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Magnetotransport near the metal-insulator transition in $Cd_{0.6}Mn_{0.4}Se$

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A $T^{-1/2}$ dependence of the log of the resistivity on temperature has been observed for $Cd_{0.6}Mn_{0.4}Se$ in the insulating phase near the metal-insulator transition. The results are consistent with the theory of Efros and Shklovskii for variable range hopping modified by the electron-electron interaction. Estimates for the Thomas-Fermi screening length derived from these data are found to increase with magnetic field.

We present here new aspects of the behavior of an n-type diluted magnetic semiconductor $Cd_{1-x}Mn_xSe$ near the metal-insulator (MI) transition. Previous experiments on $Cd_{1-x}Mn_xSe$ with $x=0.01$ and $x=0.05$ showed a large positive magnetoresistance for samples with the electron concentration near the Mott critical concentration $n_c=(0.25/a_B)^3$, where a_B is the effective Bohr radius.[1] This effect was attributed to an enhancement of potential fluctuations caused by an increase in the screening radius, due to splitting of the conduction band in a magnetic field. Our results, in combination with the theory of Efros and Shklovskii,[2] provide an experimental estimate of this effect through measurements of the temperature dependence of the resistivity at different magnetic field strengths and measurements of magnetocapacitance. We find in insulating samples a dependence of the conductivity σ on temperature T of the form $\sigma\propto\exp[-(T_0/T)^{1/2}]$, a result which has been observed in many materials including Ge,[2] and the magnetic semiconductor $Gd_{3-x}v_xS_4$, where v denotes vacancy.[3] Our analysis of the present data is consistent with the model of Efros and Shklovskii,[4] which implies the existence of a soft gap in the density of states at the Fermi level, originating from long-range Coulomb interactions between the localized carriers.[4] Thus, our results show that electron-interaction effects play a significant role in the insulating phase of this disordered system. The transport properties of the samples with the carrier concentration very close to the MI transition arise from several competing mechanisms, including Mott variable range hopping and band conduction above the mobility edge E_c and, thus, cannot be interpreted by the simple analysis applied to less conducting material.

The present investigation was carried out on several n-type Ga-doped single crystals of $Cd_{0.6}Mn_{0.4}Se$ with room-temperature electron concentration between 5×10^{17} and 1.5×10^{18} cm^{-3}. The resistivity and the Hall effect were measured using an ac van der Pauw technique.[5] Ohmic contacts were prepared by ultrasonic soldering of Cu leads with indium to the samples. The electrical measurements were performed in the temperature range 0.3–20 K and in magnetic fields H up to 80 kOe. Magnetization data were taken at 4.5 K. To measure the ac complex conductance we prepared a blocking contact on one of the parallel cleaved surfaces of a single-crystal sample, forming a capacitor with area 3.3 mm^2 and a thickness of 1.2 mm. The complex conductance was measured with a capacitance bridge, using small excitation voltages ($V<2$ meV) and a frequency of 10 kHz.

The low-temperature transverse magnetoresistance for two samples is shown in Figs. 1 and 2. The first of these samples (I) is more insulating: $n(4.2\ \mathrm{K})=3.1\times10^{17}$

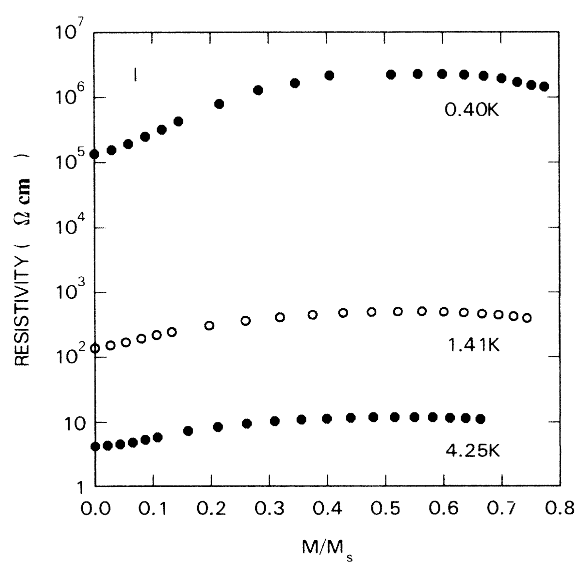

FIG. 1. Transverse magnetoresistance for sample I with $n(300\ \mathrm{K})=5.9\times10^{17}$ cm^{-3} as a function of normalized magnetization.

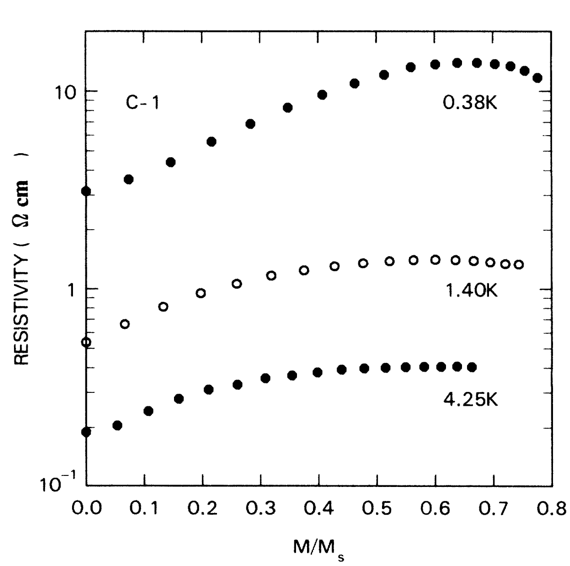

FIG. 2. Transverse magnetoresistance for sample C-1 with $n(300\ \mathrm{K})=1.43\times10^{18}$ cm^{-3} as a function of normalized magnetization.

$cm^{-3} = 0.52n(300\ K)$ with a Hall mobility at 4.2 K of 5 $cm^2/V\,sec$. The second sample (C-1) has $n(4.2\ K) = 9.7\times10^{17}\ cm^{-3} = 0.8n(300\ K)$ and a mobility of $\simeq 40\ cm^2/V\,sec$, which indicates that an appreciable number of electrons are above the mobility edge at low temperatures. We have plotted resistance as a function of the reduced magnetization M/M_s, where M_s is the saturation value defined below. The magnetic-field-dependent magnetization is the most important physical parameter describing the influence of the magnetic field on the band structure of diluted magnetic semiconductors and, therefore, on its electronic properties. This is due to the extremely strong exchange interaction between the localized moments of the Mn^{+2} ions and the spins of the carriers. M_s is a fitting parameter in the expression $M = M_s B_{5/2}(H/T_{\text{eff}})$, where $B_{5/2}$ is the Brillouin function for spin value $S=\frac{5}{2}$ and $T_{\text{eff}} = T + T_A$. T_A is another fitting parameter which reflects antiferromagnetic interactions between manganese ions. This approximate formula describes the magnetization in dilute magnetic semiconductors, if it is assumed that the magnetization of the samples comes entirely from Mn^{+2} ions, which interact antiferromagnetically.[6] We find, for $Cd_{0.6}Mn_{0.4}Se$, $T_A \simeq 10.3$ K and $M_s \simeq 0.205$ in units of the Bohr magneton. The results of magnetoresistance for both samples are qualitatively similar. A large positive magnetoresistance is observed at low fields ($H < 50$ kOe) followed by a slight negative magnetoresistance at highest fields. We do observe a field-dependent hysteresis in the magnetotransport, which we recognize to be due to the fact that the material containing 40% manganese ($x = 0.4$) undergoes a spin-glass transition at $\simeq 12$ K. However, even in the most insulating sample, where this effect is most pronounced, the hysteresis accounts for only a 5% change of resistivity and does not affect the physical arguments which we present below. To be consistent, all of the data presented here are for a zero-field cooled sample.

The log of the resistivity ρ as a function of the square root of the inverse temperature at several magnetic fields is shown for the lowest doped sample (I) in Fig. 3. In the temperature range between 0.3 and 20 K the resistivity of all samples in this concentration range [$n \sim (5\text{–}6)\times10^{17}\ cm^{-3}$] obeys a $\rho \propto \exp(T/T_0)^{1/2}$ law. Such a relation is found within the variable range hopping model, in which the Coulomb interaction between localized carriers is included.[4] Efros and Shklovskii[4] have shown that electron-electron interactions, because of their long-range nature in the insulating phase, give rise to a soft gap where the density of states $N(E)$ goes continuously to zero at the Fermi level E_F. At low temperatures this leads to deviations from Mott's $T^{-1/4}$ law, which assumes a flat density of states. Within this model the coefficient T_0 is given by $T_0 = 2.8e^2/k_B\epsilon\xi$, where k_B is Boltzmann's constant, e is the electron charge, ϵ is the dielectric constant, which includes both the lattice as well as donor-state contributions, and ξ is a localization length. The width of the gap is of order $\Delta \propto N(E_F)^{1/2}e^3/\epsilon^{3/2} \simeq 30$ K in the present case. This estimate is derived using a parabolic conduction band with effective mass $\simeq 0.2m_0$ (Ref. 7) and measured $\epsilon \simeq 37$. Since Δ is much greater than any reasonable estimate for the energy responsible for hopping conductivity, the states within the Coulomb gap are particularly important in transport and, as a consequence, the $T^{-1/2}$ law is observed. Using the measured T_0 and ϵ we obtain ξ in the range 400–500 Å.

The results for a more highly (C-2) doped sample, in which the low-temperature carrier concentration is very close to the critical Mott concentration, are shown in Fig. 4. In this case no clear $T^{-1/2}$ law is observed. We estimate the width of the quasigap Δ for this sample to be less than 5% of the value of Δ for the more insulating samples. This is due to the divergence of the dielectric constant near the MI transition, predicted by scaling theory[8,9] and observed experimentally.[10,11] The influence of the Coulomb gap on conduction, consequently, is much less important under these circumstances, since $\Delta \approx 1\text{–}2\ K \ll k_BT$ over most of the

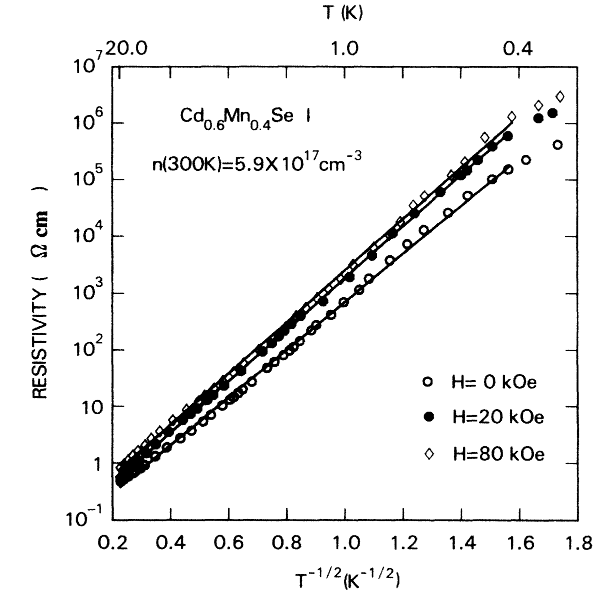

FIG. 3. Transverse magnetoresistance for $Cd_{0.6}Mn_{0.4}Se$ (I) as a function of the square root of inverse temperature at magnetic field $H = 0$, 20, and 80 kOe.

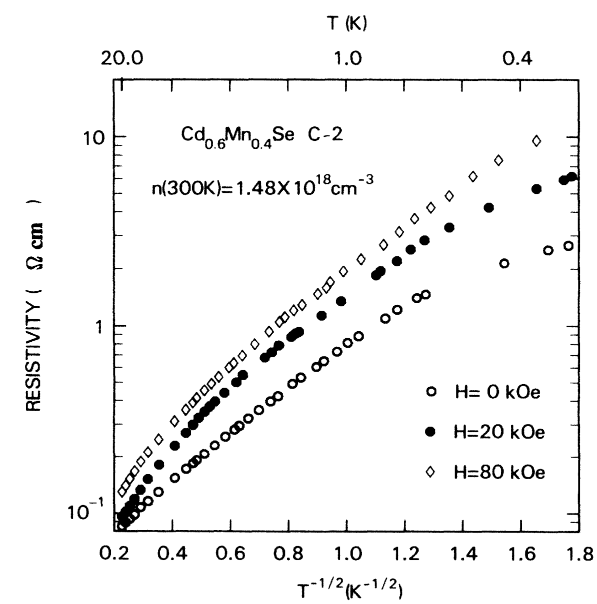

FIG. 4. Transverse magnetoresistance for $Cd_{0.6}Mn_{0.4}Se$ (C-2) as a function of the square root of inverse temperature at magnetic field $H = 0$, 20, and 80 kOe.

experimentally investigated range. In fact, the temperature dependence of the resistivity approaches $T^{-1/4}$ at 80 kOe, and a localization length derived from the coefficient T_0 using Mott's formula[12] yields ~ 120 Å. We hesitate, however, to place much significance on this result, since the data only span a factor of 2 in $T^{-1/4}$. Also, contributions from extended states above the mobility edge to the conductivity must be considered. The presence of several competing effects on transport requires complicated analysis which, at the present, we do not pursue.

Shapira *et al.*[1] proposed that the positive magnetoresistance observed in $Cd_{1-x}Mn_xSe$ may be explained by an increase in the Thomas-Fermi radius λ_{TF} with increased magnetic field. This effect is presumed to result from a decrease in the density of states at the Fermi level when the applied magnetic field splits the conduction band. Our measurements of the temperature-dependent resistivity in the two more-insulating materials, combined with measurements of magnetocapacitance performed on the same samples, permit us to estimate $\lambda_{TF}(H)$ quantitatively, independently of this model. The dependence of the normalized capacitance C/C_0, where C_0 is the capacitance at $H=0$, of one of the samples (I) on magnetization is shown in Fig. 5 for 0.37 and 1.42 K. These data give us the variation of the total dielectric function with magnetic field. We may separate the total dielectric function ϵ into a background part, ϵ_0, which contains contributions from the lattice and all interband excitations, and an intraband part, ϵ_i, that is $\epsilon=\epsilon_0+\epsilon_i$. The static dielectric function in the Thomas-Fermi approximation is therefore $\epsilon(q)=\epsilon_0(q)+1/\lambda_{TF}^2q^2$. In the insulating regime the dielectric function goes to a constant, as $1/q^2$ is cut off by ξ^2 (ξ is the localization length) and $\epsilon(q\rightarrow 0)=\epsilon_0+(\xi/\lambda_{TF})^2$. This relation, combined with the expression for T_0, yields an expression for the Thomas-Fermi screening length, which depends only on the measurable quantities T_0 and ϵ, that is $\lambda_{TF}=2.8e^2(k_BT_0)^{-1}\times(\epsilon-\epsilon_0)^{-1/2}\epsilon^{-1}$. For the sample I, $T_0(H=0)=94.5$ K, $T_0(H=50\text{ kOe})=109$ K, $\epsilon(H=0)=37$, and $\epsilon(H=50\text{ kOe})=27$. Assuming a value of $\epsilon_0=9$, measured in pure CdSe, we obtain a 55% increase in λ_{TF} in a field of 50 kOe.

The change in screening radius may also be calculated independently from the change in the density of states, as proposed by Shapira *et al.*,[1] since $\lambda_{TF}^{-2}=4\pi e^2N(E_F)$. In a field of 50 kOe the minority-spin subband is almost completely depopulated—the band splitting of 20 meV is much larger than the Fermi energy ($E_F\simeq 13$ meV). Assuming a parabolic conduction band and degenerate statistics we obtain a 25% increase in the screening length with magnetic field. Although this estimate of the change in λ_{TF} gives the proper sign, its magnitude is much smaller than the experimentally derived value. This calculation, of course, is an oversimplification for several reasons. The use of a parabolic band approximation ignores band tails. Furthermore, changes in E_F with H, which account for Fukuyama's negative magnetoresistance,[13] have not been included. These corrections tend, however, to increase the discrepancy and lead us to the conclusion that some other mechanisms are also important in the positive magnetoresistance observed in $Cd_{1-x}Mn_xSe$.

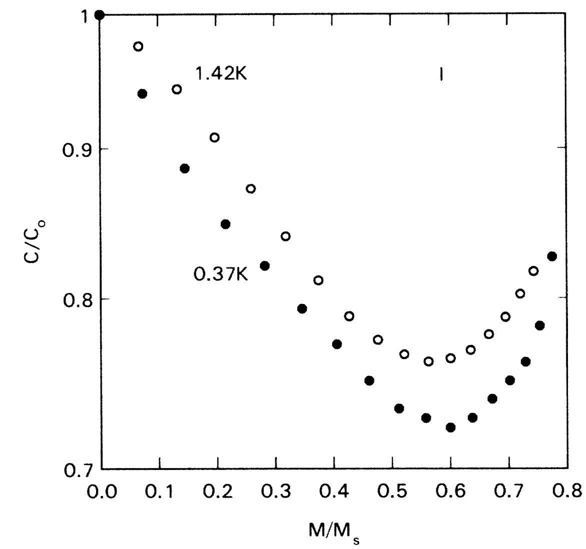

FIG. 5. Normalized capacitance for sample I vs normalized magnetization.

In conclusion, we have measured the resistivity of $Cd_{0.6}Mn_{0.4}Se$ samples as a function of magnetic field and temperature. The dielectric constant was also measured for the less-conducting samples. We find a $T^{-1/2}$ law for conductivity in the insulating phase, which suggests that Coulomb interaction effects are important in this disordered system. The variation of Thomas-Fermi screening radius obtained by applying Efros and Shklovskii's theory[4] to our data is twice as large as nearly-free-electron estimates would indicate. This result lends credence to Efros and Shklovskii's theory.[4] It also suggests that theoretical understanding of the positive magnetoresistance of $Cd_{1-x}Mn_xSe$ is incomplete.

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