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Absence of minimum metallic conductivity in $Gd_{(3-x)}v_xS_4$ at very low temperature and evidence for a Coulomb gap

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$Gd_{(3-x)}v_xS_4$ provides a convenient analog of a compensated semiconductor in which, for $x \simeq 0.3$, the mobility edge can be tuned smoothly through the Fermi energy by the application of a magnetic field. The results of a search for a minimum metallic conductivity demonstrate that, down to $T = 6$ mK, the metal-insulator transition is smooth. In the insulating regime, the temperature dependence of the conductivity was more consistent with the theory of mutual interactions than with the theory of pure localization.

Mott has predicted that in a metal at zero temperature, the conductivity cannot be arbitrarily small. Instead, when the Yoffe-Regel criterion ($k_F l \gtrsim 1$) is violated, the conductivity will drop abruptly from a finite value

$$\sigma_{\min} = C\frac{e^2}{\hbar a_E} \ , \tag{1}$$

to zero.[1] In Eq. (1), C is a dimensionless constant (between 0.025 and 0.050), and a_E is approximately the distance between electrons at the critical concentration for the metal-insulator (MI) transition, $a_E \simeq n_s^{-1/3}$. (In circumstances where another length limits the diffusion of the carriers, then it replaces a_E.) However, Abrahams, Anderson, Licciardello, and Ramakrishnan[2] have predicted that (at $T = 0$) the transition from metal to insulator should be smooth;

$$\sigma \sim (E_F - E_c)^{\nu}, \quad E_F > E_c \ ,$$
$$\sigma = 0, \quad E_F < E_c \ . \tag{2}$$

That is, the conductivity should scale continuously to zero with an exponent $\nu \simeq 1$. Both of these theories describe the behavior of noninteracting electrons moving in random potentials. The steadily advancing theory of interactions among the carriers in a random potential[3] also arrives at a continuous MI transition through more complex scaling arguments. Experimental studies of MI transitions have been performed in many materials including Si:P,[4] Ge:Sb,[5] Nb:Si,[6] and $Gd_{(3-x)}v_xS_4$ (v denotes vacancy).[7] The results from these experiments seem to favor the scaling arguments of Ref. 2 or 3, but there are still points in contention. A review of the experimental evidence for $\sigma_{\min}$ is given by Mott and Kaveh.[8] In this Rapid Communication, we will describe experiments on $Gd_{(3-x)}v_xS_4$ which provide no evidence for minimum metallic conductivity even down to $T = 6$ mK. Also, measurements of the hopping conductivity on the insulating side of the metal-insulator transition will be discussed.

$Gd_{(3-x)}v_xS_4$ is the equivalent of a compensated semiconductor where random potential fluctuations due to impurity and defect states are much greater than expected from the net carrier concentration alone. According to Ref. 8, this condition should be favorable for the observation of $\sigma_{\min}$. At constant x, the $Gd_{(3-x)}v_xS_4$ can be tuned from insulating to metallic by increasing the magnetic field. For $x = 0$, the system is a ferromagnetic metal, and for $x = \frac{1}{3}$, it is an antiferromagnetic insulator.[9] In the latter case, the donor electron is bound by a ferromagnetic polarization of the neighboring Gd atoms and the random potential fluctuations due to the vacancies; it forms a bound magnetic polaron.[10] At zero magnetic field, the polaron is immobilized by the antiferromagnetic lattice around it: an insulator. For a sample with $x \simeq 0.3$ at $H = 0$, the Fermi energy E_F is just below the mobility edge E_c. As the magnetic field increases, the disorder decreases pulling the mobility edge down through the Fermi energy; the insulator becomes a metal. We expect the gap between E_F and E_c to be proportional to $H - H_c$ so that in the scaling view the conductivity should be described by[7]

$$\sigma = A(H - H_c)^{\nu} \tag{3}$$

on the metallic side of the MI transition. This was verified for $\nu = 1.0$ and temperatures $T > 55$ mK.[7]

The present experiment is divided into two parts. The first purpose of the experiment was to extend previous work[7] to much lower temperature. This was done to assure that $\sigma_{\min}$ had not been missed because of thermal smearing in the original experiment. The second part of the experiment was a study of the activation law for the conductivity on the insulating side of the MI transition.

The sample (number 2 from Ref. 7 with $x = 0.325$ and $n = 1.6 \times 10^{20}/\text{cm}^3$) was mounted inside the mixing chamber of a dilution refrigerator capable of temperatures as low as 6 mK. The resistance was measured as a function of magnetic field (perpendicular to the current) by four-probe, ac resistance techniques.

In Fig. 1, the conductivity is plotted as a function of the magnetic field. As expected from the previous experiment, the data are described very well by Eq. (3). On the metallic side, except for the rounding near the metal-insulator transition, the conductivity is proportional to $(H - H_c)$; $\nu = 1.0$. By extrapolating the linear part of $\sigma(H)$ to $\sigma = 0$, we obtain the critical magnetic field $H_c = 3.95$ T. From Eq. (1), with $C = 0.05$ and with a limiting length calculated from the critical concentration for the system [$a_E = n_c^{-1/3} = (8 \times 10^{19}/$

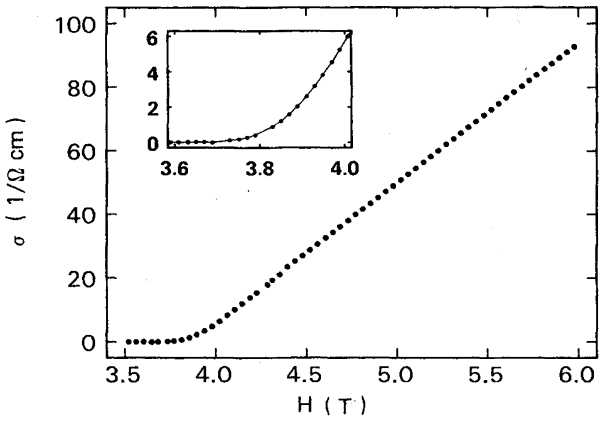

FIG. 1. Conductivity as a function of the magnetic field at $T=6$ mK. For this sample, Mott's minimum metallic conductivity is approximately 50 $(\Omega\,\mathrm{cm})^{-1}$. The insert is an expanded view of the transition region showing the rounding of the transition.

$\mathrm{cm}^3)^{-1/3}=23$ Å], the minimum metallic conductivity is estimated as $\sigma_{\min}\simeq 50$ $(\Omega\,\mathrm{cm})^{-1}$. The experiment clearly precludes this value.

These data are in agreement with both of the scaling theories of the MI transition: the localization theory[2] and theory of interactions in a large magnetic field ($\mu_B gH \gg k_B T$).[3] Both predict $\nu=1$. The usual intuition is that as the magnetic field increases, the Landau orbit shrinks, and the electrons become more localized as observed in the experiment on InP.[11] $Gd_{(3-x)}v_xS_4$ exhibits the opposite behavior: as the magnetic field increases, the polaron size increases, and the electron is less localized. [However, even if the Landau orbit size were the limiting confinement length for our sample, at $H=4$ T, $\sigma_{\min}\simeq 10$ $(\Omega\,\mathrm{cm})^{-1}$— still high enough to be excluded by the data in Fig. 1.] It should be mentioned in passing that the authors of Ref. 11 claim that $\sigma_{\min}$ is in evidence in the magnetoresistance of InP. In our opinion, the published data do not support this conclusion, since the (positive) magnetoresistance is continuous in magnetic field. More detailed measurements to search for a discontinuity in InP would be of great interest.

The transition from $\sigma=0$ to $\sigma\propto(H-H_c)$ is smeared slightly (see the insert in Fig. 1). The rounding occurs for $\sigma\lesssim 5$ $(\Omega\,\mathrm{cm})^{-1}$ and for a range of $\delta H_c\simeq 0.1$ T in the critical magnetic field. Since the rounding is independent of temperature (below $T\simeq 0.5$ K) and independent of the ac measurement frequency (above 5 Hz), we believe that it represents the equilibrium transport in the sample and not long thermal or spin-fluctuation relaxation times. Knowing (from Ref. 10) that the gap $(E_F-E_c)\simeq 70$ K at $H=0$ and zero at $H=H_c$, we estimate that $\delta H_c\simeq 0.1$ T corresponds to thermal broadening of ~ 1 K. Since our sample temperature is a factor ~ 100 lower, we are confident that the rounding of $\sigma(H)$ near H_c does not come from thermal broadening. We suppose that it may be the result of inhomogeneity in the distribution of vacancies in the sample. From the proportionality[7] between carrier concentration and H_c, we can show that $\delta H_c\simeq 0.1$ T implies a variation in carrier concentration $\delta n\simeq 4$–$5\times 10^{18}/\mathrm{cm}^3$ or about 3%.

The second phase of the new experiment was a study of the temperature dependence of the conductivity in the insulating phase. On the insulating side of the MI transition,

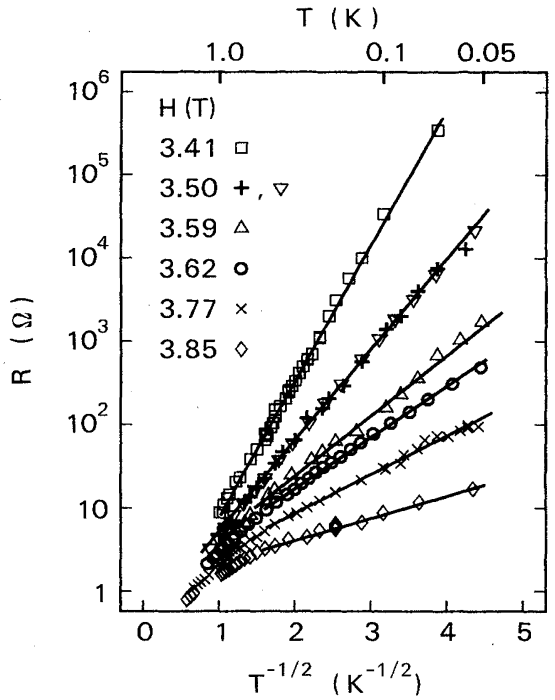

FIG. 2. Resistance as a function of $T^{-1/2}$ at various magnetic field strengths. The straight lines illustrate the region where $\ln(R)\propto T^{-1/2}$ is obeyed.

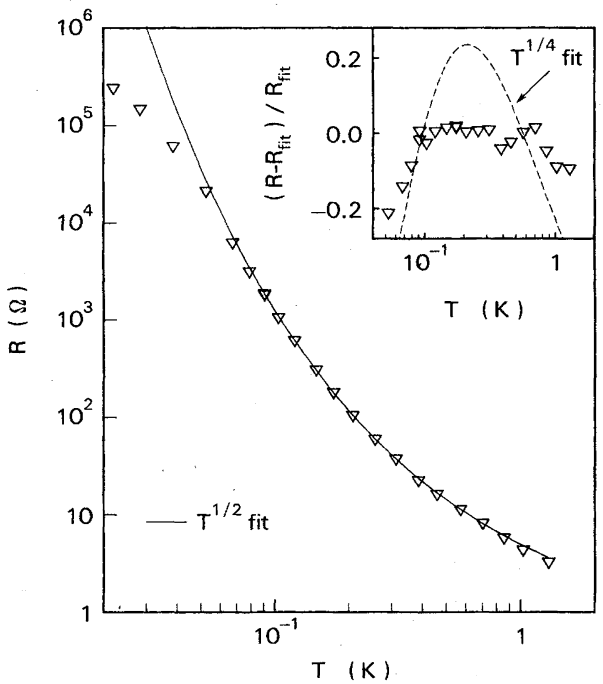

FIG. 3. Resistance data for $H=3.5$ T illustrating the change in the activation law at very low temperatures. The solid line is the fit to resistance predicted by the theory of variable range hopping with interactions $\{R=R_0\exp[(T_0/T)^{1/2}]$ with $R_0=0.38$ Ω and $T_0=6.5$ K$\}$. The insert is a "deviation graph" which compares the fit quality for the exponents $\frac{1}{2}$ and $\frac{1}{4}$. The triangles are the deviation of the data from the best fit to a $T^{-1/2}$ law, and the dashed line represents the best fit of a $T^{-1/4}$ law.

the conductivity is thermally activated. The independent particle model predicts that the resistance of the sample will be given by $\ln(\rho) \propto (T_0/T)^{1/4}$ from the variable range hopping process.[12] An extension of this theory, however, which includes the Coulomb interactions among the carriers[13] predicts a gap in the density of state, and from that, an exponent of $\frac{1}{2}$ in place of $\frac{1}{4}$. We have measured the resistance of our samples in the insulating regime ($H < H_c$), and we find that their behavior is more consistent with the model containing interactions than with pure variable range hopping. Some of our resistance data are plotted versus $T^{-1/2}$ in Fig. 2. Over most of the temperature range the resistance follows the $T^{-1/2}$ activation law indicating that interactions are perturbing the density of states. For low temperatures and low magnetic fields ($k_B T < \Delta_c < E_c - E_F$, where Δ_c is the width of the Coulomb gap), the data fall on straight lines. As H nears H_c, the range of temperature over which the $T^{-1/2}$ law is obeyed shrinks.

The data for $H = 3.5$ T have been replotted in Fig. 3. At temperatures below $T \simeq 70$ mK, the resistance no longer follows the $T^{-1/2}$ dependence. The temperature at which the activation law changes varies from sample to sample, and the resistance at which the change occurs (for a given magnetic field) is independent of the bridge excitation. This leads us to believe that the change in temperature dependence is not the result of spurious heating of the sample. It appears to be due to (as yet undetermined) changes in the physics of the sample. In the insert, we have displayed the same data after subtracting out the fitted $T^{-1/2}$ dependence. We have also included the best fit to the $T^{-1/4}$ law for comparison. The data clearly indicate the importance interactions in the variable range hopping mechanism in the temperature range $0.07\ \text{K} < T < 0.9\ \text{K}$. At temperatures above this range, the exponent is smaller. This may indicate that the temperature is larger than the Coulomb gap (implying $\Delta_c \simeq 0.8$ K at $H = 3.5$ T), and that the conduction is dominated by another mechanism, possibly the pure variable range hopping process. Following this assumption, we may estimate the dielectric constant. From Ref. 13, $\kappa = (e^3\sqrt{g_0}/k_B\Delta_c)^{2/3} \sim 1000$, where g_0 is the unperturbed density of states; this large value implies (as we already knew) that the experiment is performed very near the MI transition.

In summary, we have studied the metal-insulator transition in $Gd_{(3-x)}v_xS_4$ at temperatures down to $T = 6$ mK, and we have found no evidence for a minimum metallic conductivity. Instead the data show a smooth transition from insulator to metal which is consistent with the scaling theories which arise from consideration of either noninteracting electrons (localization) or interacting electrons in a random potential. Studies of the activation of the conductivity on the insulating side of the transition favor the $\ln(\rho) \propto (T_0/T)^{1/2}$ prediction, that is, the theory of variable range hopping in the presence of Coulomb interactions. The weight of the evidence seems, therefore, to support the conclusion that the MI transition is driven by interactions in this system.

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