Corrections to the One-Dimensional Density of States: Observation of a Coulomb Gap?

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We report the first systematic study of the corrections to the electron density of states of a 1D system, ultranarrow granular aluminum wires. These corrections do not have the $V^{-1/2}$ dependence predicted by theory, but are significantly larger than the corrections observed in corresponding bulk samples. At high magnetic fields, low temperatures, and very low voltages, we see evidence of a logarithmic gap in the density of states.

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Over the past two decades, there has been considerable interest in developing a model of conduction in randomly disordered systems and, in the last couple of years, dramatic progress has been made.[1] Localization effects are understood to the point that it is now possible to use the measured transport properties of these systems to determine quantities such as the electron inelastic scattering rate.[2] Interaction effects are expected to influence strongly the single-particle density of states,[3] but have received relatively less attention. Since these effects could not be separated by earlier temperature-dependent resistance measurements, low-field magnetoresistance measurements were employed to isolate and study localization effects.[4] In this experiment, we used another technique, tunneling, to probe interaction effects.

Recently we measured the logarithmic corrections to the density of states in quasi-2D films of quench-condensed tin through the use of tunneling.[5] This is possible because, within smearing factors of a few times kT, a measure of the conductance ($G = dI/dV$) of a metal-insulator-metal tunnel junction is a determination of the relevant density of states. Encouraged by our results in 2D, we have made a similar measurement in 1D where the effect is expected to be larger, but the theoretical understnading is less complete.[4] This study has been done with wires of granular aluminum (Al) and the observed corrections to the density of states, which are attributed to 1D interaction effects, are at least an order of magnitude greater than what is seen in bulk samples of the same material.[6]

We chose to make the 1D wires from granular Al because this material has already been extremely well characterized in 3D. In addition, we were able to vary the bulk resistivity over many orders of magnitude by resistively evaporating Al at ~ 30 Å/sec in partial pressures of oxygen from 8×10^{-5} to 5×10^{-4} Torr. Although we did not measure it, this technique is well established for making granular films with ~ 30-Å Al particle size.[6,7] Since the metal grains are at least an order of magnitude smaller than any important length scale in the problem, the granularity should not influence the effects under study.

To fabricate a wire, we used the shadowing technique described in detail by Flanders and White.[8] After a shallow step was etched in a thermally oxidized silicon wafer, the Al flim was deposited at a glancing angle onto the step edge creating a wire with a square cross section. The advantage of this technique is that the linewidths are precisely determined by easily controlled fabrication parameters: the SiO_2 etch depth and the Al film thickness. After the wire was deposited, it was oxidized in air for 1 h and clean Al counterelectrodes were deposited through a stencil mask. Individual wires were 750×750 Å^2 in cross section and up to 4 mm long with sixteen 25-μm-wide electrodes that were spaced at 250 μm. The electrode configuration was chosen to allow four-terminal measurements of both the junction conductance and the wire resistance.

We varied the resistivity over almost 4 orders of magnitude and evaporated a 2D film along with each wire to monitor the material properties. When the film resistivities are plotted versus the superconducting critical temperatures (T_c), the familiar resistivity versus T_c relation for granular Al (which peaks at a resistivity corresponding to the Mott number) is observed. A comparison with the bulk data of Dynes and Garno[6] shows good agreement. The measured four-terminal resistance of the wires was not more than a factor of 2 larger than what would be predicted from the film in all cases. We attribute any additional resistivity to increased boundary scattering and uncertainty in wire length. When several junctions on the same wire were probed, the junction characteristics were almost identical. Furthermore, the resistive transitions in the films were extremely sharp (~ 10 mK wide) indicating that they were homogeneous on a macroscopic scale. We noticed that, although the resistive transition in the corresponding wire started at the same temperature, it had a long tail, especially at resistivities approaching the Mott number. This could be a result of the competition between localization and superconductivity in the structures, a problem we are currently studying in more detail.

At first, conductance measurements were made with the wires in the superconducting state to insure that

the voltage was being dropped across the junction. The appearance of a sharp superconducting energy-gap structure in the conductance traces is additional evidence for the quality of the junction. Except for structure at the energy gap, the superconducting corrections to G are small compared to the conductance variations in the measurement, and so the data are directly interpreted as the electron density of states, $N(E)$. The junctions were of high quality with conductances below the gap limited by thermal excitations.

A conductance trace for a typical junction is illustrated in Fig. 1(a). The energy-gap structure is clearly visible at about 0 V and the extra noise at ± 25mV is present because the critical current of the wire has been exceeded. The correction to the 1D density of states, seen here as a marked reduction in the junction conductance below 25 mV, is large enough to see in the junction I-V characteristic. Reproducible structure reminiscent of that seen in single 1D loops and wires as a function of field[9,10] was observed in the conductance of junctions on lower-resistivity wires, but unlike localization and interaction effects, the size of this structure does not scale with resistivity.

For the analysis, we chose eleven samples on which we had complete four-terminal measurements of the junction resistance and the junction conductance. A representative selection of these data is shown in Fig. 2 where the junction conductances (normalized to their values at 20 mV) are plotted versus the voltage across the junction. On this scale, the conductance of the low-resistivity samples appears to be almost flat, but, as the sample resistivity increases over 2 orders of magnitude, the low-V corrections reduce the density of states substantially.

For corrections to the density of states resulting from electron-electron interactions, the voltage dependence of the corrections is predicted to vary with the effective dimensionality of the sample, d (Ref. 3):

$$dN \sim \hbar D^{-d/2} |V|^{(d-2)/2}, \quad d=1,3, \tag{1}$$

$$dN \sim \hbar D^{-d/2} \ln[|V|\tau/\hbar], \quad d=2. \tag{2}$$

In these expressions, D is the 3D diffusivity, τ is the elastic scattering time of the electron, and the length scale for determining sample dimensionality is given by $(\hbar D/kT)^{1/2}$. The square-root dependence of the 3D density of states has been confirmed by experiments on several very different systems[6,11] and the 2D logarithmic dependence has been established in indium oxide[12] and tin films.[5] In 2D and 3D, then, experiments confirm the behavior predicted by (1) and (2).

The Al'tshuler and Aronov prediction for 1D systems is more difficult to understand. From scaling arguments, we expect a wire to be an insulator at $T=0$, and so the 1D density of states should vanish at the Fermi level ($V=0$), rather than diverge as (1) suggests. In an earlier paper, Efros and Shklovskii[13] did show that Coulomb interactions between localized electron states generally imply that the electron density of states goes to zero at the Fermi level. Using a simple energy argument, they demonstrate that, in 2D and 3D, the density of states scales as $N(E) \propto |E|^{d-1}$. In the 1D case, these simple arguments do not explicitly lead to a gap; however, Efros and Shklovskii found that, for various model interactions, a gap is created. They are vague about the functional form of this gap

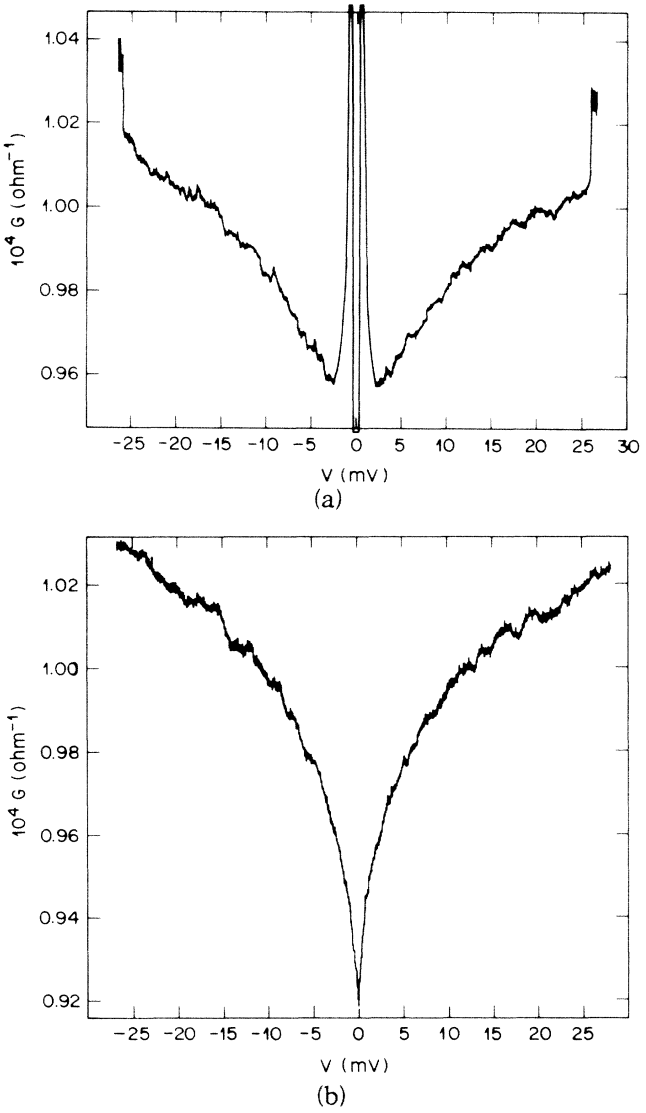

FIG. 1. (a) Trace of conductance (G) vs applied voltage (V) for a 100000-Ω junction at ~ 1.2 K. The granular Al wire had resistivity $= 8.2\times 10^{-5}$ Ω cm. Note the superconducting energy-gap structure at ~ 0 V and the extra noise due to I_c at ± 25 mV. (b) High-field (60 kG) conductance for the junction in (a). The dramatic dip at ~ 0 V was previously obscured by the superconducting energy-gap structure.

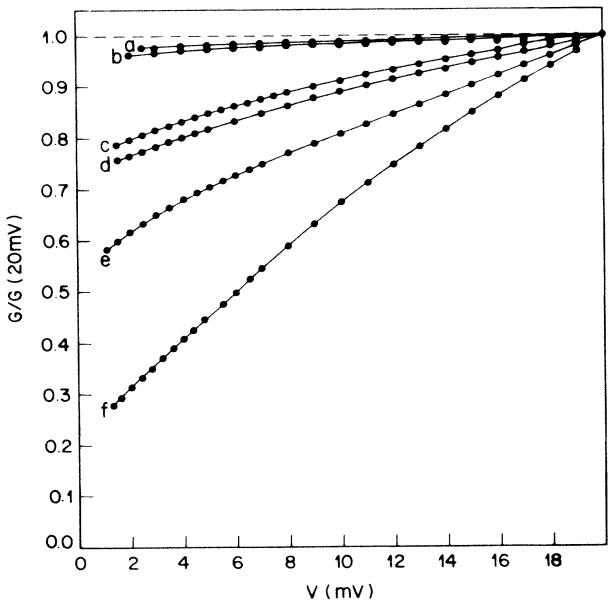

FIG. 2. Junction conductance normalized to $G(20\ \text{mV})$ vs applied voltage (V) on a linear scale for six granular Al wires with resistivities (a) 1.72×10^{-5} Ω cm, (b) 5.13×10^{-5} Ω cm, (c) 5.50×10^{-4} Ω cm, (d) 7.43×10^{-4} Ω cm, (e) 1.33×10^{-3} Ω cm, (f) 2.20×10^{-3} Ω cm.

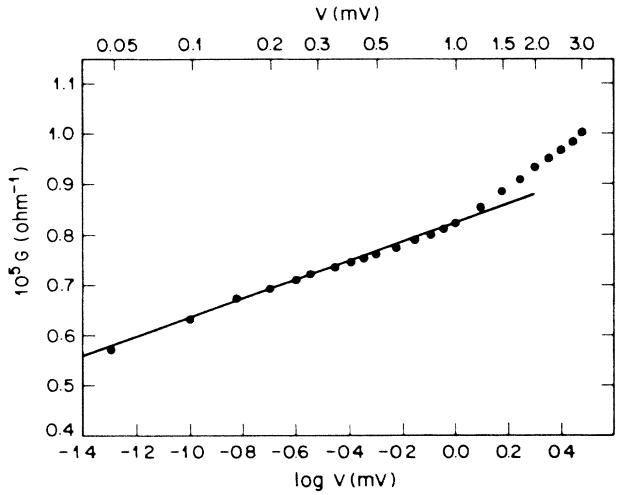

FIG. 3. Low-V conductance (in the region of the dip) vs applied voltage on a logarithmic scale for a wire with resistivity $=1.86\times10^{-3}$ Ω cm. Data were taken at 50 mK.

since it appears to depend on the particular model chosen, but they do suggest that the density of states should tend to zero at the Fermi level with a dependence on V that is slower than linear (and possibly logarithmic). Although some form of this "Coulomb gap" is expected in an interacting system, until now it has not been observed.

We have attempted to fit the data of Fig. 2 by the form suggested in Eq. (1) and find that there is no range of voltage over which we obtain a convincing fit. Neither at low V or at high V do we find a linear dependence of dI/dV vs $V^{-1/2}$. In order to address questions about the dimensionality of the samples, we also compared the data with the 3D expression. The fits in this case are better, but not nearly as good as those obtained for 3D granular Al samples. Moreover, the size of the effect (determined from the slopes) is at least an order of magnitude larger than the effect in corresponding 3D samples. In fact, most of our data are from samples in a resistivity range where there was no measurable 3D effect. We found that wires of material with 3D resistivities greater than twice the Mott number were insulating at low temperatures.

The qualitative expectation in this experiment was that, if these wires were 1D, the density of states would go to zero at E_F. When we found in Fig. 2 that an extrapolation to low voltage suggests a *finite* density of states at $V=0$, it became clear that a careful investigation of this quantity at low V was important. This region was obscured by the energy gap structure for wires in the superconducting state, and so a magnetic field (up to 100 kG) was applied to quench the superconductivity. The results were startling. As seen in Fig. 1(b) for the junction from Fig. 1(a), the conductance falls off rapidly in the region that was previously obscured.

Notice that, although the high-field trace is slightly noisier, the structure at higher V in Fig. 1(a) is reproduced in Fig. 1(b), so that our interpretation of G as $N(E)$ is still valid. The dip, which has been observed now in four samples with resistivities that span the range of the data, showed no field dependence between 35 and 100 kG and seemed to be rounded off by kT smearing in all samples to as low a temperature as 50 mK. A detailed study of the temperature dependence of the dip showed that the rounding occurred at approximately $5.4k_BT$, consistent with the latter conclusion. Although the variation is not large enough to make possible a conclusive statement about the functional form of the conductance, $G(V)$ in the dip is certainly consistent with $\ln(V)$ over one decade of voltage (see Fig. 3).

This "logarithmic" dependence is observed over a very small energy range and it dominates only below 1 mV in the samples studied. The range does depend, in a weak way, on the resistance of the wire, with the higher-resistance samples showing the effects to higher energy. It is expected that at lower temperatures the lower-voltage behavior will persist. This apparent logarithmic depression of the density of states resolves the problem from Fig. 2 [where it appears that $N(0)$ is finite] and suggests the possibility that this is a manifestation of a "Coulomb gap" in a 1D wire. At higher voltages, the logarithmic behavior is dwarfed by

the power-law dependence. Although the functional form is not as predicted, this power-law dependence could be some form of the corrections calculated by Al'tshuler and Aronov.

We do expect an energy-dependent crossover from 1D to 3D for our samples. However, the observation of a strong voltage dependence above 1 mV in these wires (in contrast to the 3D samples), the apparently logarithmic voltage dependence below this energy, and the $R_{\square}$ dependence of the crossover region all suggest that simply ascribing this to a dimensional crossover is not correct. Moreover, we have ruled out heating and corrections to the tunneling matrix elements as possible explanations because this is a zero-bias effect which is *not* seen in bulk samples of the same material.

In conclusion, we have measured the corrections to the 1D density of states in granular Al wires and find that they are much larger than the corrections in corresponding 3D samples. The 1D data do not agree with the theoretical prediction, $G(V) \sim V^{-1/2}$, but it is not clear over what voltage range the theory applies. At high magnetic fields, a dramatic dip appears in the low-V conductance and we speculate that we are perhaps observing the Efros-Shklovskii Coulomb gap.

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