Low-Temperature Transport in the Hopping Regime: Evidence for Correlations Due to Exchange

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Activated conduction, $\rho=\rho_0\exp[(T_0''/T)^x]$, with x equal to or close to 1 is observed for insulating Si:B at low temperatures, indicating the presence of a "hard" gap in the density of states. A magnetic field suppresses this unexpectedly strong temperature dependence, changing it to the variable-range-hopping form $\rho(H)=\rho_0(H)\exp\{[T_0'(H)/T]^{1/2}\}$ expected for a "soft" parabolic Coulomb gap. This suggests that the density of states is determined by electron correlations due to spin as well as charge.

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Variable-range hopping of the form

$$\rho=\rho_0\exp[(T_0/T)^{1/4}] \qquad (1)$$

was predicted by Mott [1] for systems in three dimensions on the assumption that the density of states near the Fermi energy is constant (or a slowly varying function of energy). Subsequent work has demonstrated that long-range Coulomb interactions cause a depletion [2] of single-particle states near the Fermi energy. By considering one-electron transitions, Efros and Shklovskii [3] (ES) found a parabolic [4] "Coulomb gap" of the form $|E-E_F|^2$. Inclusion of multielectron effects generally leads to further reduction of the density of states near the Fermi energy, and to a region where there are effectively no states within a narrow but finite range of energy [5,6]. Assuming that the conductivity is determined by the single-particle density of states [4], Efros and Shklovskii [3] showed that a parabolic gap yields variable-range hopping with an exponent $\frac{1}{2}$ instead of $\frac{1}{4}$, that is,

$$\rho=\rho_0\exp[(T_0'/T)^{1/2}]. \qquad (2)$$

Pollak [7] and Hamilton [8] showed more generally that for a density of states that varies as $|E-E_F|^m$, the resistivity is given by

$$\rho=\rho_0\exp[(T_0''/T)^x] \qquad (3)$$

with an exponent $x=(m+1)/(m+4)$.

Variable-range hopping with an exponent of $\frac{1}{2}$ has been found in many systems [9]. There is recent experimental evidence, however, that a crossover occurs in some materials at very low temperatures to a new regime where the resistivity depends more strongly on the temperature, obeying Eq. (3) with an exponent x larger than $\frac{1}{2}$. Deviations from variable-range hopping have been observed [10] in transmutation-doped n-type Ge, and a crossover with decreasing temperature to simply activated conduction ($x=1$) has been found in amorphous GeCr [11] and irradiated polymer films [12]. Similar behavior has been observed by van der Heijden *et al.* [13] in ion-implanted Si:As samples. At relatively high temperatures (above 1.5 K), Shafarman, Koon, and Castner [14] have measured resistivities of insulating Si:As samples and found them to vary even faster with temperature than the simply activated form. Most recently, Terry *et al.* [15] have found simple activation which they attribute to polarons in the dilute magnetic material CdMnTe:In.

Shlimak [10] proposed that the strong temperature dependence observed at very low temperatures is due to the presence of a finite "hard" gap in the density of states caused by spin-spin interactions. He suggested further that sufficiently high magnetic fields should eliminate this "magnetic" gap. In this paper we report measurements which demonstrate that the low-temperature resistivity of uncompensated p-type insulating Si:B exhibits simply activated behavior in the absence of a field; the behavior changes to variable-range hopping when a magnetic field is applied. This provides evidence for a density of states that is determined by correlations among electrons due to their magnetic moments as well as their charges.

The nominally uncompensated Czochralski-grown insulating Si:B used in these studies was obtained from PureSil Inc. Samples were cut from 0.3-mm-thick, 5-cm-diam wafers into thin bars of approximate dimensions 8 mm by 1.5 mm. All samples were etched in a CP-4 solution to remove any damaged surface layers. Electrical contacts were made by first depositing four thin strip-shaped Al films on each sample and then attaching Au wires to the Al by a special arc-discharge technique [16]. The resistance was measured by standard ac low-frequency (15 Hz), four-terminal techniques in an Oxford model 75 dilution refrigerator down to about 50 mK and in magnetic fields up to 8 T. Different excitation currents were used to ensure Ohmic behavior. Measurements at higher temperatures were obtained in a standard ^{4}He glass Dewar.

The zero-field resistivity of a typical sample of Si:B with dopant concentration below the metal-insulator transition is shown on a semilogarithmic scale as a function of $T^{-1/2}$ in Fig. 1(a) and as a function of T^{-1} in Fig. 1(b). The line in Fig. 1(a) demonstrates that the resistivity varies more rapidly than the ES form, Eq. (2), and that there is no range of temperature over which ES hopping provides a satisfactory fit. Figure 1(b) shows that at the lowest temperatures accessible to our experiments, the exponent x of Eq. (3) is close to or equal to 1. The data are consistent with simply activated conduction, with a characteristic temperature $T_0''=0.37$ K, corresponding to

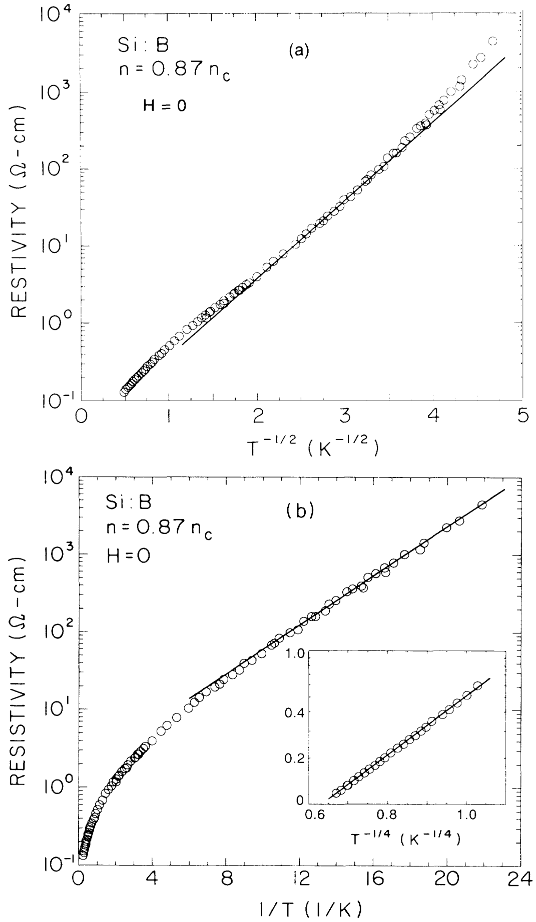

FIG. 1. The resistivity of insulating Si:B plotted on a logarithmic scale as a function of (a) $T^{-1/2}$ and (b) T^{-1}. The straight lines demonstrate that, while deviations from $T^{-1/2}$ are evident over the entire range, a reasonable fit is obtained by T^{-1} at low temperature. The inset to (b) shows data at higher temperatures plotted as a function of $T^{-1/4}$, to demonstrate that the sample crosses over to Mott variable-range hopping.

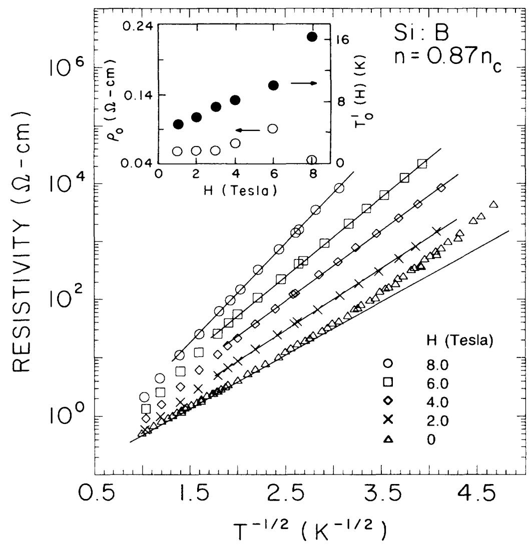

FIG. 2. The resistivity of insulating Si:B plotted on a logarithmic scale at several fixed fields as a function of $T^{-1/2}$. Inset: $\rho_0(H)$ (open circles) and $T_0'(H)$ (solid circles), obtained by fitting the data above 1 T by Eq. (2), as a function of H. The data at $H=0$ are included for comparison; the straight line denotes resistivities given by Eq. (2) with values of ρ_0 and T_0' extrapolated to zero field.

a gap energy of approximately 3.2×10^{-5} eV.

The resistivity of the same sample is plotted in Fig. 2 on a semilogarithmic scale versus $T^{-1/2}$ in various fixed magnetic fields; the zero-field data are included for comparison. Data for other samples were found to be quite similar. This figure shows clearly that the resistivity, which obeys approximately $\ln\rho \propto T^{-1}$ in the absence of a field, is consistent instead with $\ln\rho \propto T^{-1/2}$ when a magnetic field is applied [17]. Fits of Eq. (2) to the data at fixed fields yield the parameters $\rho_0(H)$ and $T_0'(H)$ which are shown in the inset to Fig. 2. The lowest line in the main figure denotes the curve obtained from Eq. (2) using zero-field extrapolations for ρ_0 and T_0'. The difference between this line and the zero-field data is thus a measure of the deviation of the resistivity from the value it would have if the gap were parabolic at $H=0$. This represents a negative contribution to the magnetoresistance superimposed on the general upward trend in resistivity with increasing magnetic field.

The resistivity of our samples in zero field is consistent with simply activated conduction; that is, it obeys Eq. (3) with $x\approx1$. We note that near-neighbor hopping, which has a similar temperature dependence, generally entails activation energies ε_3 on the order of several meV [18], compared with 0.03 meV found for the sample of Figs. 1 and 2. Moreover, Mott variable-range hopping is observed at higher temperatures [see the inset of Fig. 1(b)], ruling out the possibility that the activated conduction found at lower temperature is due to near-neighbor hopping.

We attribute the simply activated conduction found in Si:B to the presence of a gap in the density of states near the Fermi energy. That our samples are nominally uncompensated might suggest that there is a lower-energy Hubbard band corresponding to singly occupied dopant centers which is completely filled, separated by an energy gap from an empty band of states associated with a second hole on a dopant atom already occupied by one hole. It is unlikely, however, that a gap of 0.03 meV would be found between bands known to have typical energy widths on the order of tens of meV. Moreover, there is strong evidence [19] that interactions lead to overlap of the bands for dopant concentrations well below the critical concentration for the metal-insulator transition.

A magnetic field on the order of 1 T suppresses the activated behavior observed in zero field and gives rise instead to variable-range hopping. We note that large negative magnetoresistances measured [20] in some materials have been attributed to quantum interference between different forward-scattering paths [21]. This process entails intermediate scattering centers between hopping sites, and requires that the material be in the variable-range-hopping regime. Since our samples do not exhibit variable-range hopping in zero field at very low temperatures, it is unlikely that orbital effects of this type are responsible for our observations.

We suggest that the magnetic field affects the form of the hopping transport through its effect on the electrons' spin. Thus, a "hard" gap exists in the density of states, becoming a "soft" gap of approximately parabolic form when a field on the order of 1 T is applied. That there is a crossover to a qualitatively different regime when a magnetic field is applied indicates that the zero-field gap is indeed of magnetic origin, as suggested by Shlimak [10]. We suggest that a magnetic field causes a change in the form of the density of states by aligning the localized magnetic moments that are known to exist in Si:B [22]. The form of variable-range hopping observed in a magnetic field implies the density of states has a soft parabolic gap, which is a manifestation of correlations between electrons due to their charges. Our experimental results imply that in the absence of a magnetic field there exists either a hard gap or a sharp decrease in the density of states near E_F due to correlations among the electrons not only due to their charges but also by virtue of their magnetic moments.

The interaction between moments here is governed by direct wave-function overlap. The exponential decay of the wave functions and the random spatial distribution of the dopants yield an extremely broad distribution of exchange energies. Moreover, this energy distribution varies with temperature [23]. We should point out that there is currently no theoretical justification for the suggestion that there exists a gap due to spin-spin interactions. The role of spin-spin correlations in the hopping transport and the effect of the broad distribution of exchange energies are interesting questions that require theoretical investigation.

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