Magnetic-field-induced crossover from Mott variable-range hopping to weakly insulating behavior

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In three-dimensional n-CdSe samples that obey Mott variable-range hopping, $\rho=\rho_0\exp(T_0/T)^{1/4}$, in the absence of a magnetic field, we report a field-induced crossover at low temperatures to a resistivity that exhibits a weak power-law divergence, $\rho=\rho_0T^{-\alpha}$, with an exponent α that decreases slowly with increasing field.

There is considerable current interest in the magnetotransport of insulators that exhibit variable-range-hopping conductivity. Interesting, complex behavior has been found as a function of magnetic field. A substantial initial decrease in resistance, which saturates at fields around 2 or 3 T,[1–8] has been attributed to quantum interference effects.[9–11] A second and apparently distinct decrease or minimum in the resistivity has been observed at higher fields in several materials. In two-dimensional modulation-doped GaAs/$Al_xGa_{1-x}As$ heterostructures, a very large decrease at intermediate fields signals a transition from an Anderson insulator to a quantum Hall conductor.[1–3] A similar, albeit considerably smaller, minimum in two-dimensional layered δ-doped GaAs (Refs. 4 and 5) has been attributed by Raikh[5,12] to a decreased overlap between dopant wave functions in a magnetic field, resulting in a narrowing of the impurity band, a shift of the Fermi energy toward the center of the band, and a consequent increase of the density of states at the Fermi energy. At much higher fields, the orbital shrinkage of the impurity wave functions is expected to give a rapid increase in resistance.[13]

We have previously reported[14] resistivity minima at intermediate fields in three-dimensional samples of heavily doped, compensated CdSe:In which are qualitatively similar to those found in two dimensions, and which we attributed to the mechanism proposed by Raikh.[5,12] In deeply insulating samples of CdSe:In, we now report a field-induced crossover from strongly localized behavior in zero field to weakly insulating behavior in a magnetic field, causing unusually large decreases in resistivity of more than an order of magnitude at low temperatures. The resistivity in the absence of a magnetic field obeys Mott variable-range hopping, $\rho=\rho_0\exp(T_0/T)^{1/4}$, diverging exponentially as the temperature approaches zero. In magnetic fields of 3 T and higher, the resistivity exhibits instead a weak power-law divergence, $\rho=\rho_0T^{-\alpha}$, with an exponent α that decreases slowly with increasing magnetic field.

The three Czochralski-grown, compensated CdSe:In samples used in this study were obtained from Cleveland Crystals. An ultrasonic iron was used with indium solder to attach gold leads to samples of approximate dimensions $0.3\times0.8\times0.05$ cm^3. Room-temperature Hall-coefficient measurements indicate net carrier concentrations of 1.6×10^{17} (sample A), 1.2×10^{17} (sample B), and 1.0×10^{17} cm^{-3} (sample C) corresponding to $0.57n_c$, $0.43n_c$, and $0.36n_c$, respectively, based on a critical concentration n_c of 2.8×10^{17} cm^{-3} estimated from the Mott criterion[15] and from earlier measurements.[7,8] Standard four-terminal dc techniques were used in an Oxford Model 75 dilution refrigerator equipped with a 9-T superconducting magnet. Power inputs were maintained below 10^{-13} W at the lowest temperatures, and the dependence on current was carefully monitored to ensure linearity and to monitor self-heating. The magnetic field was applied in all cases perpendicular to the current direction. Data were taken down to temperatures between 70 and 80 mK, depending on the sample.

The resistivities of samples B and C shown in Fig. 1 exhibit Mott variable-range hopping, $\rho=\rho_0\exp[(T_0/T)^x]$, with exponent $x=\frac{1}{4}$, as expected in three dimensions. A good

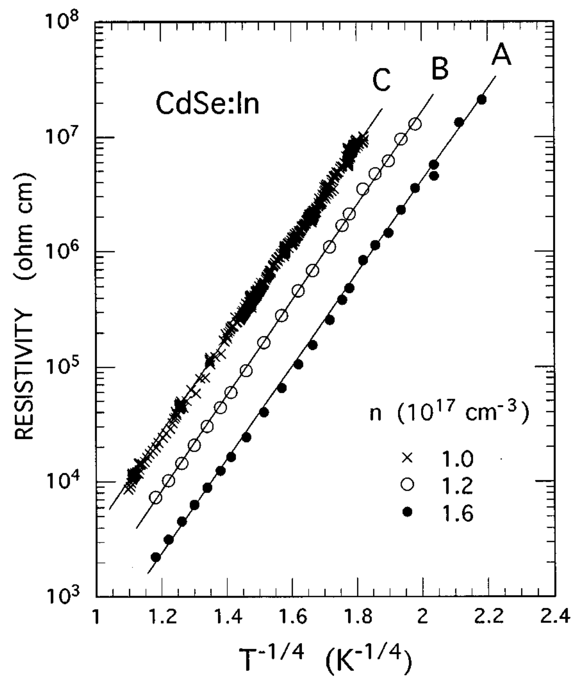

FIG. 1. Resistivity in zero field vs $T^{-1/4}$ on a semilogarithmic scale for three insulating, n-type CdSe:In samples with dopant densities $0.57n_c$ (sample A), $0.43n_c$ (sample B), and $0.36n_c$ (sample C) (based on a critical concentration $n_c=2.8\times10^{17}$ cm^{-3}). The resistivity obeys Mott variable-range hopping $\rho=\rho_0\exp[(T_0/T)^{1/4}]$ with $T_0\approx7400$, 8400, and 8400 K, and $\rho_0=0.037$, 0.083, and 0.30Ω cm for samples A, B, and C, respectively.

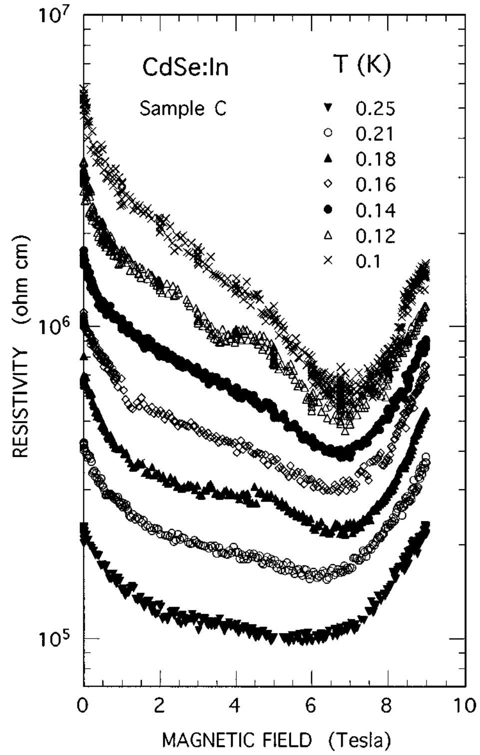

FIG. 2. Resistivity of sample C vs magnetic field on a semilogarithmic scale at different temperatures, as indicated.

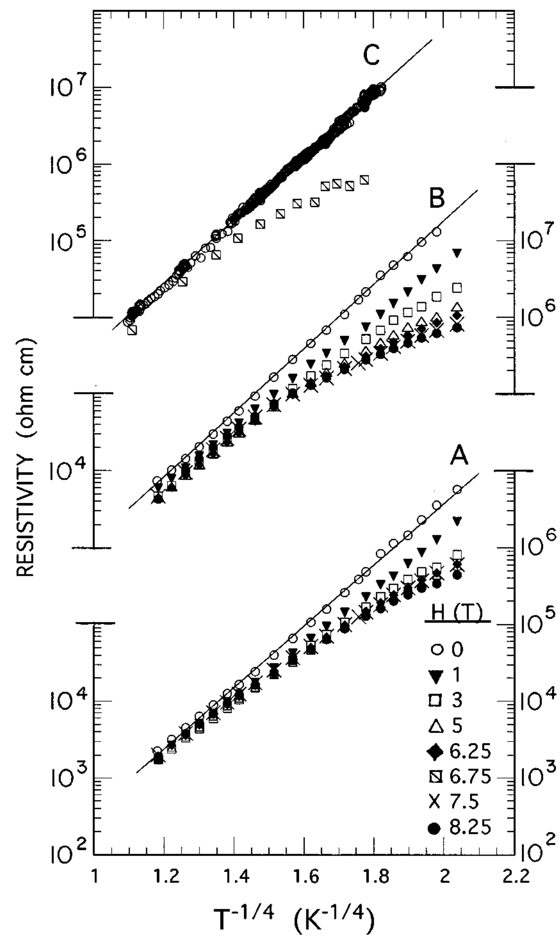

FIG. 3. On a semilogarithmic scale, the resistivity vs $T^{-1/4}$ in several magnetic fields, as labeled, for three insulating, n-type CdSe:In samples.

fit is also obtained using $x=1/4$ for sample A, although a small upward deviation toward a higher exponent indicates that electron-electron interactions[13] may play some role in this sample.[16] We note that the resistivity changes with temperature by three or four orders of magnitude, establishing that all three samples are in the strongly localized regime. While the three curves of Fig. 1 have different prefactors $\rho_0=0.037$, 0.083, and 0.30 Ω cm for samples A, B, and C, respectively, they have similar slopes yielding $T_0=7400$ K for A and $T_0=8400$ K for B and C. Using the standard expression for Mott variable-range hopping, $kT_0 \sim 18/N(E_F)\xi^3$ [where $N(E_F)$ is the density of states at the Fermi energy and ξ is the localization length], a very rough estimate[8] for $N(E_F)$ of 2×10^{19} (eV cm^3)$^{-1}$ yields a localization length ξ on the order of 100 Å. We note that this localization length is comparable with the magnetic length $l_H=(\hbar c/eH)^{1/2}$ at about 7 T.

The resistivity of sample C is shown on a semilogarithmic scale in Fig. 2 as a function of magnetic field to 9 T at several different temperatures between 0.1 and 0.25 K, as indicated. The resistivity exhibits an initial sharp drop, followed by a second decrease around 7 T. Although present at all measured temperatures, the latter becomes quite apparent below 0.25 K and deepens as the temperature is further reduced. This is illustrated in Fig. 3, where the resistivity is plotted as a function of $T^{-1/4}$ on a semilogarithmic scale in several fixed magnetic fields for all three samples (note the broken scale). As the magnetic field is increased and the temperature is reduced, the resistivity drops progressively further below its zero-field value, an effect that becomes more pronounced as the samples become more insulating.

At our lowest experimental temperatures the resistance of sample A has changed in 8.25 T by more than a factor of 10 from its zero-field value; the ratio of resistances should be considerably larger for samples B and C at the same temperature, and for all samples at lower temperatures. The question arises whether the resistivity exhibits insulating behavior in a magnetic field, diverging as $T\rightarrow0$ although more slowly than in zero field, or whether it tends toward a finite value at 0 K, thus entering a metallic phase. This is examined in Fig. 4(a), where[17] $\partial(\ln\sigma)/\partial(\ln T)=(T/\sigma)(\partial\sigma/\partial T)$ is plotted as a function of T on a double logarithmic scale for sample B. Since the zero-temperature conductivity is finite for a metal and zero for an insulator, this quantity should tend toward zero at $T=0$ in a metal, and should stay finite or diverge in an insulator. In particular, $\partial(\ln\sigma)/\partial(\ln T)\propto T^{-x}$ with $x=\frac{1}{4}$ for Mott variable-range hopping; if the exponent $x=0$ then $\partial(\ln\sigma)/\partial(\ln T)=\alpha$ and the conductivity has the form $\sigma \propto T^{\alpha}$, a weaker (power-law) divergence for the resistivity. The value of the slopes x of the curves of Fig. 4(a) are plotted as a function of magnetic field in Fig. 4(b), yielding $x\approx\frac{1}{4}$ at 0 and 1 T, and a slope x consistent with 0 at magnetic fields of 3 T and higher. Within the accuracy of these data, it appears that the material remains insulating in a magnetic field, and that the (Mott variable-range hopping) exponential divergence in zero field crosses to a weaker, power-law divergence, $\rho\propto T^{-\alpha}$, in magnetic fields of 3 T and higher. Al-

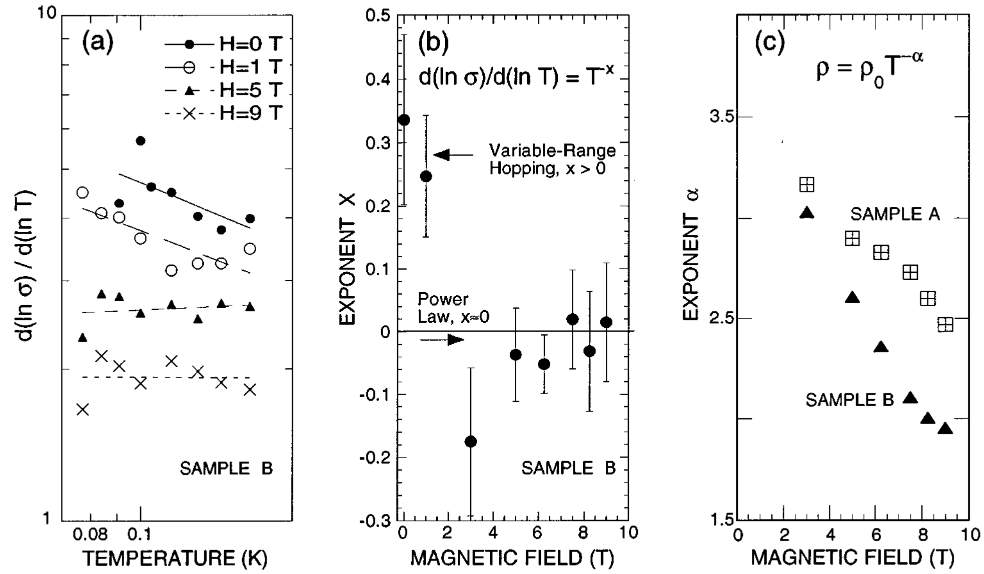

FIG. 4. (a) $\partial(\ln\sigma)/\partial(\ln T)$ vs T on a log-log scale for sample B in various different magnetic fields, as labeled. (b) The slope x as a function of magnetic field. (c) The exponent α as a function of magnetic field (see text).

though smaller by more than a factor of 20 than its zero-field value at the lowest temperatures of our measurements, we note that the resistivity in a magnetic field remains large and typical of an insulator. However, we cannot exclude the possibility that it is entering a metallic phase; as shown in Fig. 4(c), the exponent α, given by the numerical value of $\partial(\ln\sigma)/\partial(\ln T)$, decreases slowly as the field is raised, a decrease that is cut off at fields above the minimum (see Fig. 2).

The initial decrease in resistivity observed in many materials in small magnetic fields ($l_H \gg \xi$) has generally been attributed to quantum interference between forward-scattering hopping paths.[10,11] Here the probability of a hop between initial and final states is determined by the superposition of all possible paths connecting the states through intermediate (thermally inaccessible) scattering events. By altering the phases, a magnetic field changes the hopping probability and, when suitably averaged over a macroscopic sample, yields a net decrease in the resistivity. Although the magnetoresistance measured for our samples below 1 or 2 T may be due to this process, we note that it is considerably larger than this theory predicts.

There are several possible explanations for the magnetoresistance we observe at intermediate fields. Pichard *et al.*[18] and Lerner and Imry[19] have shown that a strong magnetic field ($l_H \ll \xi$) causes a substantial increase in the localization length: by breaking time-reversal symmetry, the field eliminates the coherent time-reversed, backscattered paths that lead to (weak) localization. Unfortunately, there exist no detailed calculations for three-dimensional systems against which to compare our data. Alternatively, Azbel[20] has predicted in disordered systems that Landau levels should produce oscillations in the resistivity with increasing field and a series of insulator-metal-insulator transitions in three dimensions, giving rise to strong negative magnetoresistance in certain field ranges. We note, however, that we have not found any additional oscillations in the resistivity of these and several other samples of CdSe:In studied in fields up to 19 T.

An interesting possibility is provided by a simple extension of the model proposed by Raikh.[5,12] The magnetic length is comparable with the localization length at typical fields of our experiments, and a simple estimate based on the theory developed in Ref. 13 shows that there is appreciable orbital shrinkage. Based on mobility studies[8] of other CdSe samples obtained from the same sources, we estimate that the compensation of the samples used in the present study is approximately 0.25–0.30, placing the Fermi level somewhere above the middle of the lower Hubbard band. By decreasing the overlap between donor wave functions, a magnetic field narrows the impurity band and yields a larger density of states at the Fermi energy and a smaller resistivity. Within this model, the crossover of the resistivity to a power-law divergence may be due to a Fermi level that approaches the mobility edge separating the localized states at the band edges from extended states in the middle of the band. We note that the strong similarity between our data and the magnetoresistance of two-dimensional (2D) electron gases may thus derive from the fact that in both cases the Fermi energy approaches delocalized states.[21]

To summarize, in deeply insulating samples that obey Mott variable-range hopping with large characteristic temperatures $T_0 \approx 10^4$ K, we find that the application of a magnetic field of several T causes the resistivity at 70 mK to decrease by more than an order of magnitude, an effect that should be more dramatic at even lower temperatures. Moreover, the exponential divergence of the resistivity in zero field becomes a much weaker power-law divergence when a magnetic field is present. Careful measurements at much lower temperatures are required to determine whether the material is entering a metallic phase.

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[16] The samples used here, obtained from Cleveland Crystals, exhibit Mott hopping down to the lowest measured temperature. In contrast, Efros-Shklovskii variable-range hopping $\rho=\rho_0\exp[(T_0/T)^{1/2}]$ was found for CdSe:In samples obtained from the Polish Academy of Sciences (PAS) with dopant concentrations closer to the metal-insulator transition [see Y. Zhang, P. Dai, M. Levy, and M. P. Sarachik, Phys. Rev. Lett. **64**, 2687 (1990)]. This may indicate that Mott hopping, which characterizes the behavior of just-insulating material, reappears in very insulating samples. The difference may also be due to a smaller degree of compensation and to a narrower Coulomb gap in the Cleveland Crystal samples. Indeed, smaller compensations were inferred for these than for samples obtained from the PAS from transport studies at higher temperatures (Ref. 9) and photoemission experiments [Miguel Levy, W. K. Lee, and M. P. Sarachik, Phys. Rev. B **45**, 11 685 (1992)].
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[21] In 2D, theory predicts that delocalized states exists at discrete values of energy at any finite magnetic field, but there is complete localization at $H=0$. On the other hand, theory allows for a metal-insulator transition in zero field in 3D, and a mobility threshold separates localized and extended states. In both cases, however, the approach of the Fermi energy to delocalized states yields similar magnetoresistance, as observed.