Resistance Fluctuations in Thin Bi Wires and Films

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We have observed fluctuations in the low-temperature resistance of small-diameter Bi wires, and Bi films. These fluctuations appear most clearly as a function of time. They become larger as the sample is made shorter, and as the temperature is reduced. Their magnitude and temperature dependence are in reasonable agreement with the recently developed theory of "universal" resistance fluctuations in one- and two-dimensional conductors. According to the theory, the fluctuations we have observed are due to the motion of single (or a small number of) scattering centers.

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When one discusses the properties of a disordered system, it is common to consider an average over the impurity distribution. This is equivalent to performing an average over an ensemble of statistically similar systems, and is usually appropriate for describing a real macroscopic system. However, recent work has shown that for a disordered conductor, ensemble averaging is sometimes not appropriate.[1-9] In this case, the relevant length scale which determines if a system will "self-average" is the phase-breaking length, L_ϕ, which is the length over which an electron loses phase coherence, typically by inelastic scattering. A system whose dimensions are comparable to or less than L_ϕ, must be treated as a single member of an ensemble of statistically similar systems. It is then necessary to estimate the fluctuations of a given property as one considers different members of the ensemble. The theory[2,3] predicts that the fluctuations in the conductance, δG, have a universal magnitude which is of order e^2/h. These fluctuations have been observed in narrow Au and Au-Pd strips (i.e., wires),[10] and in narrow metal-oxide-semiconductor field-effect-transistor-type structures.[11-13] In this paper we report observation of fluctuations in thin Bi wires and films. The fluctuations that we find appear, in some cases, to be due to the motion of single scattering centers.

Thin Bi films were produced by dc sputtering onto glass substrates which were cooled to 77 K. They had resistivities of 2.4×10^{-3} Ω cm at 4 K. Thin (i.e., very-small-diameter) wires were fabricated from these films by use of substrate step techniques.[14]

Results for the resistance as a function of temperature for a wire which was 460 Å in diameter and 60 μm long are shown in Fig. 1. Each symbol represents an average over approximately two minutes of measuring time, and the different readings at a given temperature were obtained approximately fifteen minutes apart. It can be seen that there are fluctuations among the values obtained at any given (fixed) temperature. Above about 0.8 K, the magnitude of these fluctuations is approximately constant, and is equal to the noise in the resistance-measuring system. However, at lower temperatures the fluctuations are seen to grow much larger. These are the universal conductance fluctuations. We also note that in Fig. 1 the resistance levels off, or even decreases somewhat, at the lowest temperatures. This behavior can be understood in terms of a competition between localization and electron-electron interaction effects. It is not of interest for the present discussion, and will be considered in detail elsewhere.[15]

The results in Fig. 1 show that the universal fluctuations can be observed in a single sample. According to the theory,[5,7] a *single* scattering center must move at least a distance k_F^{-1} to effectively change from one member of the ensemble to another. If in addition, $k_F L_e$ is of order unity, where L_e is the elastic mean free path, this will, on the average, cause a fluctuation in the conductance $\overline{\delta G} \sim e^2/h$. For our Bi we estimate $k_F^{-1} \sim 3.9$ Å, and $k_F L_e \sim 2.0$. The motion of scattering centers can

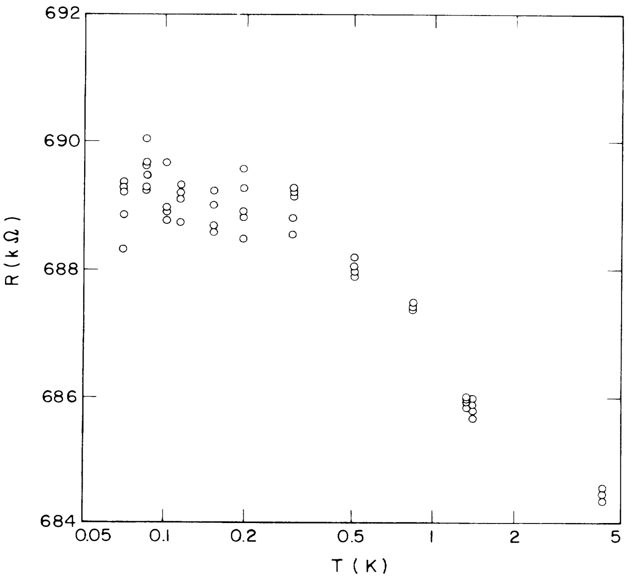

FIG. 1. Resistance as a function of temperature for a thin Bi wire.

thus lead to large fluctuations of the sample resistance with time, even when the temperature, etc., is held fixed. This is precisely the behavior seen in Fig. 1.

Figure 2 shows results for the "peak-to-peak" fluctuation, observed in measurements like those in Fig. 1, as a function of temperature. Here we show data for the wire considered in Fig. 1, and also for a film whose length, width, and thickness were 16 μm, 8 μm, and 70 Å, respectively. For both samples the magnitude of the fluctuations is seen to increase as the temperature is reduced. There is a large amount of scatter in the data, which is inevitable given the nature of the phenomena, and the manner in which we have measured the fluctuations. However, in both cases the fluctuations at the lowest temperatures are about an order of magnitude larger than at the highest temperatures. Simultaneous measurements on much longer samples, which would not be expected to exhibit the universal fluctuations, showed fluctuations only at the level of the system noise at all temperatures. In addition, measurements on samples of different sizes, both larger and smaller than those considered in Fig. 2, showed that the universal fluctuations become larger as the sample size is reduced.

In Fig. 3 we show the resistance of the thin film considered in Fig. 2 as a function of time. Here the resistance was measured once every second, and the sample was monitored continuously. We see that the resistance is constant (aside from the system noise) for relatively long periods of time, but that abrupt transitions occur at which the resistance switches to a new value. In addition, the sample resistance often switches back to its original value. This behavior is consistent with the interpretation mentioned above; namely, the resistance changes occur when a single scattering center changes location. The resistance then switches back and forth between two different values, as the scattering center moves between two different, and nearly energetically equivalent, positions. The magnitude of the switching events seen in Fig. 3 is the same as that of the fluctuations seen (at the same temperature) in Fig. 2, indicating that the two different measurements refer to the same fluctuations. Hence, we believe that the fluctuations seen in Figs. 1 and 2 are due to switching events like those in Fig. 3. While many of the events we have observed are similar to Fig. 3, some show much slower changes, occurring over a span of many minutes, suggesting that many atoms are involved in some kind of structural rearrangement. Nevertheless, these slower fluctuations are of the same magnitude as the fast fluctuations shown in Fig. 3. This will all be discussed in more detail elsewhere.[16]

The theory predicts that the magnitude of the conductance fluctuations, for a sample whose dimensions are less than the phase-breaking length, is, on average, given by[2-5,7] $\overline{\delta G}\cong e^2/h$. A sample which is larger than L_ϕ can be thought of as a combination of independent subsys-

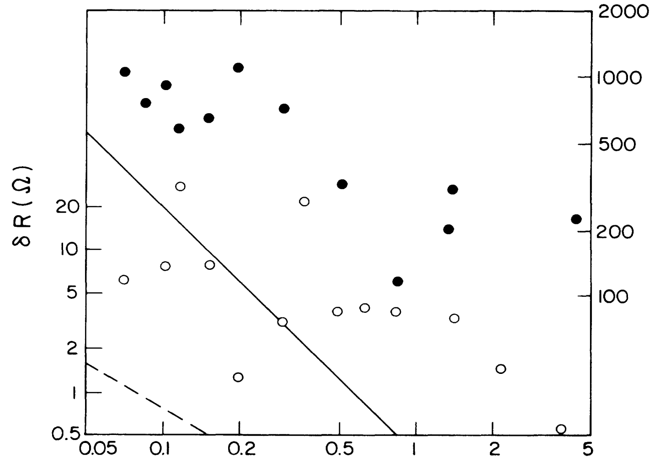

FIG. 2. Magnitude of the fluctuations, as derived from measurements like those in Fig. 1, as a function of temperature for two samples. Open circles (right scale) are for the wire considered in Fig. 1. Filled circles (left scale) are for a thin film; this sample had a low-temperature resistance of approximately 7900 Ω. The lines are the theoretical prediction $\overline{\delta G_1}$; the solid line is for the wire and the dashed line is for the film. For both samples the noise at the highest temperatures is, to within the uncertainties, equal to the system noise. Note also that the system noise has not been subtracted from these results.

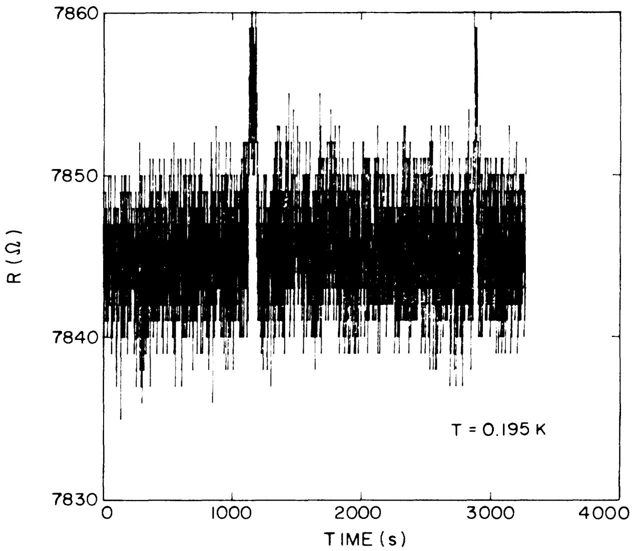

FIG. 3. Resistance as a function of time for the thin film considered in Fig. 2, at $T=0.19$ K. The rapid fluctuations seen, e.g., for times less than 500 s, are due to the *system noise.* The fluctuations of interest here are the changes in the resistance which have a magnitude of approximately 15 Ω for this sample. Such switching events, which are due to the universal fluctuations, occur here at time ~1200 and 2900 s. The digitizing resolution of the apparatus was 1 Ω, and this is also visible in the figure.

tems, each of size L_ϕ (in length and/or width). If one assumes that *all* of the subsystems are fluctuating independently, one finds[17,18] $\overline{\delta G} = (L_\phi/L)^{3/2}e^2h$, in one dimension, and

$$\delta G = (W/L_\phi)^{1/2}(L_\phi/L)^{3/2}e^2/h,$$

in two dimensions. Here L and W are the sample length and width, respectively. However, it is possible that only one of the subsystems fluctuates, while the rest are "inactive." In this case one finds a different result,[7] $\overline{\delta G_1} = (L_\phi/L)^2 e^2/h$, in both one and two dimensions. The sample size can be measured very easily, and the only other (sample dependent) parameter in the theory is L_ϕ. This can be obtained from magnetoresistance measurements of weak-localization effects,[19] which we have performed on these a number of other similar samples.[16,20]

The results in Fig. 3 suggest that only a single subsystem is fluctuating, and if so, $\overline{\delta G_1}$ is appropriate. If we use the results for L_ϕ obtained from magnetoresistance studies, they yield the lines in Fig. 2. We see that the theory is too low by about an order of magnitude. Given that the theory of subsystem averaging is only a qualitative one, and the experimental uncertainties in estimating quantities such as k_F, L_e, and L_ϕ from independent measurements, this level of agreement is reasonable. It is quite conceivable that a quantitative treatment of the averaging effects could yield corrections which could bring the theory into agreement with our results.[21] Another source of uncertainty in the analysis concerns precisely how to (experimentally) properly average the sizes of the fluctuations (e.g., peak to peak versus rms), and also not discriminate against, for example, the smaller fluctuations. These problems can and will be addressed in future experiments. It is also conceivable that the fluctuations we observe are due to fluctuations in many subsystems. The predictions for this case are about a factor of 10 higher than the lines in Fig. 2, and are thus in somewhat better agreement with our results. However, the results in Fig. 3 seem to suggest that in this case only one subsystem is fluctuating, and hence that $\overline{\delta G_1}$ is indeed appropriate.

It is important to put our work into perspective with previous results in this area. First, our sample dimensions, as compared with L_ϕ, were much larger than in previous experiments, which has allowed us to test the theory in the limit in which a significant amount of ensemble averaging occurs. Second, we have been able to use magnetoresistance measurements in conjunction with the theory of weak localization to determine L_ϕ in samples which are the same, or essentially[22] the same, as those in which the fluctuations have been studied. In many of the previous experiments this was not accomplished (as the fluctuations themselves sometimes made this impossible), and L_ϕ could only be estimated from measurements on much larger samples. Third, our results for Bi films appear to be the only measurements so far of the fluctuations in two dimensions. Finally, our samples exhibit the fluctuations most clearly as a function of time, in contrast to nearly all previous cases, where the fluctuations were observed as a function of magnetic field and/or Fermi energy.[23]

In summary, we have observed resistance fluctuations in thin Bi wires and films. We have presented detailed results for the magnitude and temperature dependence of the fluctuations, and also for the temporal behavior. Our results are in reasonable agreement with the theory of universal fluctuations in disordered conductors. So far as we know, this is the first quantitative, or even semiquantitative comparison with the theory of Feng, Lee, and Stone.[7] Our results indicate that, as proposed by those authors, it should be possible to use these fluctuations as a tool to study the dynamics of scattering centers in disordered conductors. For example, it is clearly important to determine if the impurity motion observed via measurements similar to those in Fig. 3 is thermally activated, or involves tunneling. This and similar questions can be answered by future experiments.

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[15] It is tempting to ascribe this simply to Joule heating, but magnetoresistance measurements (D. E. Beutler and N. Giordano, to be published) clearly show that the sample is still cooling at temperatures down to at least 0.1 K.

[16] Beutler and Giordano, Ref. 15.

[17] One must also consider "energy" averaging effects (Ref. 6), but it turns out that this is not important for our samples (Ref. 16).

[18] We note that the theory (Refs. 2, 3, and 5) predicts $\overline{\delta G} = Ce^2/h$, where C is a constant of order unity which depends on the dimensionality, etc. (typically C lies in the range 0.5–1.5). In addition, Ref. 7 also predicts that $\overline{\delta G}$ will not take on its "full" value unless the scattering center moves at least a distance k_F^{-1}, and $k_F L_e$ is of order unity. Given the uncertainty in these values and in the measurements, we have not included these factors in evaluating $\overline{\delta G_1}$. They would be expected to reduce the theoretical values by perhaps a factor of 2.

[19] See, for example, G. Bergmann, Phys. Rep. **107**, 1 (1984).

[20] In general, $L_\phi \sim T^{-p/2}$, where $p \sim 1$ for films [see, for example, F. Komori, S. Kobayashi, and W. Sasaki, J. Phys. Soc. Jpn. **52**, 368 (1983)], and we have found $p \sim 0.6-1.5$ for wires, depending on their diameter (with larger wires having larger values of p). For the wire considered here, $L_\phi \sim 1500$ Å at 0.1 K, while for the film, $L_\phi \sim 3000$ Å at 0.1 K. Electron-electron scattering appears to be the dominant source of phase breaking in these samples.

[21] P. A. Lee, private communication.

[22] More precisely, we obtained L_ϕ from direct magnetoresistance measurements on the wire considered in Figs. 1 and 2. These measurements were not made for the film considered in this paper, but were made on films with similar properties, both by us (Ref. 16) and by Komori, Kobayashi, and Sasaki (Ref. 20).

[23] See, however, Ref. 13.