong to a new universality class due to a giant spin-splitting effect. The transition is shown to be driven by the electron-electron interactions and the newly predicted critical behavior of the conductivity is confirmed.

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Recent works on electron transport in the vicinity of the Anderson-Mott transition[1-3] come up with differing conclusions on whether the scaling hypothesis of Abrahams *et al.*,[4] with the effects of electron-electron interactions taken into account, is actually valid[5-8] in real systems or not.[9] In any case it becomes clear that the transition is quite sensitive to details of electronic properties of the material.[1-9] Thus in order to tell a particular universality class, it is essential to study systems in which all relevant interactions are well understood. Here we report on the studies of the metal-insulator transition (MIT) in two semimagnetic semiconductors,[10] *n*-$Cd_{0.95}Mn_{0.05}Se$ and *p*-$Hg_{0.915}Mn_{0.085}Te$. There are several reasons that make these materials interesting for the physics of MIT. First, a transition from the *insulating to metallic* phase takes place on *increasing* magnetic field. This seems to be a unique property of semiconductors which contain magnetic ions.[2] Second, results of magnetic,[11,12] transport,[13-15] and spectroscopic[11,16] studies of CdMnSe and HgMnTe are accurate enough to conclude that (i) the novel features of the MIT arise from a giant exchange spin splitting and (ii) the corresponding universality class is of a new type. In this universality class the transition is driven by disorder-modified electron-electron interactions. Thus our results provide an experimental test of the theory which has been proposed by Finkelstein,[6] and then by Castellani *et al.*[7] Finally, we note that the magnetic field makes the valence band of HgMnTe markedly anisotropic. This then allows us to compare our results with the theory of Wölfle and co-workers[8] on the MIT in anisotropic systems.

Figure 1 presents electrical conductivities (inverse resistivities) measured in various magnetic fields H as a function of the temperature T down to 40 mK. The *n*-$Cd_{0.95}Mn_{0.05}Se$ sample has a net In-donor concentration, $N_D - N_A$, of 4×10^{17} cm^{-3} and the *p*-$Hg_{0.915}Mn_{0.085}Te$ sample contains 2×10^{17} excessive acceptors per cubic centimeter. In the case of *p*-

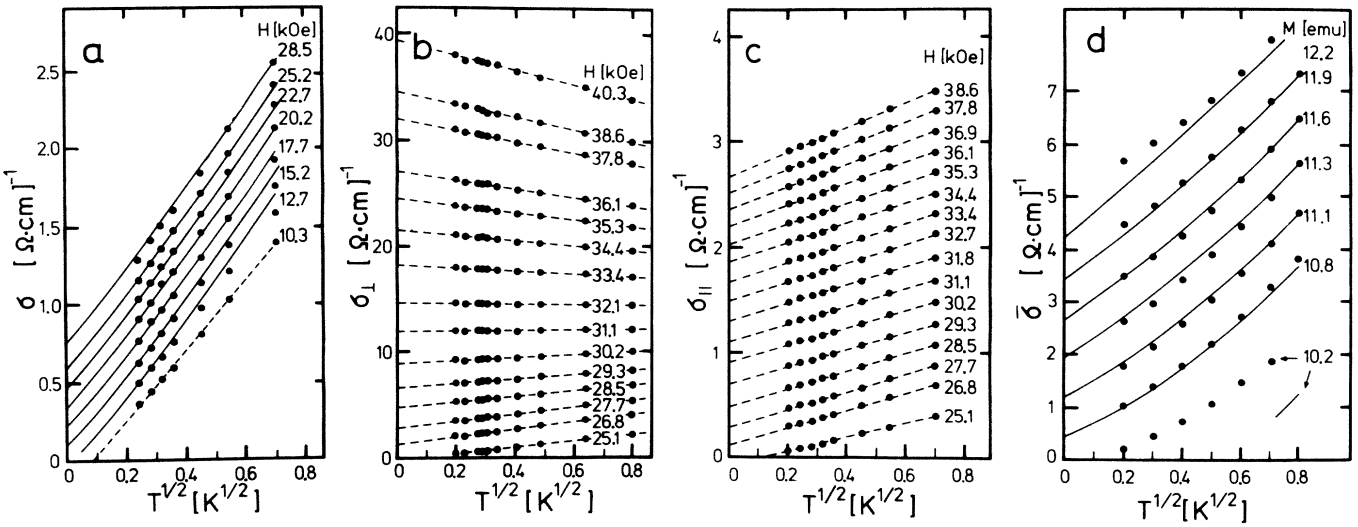

FIG. 1. Inverse resistivity σ of (a) *n*-$Cd_{0.95}Mn_{0.05}Se$ and (b)–(d) *p*-$Hg_{0.915}Mn_{0.085}Te$ vs square root of the temperature for various magnetic fields and magnetizations. The fitted solid lines obey Eq. (1); dashed lines are fits by the formula $\sigma(T,H)=\sigma(0,H)+A(H)T^{1/2}$. The Mott minimum conductivity is about 7 $(\Omega\ \mathrm{cm})^{-1}$

HgMnTe the measurements were performed for the current either perpendicular or parallel to the magnetic field, whereas in the case of n-CdMnSe only the transverse configuration has been used since the magnetoresistance of n-CdMnSe had been established[13] to be isotropic. In both systems the conductivity σ is observed to increase with the magnetic field. In order to distinguish a metal from an insulator we extrapolate the $\sigma(T,H)$ curves to their $T=0$ values. Above a critical field H_c, $\sigma(0,H)$ is finite which indicates metallic behavior. In the metallic phase the conductivity can be described by $\sigma(T,H)=\sigma(0,H)+A(H)T^{1/2}$. The $\sigma(0,H)$ value increases essentially linearly with $H-H_c$. A linear dependence of σ on $H-H_c$ and on $T^{1/2}$ for $H \geqslant H_c$ in magnetic systems has already been observed by von Molnar *et al.*[2] who studied $Gd_{3-x}v_xS_4$.

The transition on which we report here must result from the presence of s-d-like exchange interactions since the nonmagnetic semiconductors may undergo merely a metal-to-insulator transition when a strong magnetic field is applied (as a result of shrinking of the wave functions). There are two principal effects in magnetic systems which can cause the insulator-to-metal transition by an increase of the magnetic field. The first effect is the destruction of magnetic polarons[2,13,17] resulting in an *expansion* of the impurity wave functions in the magnetic field. This may cause a continuous insulator-to-metal transition as observed in $Gd_{3-x}v_xS_4$.[2] However, a possibility of a discontinuous transition triggered by a polaron destruction has also been considered theoretically.[18] The second effect is the occurrence of a giant spin splitting $\hbar\omega_s$ due to the exchange interactions. In the mean-field approximation,[10-17,19] $\hbar\omega_s$ is proportional to the magnetization of the Mn spins. This magnetization can be described by the Brillouin function which is phenomenologically modified so that it takes the Mn-Mn antiferromagnetic interactions into account.[11,12] The splitting causes a redistribution of carriers between the spin subbands and pushes the Fermi level up, as shown schematically in Fig. 2. In the materials studied here the distance between the Fermi energy ϵ_F and the bottom of the spin-down subband is, for $H \gtrsim H_c$, about twice the distance to the bottom of the spin-up subband. This means that the bare diffusion coefficients at ϵ_F should be substantially different for these two subbands. Therefore, following Fukuyama and Yoshida[20] and Shapira *et al.*,[14] we assume that for $H \geqslant H_c$ the conductivity of the majority (spin-down) carriers scales with the size of the system to the metal, whereas that of the minority scales to the insulator. The localization of the minority carriers implies, in turn, the presence of a Coulomb gap[6,7] in their density of states (see Fig. 2). Presumably, the Coulomb gap makes the resonant spin-flip scattering (tunneling) between the

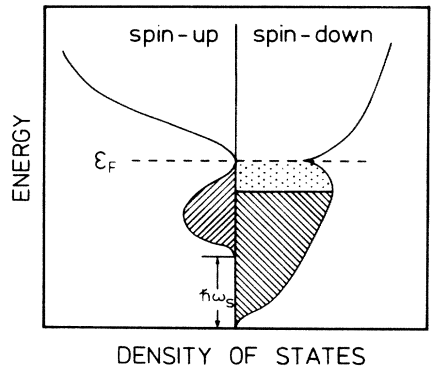

FIG. 2. Schematic picture of the density of states in semimagnetic semiconductors above the insulator-to-metal transition. The dotted region marks delocalized states. The Coulomb anomaly at ϵ_F is weak for delocalized spin-down electrons but strong for localized spin-up electrons.

subbands of minor importance and allows us to consider the subbands as being decoupled. The arguments above suggest that the nature of the MIT is entirely determined by electrons which reside in the one spin-polarized subband. Electrons in the second subband produce only an additional static random potential and serve as an electron reservoir which is depleted when $\hbar\omega_s$ increases. As discussed in details by Gaj, Ginter, and Gałazka,[17] the exchange splitting leaves the conduction band isotropic. In contrast, in the presence of the exchange splitting, the four subbands of the Γ_8 valence band become strongly anisotropic and nonparabolic.[19] In particular, the uppermost subband has the effective mass along the magnetic field, $m_{\parallel}$, equal to the heavy-hole mass $m_{hh} \simeq 0.5\ m_0$. On the other hand, the transverse mass $m_{\perp}$ depends strongly on $\hbar\omega_s$ and on the wave vector $k_{\perp}$. For small splittings, i.e., when $\hbar\omega_s \ll \hbar^2 k_{\perp}^2/2m_{hh}$, we have $m_{\perp}=m_{hh}$ whereas in the opposite limit $m_{\perp}=4m_{lh}/3$, where $m_{lh} \simeq 0.005 m_0$ is the light-hole mass. The ratio $m_{\parallel}/m_{\perp}(\epsilon_F)$ is estimated to be of the order of 10 when $H=H_c$ and $N_A-N_D=2\times10^{17}$ cm^{-3}. We estimate also that for $H \gtrsim H_c$ only the two uppermost subbands are occupied by holes.[21]

Having specified conditions under which the MIT occurs, we return to the description of the experimental results. By fitting $T=0$ conductivities with the formula $\sigma(0,H)=\sigma_c(H/H_c-1)^{\nu}$, we obtained σ_c, H_c, and ν as given in Table I.

Two important conclusions emerge from studying this table. First, in the strongly anisotropic p-HgMnTe with $\sigma_{c\perp}/\sigma_{c\parallel}$ as large as 14 we found the same values for the critical field H_c and the critical exponent ν in the transverse and longitudinal configurations (a small difference in $\nu_{\perp}$ and $\nu_{\parallel}$ results from a H dependence of the anisotropy). These findings confirm, for the first time, the theoretical predictions of Wölfle and co-workers[8] concerning the critical behavior of con-

TABLE I. Parameters obtained from fits of the extrapolated $T=0$ conductivities by the formula $\sigma(H)=\sigma_c(H/H_c-1)^{\nu}$ in n-$Cd_{0.95}Mn_{0.05}Se$ (σ) and in p-$Hg_{0.915}Mn_{0.085}Te$ [$\sigma_\perp, \sigma_\parallel, \bar{\sigma}\equiv(\sigma_\perp^2\sigma_\parallel)^{1/3}$] in the magnetic field ranges $(1.05-1.8)H_c$ in CdMnSe and $(1.05-1.5)H_c$ in HgMnTe. The parameters obtained from the description of $\sigma(T,H)$ are close to those displayed below and are given in the main text.

	σ_c [$(\Omega$ cm$)^{-1}$]	H_c (kOe)	ν
σ	0.70 ± 0.1	15.3 ± 0.3	$0.85^{+0.3}_{-0.1}$
$\sigma_\perp$	81.7 ± 2	26.6 ± 0.1	$1.08^{+0.15}_{-0.05}$
$\sigma_\parallel$	5.85 ± 0.2	26.6 ± 0.1	$0.94^{+0.15}_{-0.05}$
$\bar{\sigma}$	33.9 ± 1	26.6 ± 0.1	$1.04^{+0.15}_{-0.05}$
$\sigma_\perp$ [a]	24.9 ± 1	27.5 ± 0.1	$1.05^{+0.15}_{-0.05}$

[a]Sample with $N_A-N_D=9\times10^{16}$ cm^{-3}, not shown in Fig. 1.

ductivity in anisotropic systems. Second, our determination of ν was performed in weak magnetic fields, in the sense that the magnetic length $L_H=(c\hbar/eH)^{1/2}$ was much larger than the mean free path, but in strong fields from the point of view of the condition $L_H<L_\phi$, where L_ϕ is a phase-breaking length.[22] The renormalization-group theories of the MIT in a system of noninteracting electrons in a random potential predict[5] $\nu=\frac{1}{2}$ in such circumstances. We conclude that these theories are unable to describe the critical behavior of conductivity we have observed. Turning to the theories which do take the Coulomb interactions among electrons into account,[6] we note that the case of carriers in one spin subband has not been so far considered in the literature. Finkelstein,[23] prompted by our experimental results, derived the renormalization-group equation (RGE) for the situation under consideration. To the lowest order in G^{-1} and ϵ, where G is the dimensionless conductance and $2+\epsilon$ is the space dimensionality, he has obtained (we use notations of Ref. 6) $\beta\equiv d\ln G/d\ln L=\epsilon-1/G$ and $d\ln z/d\ln L=-1/2G$, where z is the temperature renormalization factor.[6,7] These equations differ by factors of 2 from those derived for the case of a spin-degenerate band and strong spin-disorder scattering.[6,7] It is seen that the critical index ν is expected to be 1 in accord with the results of our measurements. This agreement may indicate that higher-order terms in the β function are of minor numerical importance as long as $G\gtrsim G^*=1/\epsilon+O(\epsilon^2)$.

An important aspect of the theories which take the interactions into account[6,7] is that they provide a background for a description of the temperature dependence of the conductivity. By integrating the RGE and using the relation between the length and the temperature scales,[6,7] one obtains σ at criticality to be given as a solution of the following equation:

$$\sigma(T,y)=\sigma_c(y/y_c-1)+BT^{1/2}[\sigma(T,y)]^{\gamma}. \quad (1)$$

Here y is a parameter that controls the disorder and $\gamma=-\frac{1}{2}+1/4G^*$ is a universal critical exponent. The prefactor B, up to a constant of the order of 1, is given by

$$B=8\pi\sigma_N^{3/2}G^*(2k_BN_1)^{1/2}(8\sigma_NG^*/l)^{-1/4G^*},$$

where $\sigma_N=e^2/2\pi^2\hbar$ and N_l is the thermodynamic density of states at ϵ_F for the spin-down subband. The parameter l (assumed here to be T independent) denotes the length at which the RGE begin to be valid. We fitted Eq. (1) to the experimental results on CdMnSe with $y\equiv H$ and treating σ_c, H_c, γ, and B as adjustable parameters. This fitting procedure gives $\sigma_c=0.66\pm0.1$ $(\Omega$ cm$)^{-1}$ and $H_c=13.3^{+3}_{-1.5}$ kOe. From γ and B we get $G^*=0.41^{+0.2}_{-0.1}$ and $l=66\pm20$ Å which corresponds to $k_Fl=1.8\pm0.6$.

The above description of $\sigma(T)$ has neglected the fact that H_c may vary with T because of the T dependence of the magnetization. In the case of CdMnSe the corresponding corrections to $\sigma(T)$ are expected to be of minor importance as a result of the small value of σ_c in this material [see Table I and Eq. (1)]. However, in the case of p-HgMnTe, σ_c is large, so that we have to use the magnetization $M(T,H)$ as a parameter that controls the disorder. We approximate $M(T,H)$ by the modified Brillouin function[11,12] with the parameters $\bar{x}=0.037$ and $T_0=9.1$ K, as determined at 1.7 K.[12] We analyze $\bar{\sigma}(T)=[\sigma_\perp^2(T)\sigma_\parallel(T)]^{1/3}$ since $\bar{\sigma}$ is the appropriate scaling variable in the anisotropic case.[8] By fitting Eq. (1) with $y\equiv M$ to the results of Fig. 1(d) we obtained $\sigma_c=30\pm3$ $(\Omega$ cm$)^{-1}$, $M_c=10.6\pm1$ emu, $G^*=0.34^{+0.3}_{-0.1}$, and for $N_1=2\times10^{16}$ cm^{-3} cm^{-3} meV^{-1}, $l=230\pm20$ Å.

As shown in Figs. 1(a) and 1(d), Eq. (1) describes experimental results on the metallic side correctly. Furthermore, the parameter l has expected magnitudes. These facts provide experimental support for the current theory[6,7] of the MIT. Moreover, they substantiate our assignment of a new universality class for systems with a large spin splitting, $\hbar\omega_s\sim\epsilon_F$. Indeed, the RGE derived[6,7] for $\hbar\omega_s\gg k_BT$ but, implicitly, also for $\hbar\omega_s\ll\epsilon_F$ ("magnetic field" case in terms of Refs. 6,7) predict a dependence of σ on T which is in *disagreement* with our data as well as with those for $Gd_{3-x}v_xS_4$.[2] Finally, the results above convince us to attach significance to the value of G^* set at $0.4^{+0.2}_{-0.1}$. It will be very interesting to know if higher-order terms in the formula $G^*=1/\epsilon+O(\epsilon^2)$ would reduce G^* towards the experimental value.

In conclusion, we have observed the continuous insulator-to-metal transition in two semimagnetic semiconductors. Under our experimental conditions the coherence of backscattering and the electron-electron interactions in the Cooperon channel are suppressed by the magnetic field. The transitions are thus driven by the interactions in the diffusion chan-

nel. We have presented arguments which suggest that the transitions occur only in one spin-polarized subband. The RGE for this new universality class are found to be successful in describing the conductivity at criticality as a function of the disorder, temperature, and anisotropy.

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