Low-Temperature Transport Properties of $Cd_{0.91}Mn_{0.09}Te$:In and Evidence for a Magnetic Hard Gap in the Density of States

I. Terry, T. Penney, and S. von Molnár
IBM Research Division, T. J. Watson Research Center, P.O. Box 218, Yorktown Heights, New York 10598

P. Becla
Bitter National Magnet Laboratory, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139
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A family of resistivity curves, with different carrier concentrations, is obtained in a single sample of the dilute magnetic persistent photoconductor $Cd_{0.91}Mn_{0.09}Te$:In. These curves exhibit a crossover from an $\exp(T_0/T)^{1/2}$ form for variable-range hopping with interactions to an $\exp(E_H/T)$ form, upon reducing temperature. All data scale onto a single curve. The energy E_H is associated with a hard gap in the density of states which is magnetic in origin. The localization length is found to have the same critical behavior as the dielectric constant, on approaching the insulator-metal transition.

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On the insulating side of the insulator-to-metal transition, the presence of electron-electron interactions is believed to give rise to a depletion of the single-particle density of states close to the Fermi energy E_F, usually referred to as the Coulomb gap [1,2]. It is called a soft gap because, in 3D, the density of states goes smoothly to zero with a parabolic dependence [2,3]. Attempts to stabilize the ground state to other excitations have been made [4–6]. The inclusion of multielectron relaxation at the initial and final states of a hopping electron considered in the single-particle model has been shown to put a sharper bound on the single-particle density of states within the Coulomb gap Δ. The result is a "hard gap" where the density of states is effectively zero over a finite range of energy, E_H, with $E_H \simeq \Delta/10$ [5,6]. The existence of the hard gap and its effect on dc transport is still a controversial issue. One possible manifestation of a hard gap is, upon lowering temperature, a crossover from a resistivity of the form given by Efros and Shklovskii [2,3] for variable-range hopping (VRH) with interactions [7],

$$\rho = \rho_0 \exp(T_0/T)^{1/2}, \quad T_0 = 2.8e^2/\kappa\xi k , \tag{1}$$

to an activated form associated with transitions across the hard gap,

$$\rho = \rho_H \exp(E_H/T) . \tag{2}$$

Here κ and ξ are the dielectric constant and localization length, respectively. Experimentally, such a crossover has been observed in few systems [8,9] and is opposite to the most common crossover from nearest-neighbor hopping to VRH with decreasing temperature.

The present work demonstrates the crossover from an $\exp(T_0/T)^{1/2}$ to an $\exp(E_H/T)$ form in the dilute magnetic semiconductor $Cd_{0.91}Mn_{0.09}Te$:In, as the temperature is reduced. By utilizing the persistent photoconductivity (PPC) exhibited in this material [10], a family of resistivity curves has been obtained for various carrier concentrations n in just one sample. Furthermore, the divergence of the dielectric constant κ with increasing n is shown and used with T_0 to determine the nature of the electron localization length ξ upon nearing the insulator-to-metal transition (IMT).

The use of PPC to control n in one sample by "photodoping" makes it possible to study the transport properties of the insulating regime [11] without the problem of varying degrees of disorder encountered when investigating a series of discrete samples. In the present paper, low-temperature transport measurements ($T \simeq 300$ mK to 30 K) were made in $Cd_{0.91}Mn_{0.09}Te$:In ($N_D \simeq 10^{18}$ cm^{-3}) where the persistent photocarrier concentration, generated at a temperature of 1.4 K with an infrared-light-emitting diode (LED) ($h\nu \simeq 1.4$ eV), could be maintained for several months at temperatures below 50 K. Details of sample growth, preparation, and characterization are given elsewhere [10].

The temperature dependence of the resistivity is presented in Fig. 1 for five photogenerated carrier concentrations given in Table I. The logarithm of the resis-

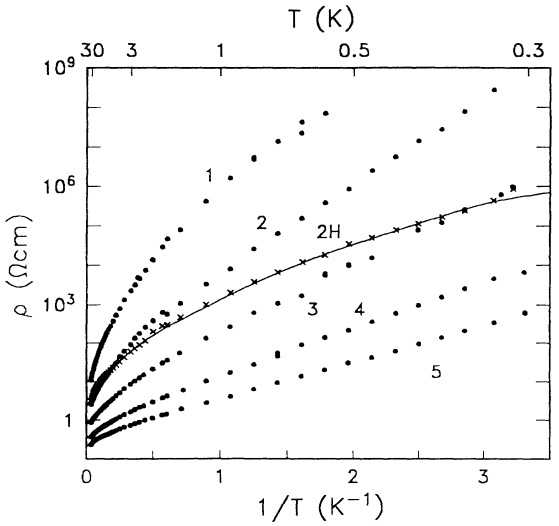

FIG. 1. Temperature dependence of the zero-field resistivity for five carrier concentrations (●) given in Table I. For curve $2H$ (× and solid line) magnetic field was 8 T.

TABLE I. Carrier concentration, n, and other parameters characterizing the curves shown in Figs. 1–4.

Curve	n (10^{16} cm^{-3})	T_x (K)	ρ_0 (Ω cm)	A	T_0 (K)	E_H (K)	κ	ξ (Å)
1	1.7	0.077	1.14	46.7	169	3.62	16.7	166
2	4.3	0.324	0.610	14.0	63.6	4.54	18.6	395
2H	4.3	≤ 0.033	1.00–0.07	≥ 39	51+3	≤ 1.30	21.0	436–25
3	7.4	0.524	0.336	7.06	26.1	3.70	23.8	753
4	11.0	0.682	0.204	3.94	10.6	2.69	28.1	1570
5	14.3	0.787	0.160	2.65	5.52	2.08	33.5[a]	2530

[a]Obtained from Fig. 3.

tivities is plotted as a function of inverse temperature and, for the lowest concentration (curve 1), it is clear that the resistivity is of a nonactivated form. However, at the higher carrier concentrations, an $\exp(E/T)$ dependence is observed for temperatures below about 2 K. If the same data are plotted as a function of $T^{-1/2}$, a very good description of the temperature dependence of the resistivity of curve 1 is observed between 0.8 and 20 K. Above 2 K, a $T^{-1/2}$ dependence is also found for the higher carrier concentrations. The $T^{-1/2}$ dependence is indicative of the presence of variable-range hopping with electron-electron interactions as originally proposed by Efros and Shklovskii (ES) [2]. The Coulomb gap arising from the interactions has a width [3], $\Delta = e^3 g_0^{1/2}/\kappa^{3/2}$, where g_0 is the background density of states. Note that without interactions, there is no soft gap, Mott VRH is observed, and the resistivity follows $\exp(T_1/T)^{1/4}$. Recently, Aharony, Zhang, and Sarachik [12] have shown that the crossover from Mott VRH to ES VRH in CdSe follows a scaling function.

A remarkable feature of the temperature dependence of the present resistivity data is that it is possible to describe all of the curves of Fig. 1 with a single scaling form,

$$\rho = \rho_0 \exp[T_0/T + E_H^2/T^2]^{1/2} = \rho_0 \exp[A(t_0)F(t)] . \quad (3)$$

This is illustrated in Fig. 2 where all of the resistivity data, shown in the inset, collapse to a single curve, $\ln(\rho/\rho_0)/A = F(t) = (t+1)^{1/2}/t$ for $A = t_0^{1/2}$ with $t = T/T_x$, $t_0 = T_0/T_x$, and $E_H = (T_0 T_x)^{1/2}$. Here, the fitting parameters are ρ_0, A, and T_x so that the number of variables describing the resistivity has been reduced from 4 (ρ_0, T_0, ρ_H, E_H) to 3. The scaling parameter T_x characterizes the temperature at which a crossover from ES VRH to variable-range hopping in the hard-gap regime occurs. The activation energy, E_H, and T_0 are found to be related, $E_H \sim T_0^{1/3}$, as shown in Fig. 3.

Experimentally (Fig. 3), E_H tends to zero as the dielectric constant κ diverges on approaching the IMT. It was previously noted that, theoretically, the soft-gap width Δ varies as $\kappa^{-3/2}$ and so for comparison we have plotted (Fig. 3) E_H vs $\kappa^{-3/2}$. Taking the unperturbed density of

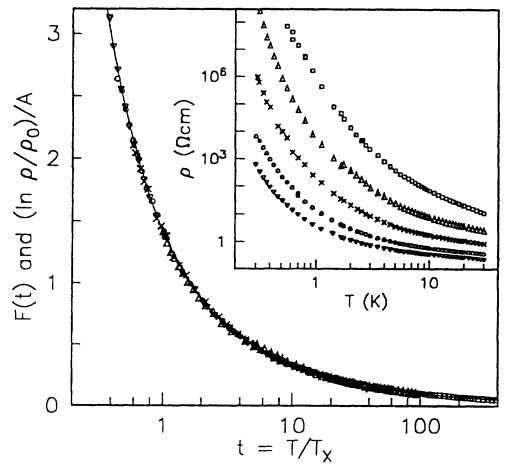

FIG. 2. Variation of the scaling function $F(t) = (t+1)^{1/2}/t$ (solid line) and the scaled resistivity data as a function of the scaled temperature t. Here $A = (T_0/T_x)^{1/2}$. The inset and Fig. 1 show the same resistivity data unscaled. The scaling parameters are given in Table I.

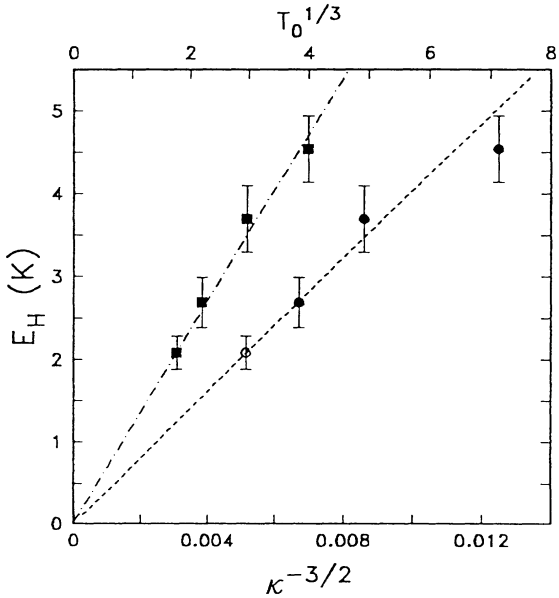

FIG. 3. Variation of the energy E_H with (■) T_0 [Eq. (1)] and (●) dielectric constant κ. The value of κ (○) is chosen to fit $E_H \sim \kappa^{-3/2}$ for the measured $E_H = 2.06$ K.

states at the Fermi level, $g_0 \simeq 10^{19}$ cm^{-3}eV^{-1}, from Ref. [10] and using values of E_H from Table I, we find $E_H \simeq \Delta/5$. This is similar to theoretical estimates of the hard-gap width in nonmagnetic systems [6]. The relationship between E_H and κ could not be determined for the highest concentration because it became impossible to remove the hopping contribution from the dielectric constant [13]. However, an estimate of the dielectric constant at the highest value of n (open circle, Fig. 3) may be obtained by extrapolating the E_H vs $\kappa^{-3/2}$ dependence.

In a large magnetic field the $\exp(E_H/T)$ form of the resistivity is lost and an $\exp(T_0/T)^{1/2}$ dependence is obtained over the whole temperature range (Fig. 1, curve $2H$, and see Table I). These results imply that there is a hard gap which must be magnetic in origin. In a nonmagnetic system, the hard gap arises from the energy change resulting from multielectron relaxation at the initial and final sites of the long-range hop [6]. In the present case, we believe that the magnetic relaxation energy which causes the hard gap is also that causing bound magnetic polarons [14]. The local magnetic environment (Mn^{2+} spins) responds to the presence of a bound electron, and reduces the total energy of the localized state via the s-d exchange interaction [15]. The hardening of the Coulomb gap results from the relaxation energy gained by the formation of a bound magnetic polaron at the final site of a long-range hop, along with the decrease in binding energy of the initial site after the locally aligned manganese spins thermalize.

For this scenario, the magnetic polaron relaxation time ($\sim$300 ps [16]) must be shorter than the time between electron hops, estimated to be $\tau \simeq (1/\nu_{\text{phonon}})\exp[AF(t \lesssim 4)] \gtrsim 600$ ps, at the upper limit of the hard-gap region. Also the effect of applying a high magnetic field is to produce a homogeneous alignment of the manganese moments which suppresses magnetic polaron formation and results in a delocalization of the bound electron [14].

A scaling equation with the form $G(t) = (t^{1/2}+1)/t$, similar to Eq. (3), may be derived from the hopping probability (γ_{ij}) between the sites i and j separated by a distance r_{ij} and of energy difference ε_{ij} [2],

$$\gamma_{ij} = \gamma_0 \exp[-2r_{ij}/\xi - \varepsilon_{ij}/T], \tag{4}$$

if $\varepsilon_{ij} = \alpha e^2/\kappa r_{ij} + E_H$. In other words, the energy difference between the two sites must be made up of the Coulomb interaction term [2] plus the energy E_H which is independent of r_{ij}. Although this simple derivation and interpretation is very appealing, the form $G(t)$ does not describe the data as well as $F(t)$, Eq. (3).

The localization length ξ as a function of n may be calculated from T_0 and κ using Eq. (1). The divergence of κ (Fig. 4) has the form

$$\kappa = \kappa_H + 4\pi n a_0 (1 - n/n_c)^{-\nu}, \tag{5}$$

where $\kappa_H = 16$ is the dielectric constant of the host, n_c is the critical carrier concentration of the IMT, and a_0 is the donor polarizability. The n found in the numerator of the second term in Eq. (5) accounts for the increase in κ solely from the increasing number of donors, observed when $n \ll n_c$ [17]. The dependence of ξ on n is given in Table I and in Fig. 4. It is clear that the electronic part of κ and ξ diverge with n in exactly the same way and therefore show the same critical behavior on approaching the IMT. This implies that ξ has an n dependence which is of a similar functional form to $\kappa(n)$ given in Eq. (5), that is,

$$\xi = \xi_H + \xi'(n)(1 - n/n_c)^{-\nu}, \quad \xi'(n) \sim n, \tag{6}$$

with $\xi_H' \sim 50$ Å and the same exponent $\nu = \nu'$.

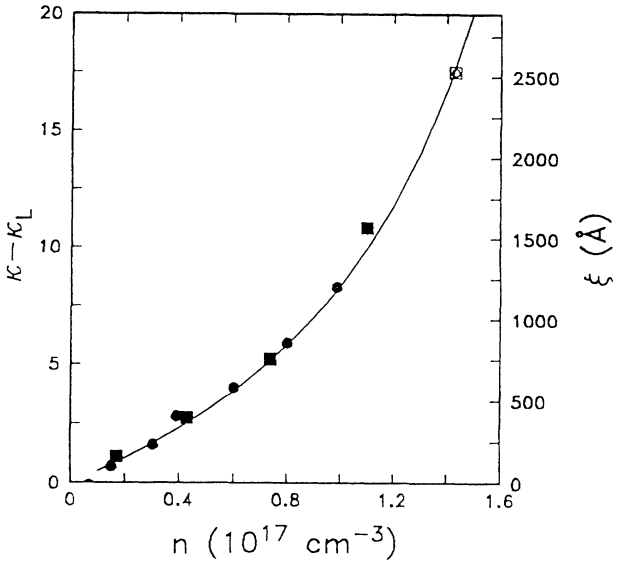

FIG. 4. Variation of the calculated localization length (ξ) (●) and the electronic part of the measured dielectric constant ($\kappa - \kappa_L$) (■) as a function of carrier concentration. The solid line is a fit by Eq. (5) with $\nu' = 1$, $n_c = 2.3 \times 10^{17}$ cm^{-3}, and $a_0 = 5.27 \times 10^{-17}$ cm^3. The κ value (○,□) is obtained from Fig. 3 (see text).

If the exponents $\nu = \nu' = 1$, a fit to the experimental results is obtained with a critical concentration of $n_c = 2.3 \times 10^{17}$ cm^{-3}. A lower or higher value of ν' can also give a fit to the data with a correspondingly smaller or larger value of n_c, but it is known from the work on a series of doped samples [18] that the insulator-to-metal transition in $Cd_{0.9}Mn_{0.1}Te$ occurs for a critical concentration $n_c \simeq (2\text{-}3) \times 10^{17}$ cm^{-3}. So it may be concluded that, on approaching the IMT, the critical behavior of κ and ξ is characterized by $\nu = \nu'$ and, in addition, it may be tentatively concluded that $\nu \simeq 1$ and $n_c \simeq 2.3 \times 10^{17}$ cm^{-3}.

The observation of $\nu' = \nu$ is consistent with magnetic-field-dependent studies of κ and ξ in $Hg_{0.92}Mn_{0.08}Te$ [19]. A similar result was inferred from an analysis of transport data of n-type CdSe [20]. These results differ from other experiments in which $\nu' = 2\nu$ has been observed

[21].

In summary, this paper has described transport properties of the diluted magnetic persistent photoconductor $Cd_{0.9}Mn_{0.1}Te$:In as a function of temperature and photogenerated carrier density. There is strong evidence to suggest that electrical transport occurs by variable-range hopping in an environment where electron-electron interactions give rise to a depletion of the density of localized states near to the Fermi level, the Coulomb gap. A transition from ES VRH to an activated transport process was observed upon decreasing temperature, and the activated resistivity may be the result of a hard gap of width $E_H \simeq \Delta/5$ in the density of states within the Coulomb gap (width Δ). It was possible to scale all the resistivity data, obtained at different carrier concentrations, onto a single curve and this was used to accurately determine both T_0 and E_H as a function of n. The hard gap could be a consequence of the s-d exchange interaction between the localized carrier and the Mn^{2+} spins. Specifically, it was proposed that the relaxation energy gained by the formation of a bound magnetic polaron at the final site of a long-range hop, along with the decrease in binding energy of the initial site after the locally aligned manganese spins thermalize, results in the hardening of the Coulomb gap. This suggests that other excitations involving magnetic interactions must also be considered when determining the form of the density of states. Finally, it was demonstrated that both the dielectric constant and the localization length exhibit the same scaling behavior on approaching the IMT and it was found that the relevant critical exponents are the same $\nu = \nu'$. In addition, it was suggested that $\nu \simeq 1$ and $n_c \simeq 2.3 \times 10^{17}\ \mathrm{cm}^{-3}$.

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