Experimental study of localization and electron-electron interaction effects in thin Au wires

W. D. Williams* and N. Giordano
Department of Physics, Purdue University, West Lafayette, Indiana 47907
(Received 22 November 1985)

We have produced wires with diameters as small as 80 Å by electroplating Au into etched nuclear tracks in mica. At low temperatures T, these wires exhibit a resistance R which increases as T is decreased, and below about 3 K, R varies approximately as $T^{-1/2}$. This, together with the magnitude of the resistance rise, is in reasonable agreement with previous results for somewhat larger lithographically produced wires made from other materials, and appears to be due predominantly to electron-electron interaction effects. The behavior at higher temperatures, 3–7 K, does not follow this functional form, and is somewhat different than has been observed in previous experiments. This behavior is not consistent with expectations based on electron-electron interaction theory alone, but may be accounted for, at least qualitatively, if one assumes that, while interactions are the major contributor to the resistance change, localization is also important in this range. By varying the thickness of the mica, it was possible to make wires as short as 1.5 μm. To within experimental error, the resistance rise is independent of the length of the wire. This appears to be different from the length dependence found for lithographically produced wires.

I. INTRODUCTION

In recent years there has been a great deal of interest in electronic transport in disordered conductors.[1–4] It is now well established that both localization and electron-electron interactions play important roles in these systems. However, while the evidence indicates that theory and experiment are in very reasonable agreement in many cases, most notably in two-dimensional systems, there are also a number of examples in which theory and experiment are not in good accord. One of the latter cases concerns the overall behavior of one-dimensional systems; that is, of thin wires.[5] There have been a number of experimental studies of thin wires,[6–17] and these have shown that while the observed behavior is generally in good qualitative agreement with the theory, there are some significant quantitative discrepancies.[11,17] It turns out that all previous experiments in which the effects of one dimensional localization and electron-electron interactions have been observed involve lithographically produced wires which have all been fabricated from thin films deposited onto various sorts of substrates. Other types of wires, in particular, wires encased in a insulator,[8] and free-standing wires,[9,12] have not shown the expected type of one-dimensional behavior. While there are good explanations for why the nonlithographically produced samples did not behave in this way, it has nevertheless been suggested that perhaps the presence of the substrate, or some similar feature, affects or modifies (for some unspecified reasons) the behavior of the wires. It is therefore of interest to study thin wires produced by nonlithographic methods, and in this paper we report the results of such a study. We have fabricated Au wires by electroplating into the very small diameter cylinders which are produced by etching nuclear tracks in mica. Wires as small as 80 Å in diameter have been made in this way, which is significantly smaller than any other nonlithographic wires which have been produced to date. We find that these wires exhibit behavior which is very similar to that found in lithographically produced samples. There are, however, some differences in detail, the significance of which is not clear at this time. While our Au wires are not free standing as perhaps might have been desired, they are certainly quite different from the lithographically produced samples, and thus we feel that our results strongly support the contention that the effects seen in the latter are not due to some peculiarities of the samples, but are indeed a universal property of thin wires. We should also note that a second motivation for our experiments was that all of the previous (successful) experiments with thin wires had involved samples made from high-resistivity alloys. It was therefore of interest to examine the behavior of wires composed of a relatively low-resistivity elemental metal. While our work was in progress, experiments with wires of this kind were reported by White *et al.*[13] As we will see, our results are in good agreement with their findings.

The remainder of this paper is organized as follows. In Sec. II, we briefly discuss the theories of localization and electron-electron interactions. In Sec. III the method used to fabricate the wires studied in this work is described, along with the measurement technique. Section IV contains our results, together with a comparison with the theories and with previous work. Section V gives the results of experiments in which the behavior was studied as a function of the length of the wire, and Sec. VI contains our conclusions.

II. THEORY

The theories of localization and electron-electron interactions have recently been reviewed elsewhere.[1–4] Here

we will only give a very brief discussion of the theoretical predictions which are relevant to our experiments. We begin with the theory of localization.

Theoretical work[5,18–20] has shown that a long wire will contain only localized states, and that the size of a localized state along the wire, $L_{\rm loc}$, is equal to the length of wire which has a residual resistance of order $2\hbar/e^2$, which is approximately 8 kΩ. Thus, at very low temperatures any wire which is longer than this will conduct via a hopping type of mechanism, and will therefore be an insulator at absolute zero. It turns out that all experiments to date with thin wires have been conducted at temperatures sufficiently high that hopping conduction was not observed.[21] In the high-temperature regime appropriate to our experiments, the theory predicts that in the absence of any spin dependent scattering, localization will cause a thin wire to have an extra resistance, ΔR, which is of the form

$$\frac{\Delta R}{R_0} = \frac{L_{\rm in}}{L_{\rm loc}} = \frac{(D\tau_i)^{1/2}}{L_{\rm loc}} . \tag{1}$$

Here R_0 is the residual resistance, $L_{\rm in}$ is the inelastic diffusion length, which is the distance an electron diffuses between inelastic scattering events, D is the electron diffusion constant (which arises from the elastic scattering), and τ_i is the inelastic scattering time. Recent work[17,22] has shown that $L_{\rm loc}$ corresponds to a residual resistance of $R_T = 2\pi\hbar/e^2 \sim 25.8$ kΩ, so that (1) can be rewritten as

$$\frac{\Delta R}{R_0} = \frac{\rho(D\tau_i)^{1/2}}{AR_T} , \tag{2}$$

where A is the cross-sectional area of the wire, and ρ is the residual resistivity. Hence, the resistance should increase as the wire is made smaller, as the temperature is lowered (since this will cause τ_i to increase), and as ρ is increased. Since $D \sim 1/\rho$, (2) predicts that $\Delta R/R_0$ will vary as $\rho^{1/2}$.

The prediction (2) is expected to be appropriate in the limit that spin-dependent scattering is negligible. However, this is almost certainly not the case for Au. Indeed, from experiments on thin films we would expect that Au should be in the strong spin-orbit scattering limit.[2–4] In analogy with the case in two dimensions, and with some recent calculations,[2–4,15] we expect that, to a first approximation, spin-orbit effects will change the sign of ΔR in (2), and reduce its magnitude by typically a factor of two. Thus, in this case localization causes the resistance to decrease as the temperature is lowered. Whether or not spin-orbit scattering is important, the temperature dependence of ΔR is determined by τ_i. It is generally expected, and commonly found, that τ_i varies with temperature as $\tau_i \sim T^{-p}$, where p is a small integer, typically 1 or 2. The value of p depends on the dominant inelastic scattering mechanism.[2,5,10]

In addition to localization, electron-electron interactions also cause an anomaly in the resistance at low temperatures. The theory predicts that interactions will cause a resistance rise of the form[4,23,24]

$$\frac{\Delta R}{R_0} = \frac{(2 - \frac{3}{4}F)\rho}{AR_T} \left[\frac{2D\hbar}{k_B T}\right]^{1/2} , \tag{3}$$

where F is a (positive) screening factor which is less than unity. Note that electron-electron interactions are expected to be distinct from localization; the quantity R_T appears in (3) only because the same combinations of fundamental constants happen to arise in interaction theory. Comparing (3) with the discussion in the previous paragraph, we see that the two theories make similar predictions, except that for our Au wires the resistance rise due to localization should, because of spin-orbit scattering, be negative, in contrast to (3), which is always positive. In real wires we would expect both localization and interactions to be present. Unfortunately, it is not clear how the two effects will combine; i.e., whether their effects are simply additive, or if they can interfere in some way. In two dimensions they appear to simply add.[2] Some previous experiments with thin wires[11,17] are not consistent with (2) (as modified by spin-orbit effects) or (3) alone, or with a simple addition of the two predictions, although other recent experiments in this area[15,16] do appear to be consistent with this method of combining the two effects.

III. EXPERIMENTAL TECHNIQUE

A. Fabrication

For this work, we have fabricated Au wires as small as 80 Å in diameter using a method first described by Possin.[25] The details of the method and the refinements we have developed have been reported elsewhere.[26,27] Here we will only give a brief description of the technique with an emphasis on those features which are most relevant to our experiments.

Initially a piece of mica, typically 5 μm thick, was irradiated with fission fragments from a ^{252}Cf source. This produced damage tracks which were then etched out with dilute HF to give cylindrical holes in the mica.[28] A film of Ag was then evaporated onto one side of the mica. Next a drop of electroplating solution was placed onto the opposite side of the mica, an electrode was placed into the solution, and Au was electroplated into the etched tracks. After the tracks were filled with Au, a layer of Ag was evaporated onto the open side of the mica. The result was a collection of thin Au wires connected to two Ag films which served as contacts. The diameter of the etched tracks, and hence also the size of the wires, was varied by varying the etching time, and could be as small as 80 Å.

It was obviously very important to determine the size of the etched tracks, since this determined the size of the resulting wire. The track size was measured *in situ* during the etching process using a technique developed by Bean and co-workers.[29] The acid used to etch the mica, in our case dilute HF, was used as an electrolyte to measure the conductance of the track (filled with electrolyte). From the measured conductance the size of the etched track could be determined as the etching was taking place. The size of the resulting track could also be confirmed after the etching process was completed by filling the track with an electrolyte which did not etch the mica, such as a

KCl solution, and measuring the conductance.[29] A final check was obtained via direct observation with either a transmission or scanning electron microscope.[27] These methods of measuring the track size all gave the same result to within the overall errors of about 10%. Since they agreed for selected samples, in practice the measurement with the HF solution was the only one made in the majority of cases.

It is important to note that each piece of mica contained more than one etched track, and hence in general more than one wire. Since the tracks, and thus also the wires, in a given piece of mica were all approximately the same size,[30] this was not a problem. The number of tracks in a sample was chosen to optimize the overall yield without making the sample resistance inconveniently small. The smallest wires had the lowest yield (as measured by the number of continuous wires produced per etched track), so these samples were made with the largest numbers of etched tracks. The samples with larger wires had higher yields, and hence these were prepared with smaller numbers of tracks. Unfortunately, the number of wires in a given sample could not be determined precisely from the known number of tracks, since an unknown number of the tracks would become blocked during the electroplating process. The procedure used to determine the number of wires in a sample will be described in Sec. IV.

B. Measurement system

The sample resistance was measured as a function of temperature using a ^{4}He cryostat of standard design.[27] The sample was mounted on a Cu block in a vacuum can which was immersed in liquid ^{4}He. The temperature was measured with an accuracy of better than ± 0.01 K, with a calibrated Ge thermometer mounted on the Cu block. The resolution and stability was approximately ± 0.001 K. The temperature was adjusted and controlled using a heater which was also attached to the Cu block. Since the samples had a resistance typically in the range $1-10^4\ \Omega$, and the cryostat leads had a resistance of about 5 Ω, it was necessary to measure the sample resistance in manner which was insensitive to the lead resistance. This was accomplished using a four-lead arrangement, with two separate leads attached to each side of the sample (i.e., each Ag film), in an ac Kelvin double bridge type setup,[31,27] which employed a PAR 124A lock-in amplifier as the detector. The sample current was always kept sufficiently low that Joule heating (which could be readily observed at high currents) was negligible. Typical currents were in the range $10^{-8}-10^{-4}$ A, depending on the size of the wires and the number which were present in the sample.

IV. EXPERIMENTAL RESULTS AND DISCUSSION

A. Preliminary considerations

As was discussed in the previous section, each sample contained a number of wires, all of the same size, in parallel. The number of wires in a sample could be determined from the known diameter and length of the tracks (and hence wires), together with the measured resistance, assuming that the resistivity is also known. However, there was no simple way of determining the resistivity, since one could not assume that electroplating onto a sheet, etc., would give Au with the same resistivity as electroplating into an etched track. To determine the resistivity of the Au in the tracks, we combined the measured resistances of many samples of various sizes, together with the fact that the number of wires in a given sample must be "quantized." Figure 1 shows some results for ρ_{RT}/N, where ρ_{RT} is the room-temperature resistivity of the Au, and N is the number of wires in the sample. This ratio was derived from the measured room-temperature resistance, R_{RT}, since the two are related by

$$\frac{\rho_{RT}}{N} = \frac{\pi d^2 R_{RT}}{4L_w} , \tag{4}$$

where d is the diameter of the wires in the sample, and L_w is the sample length. Since N cannot be less than unity, the quantity ρ_{RT}/N cannot be greater than ρ_{RT}, corresponding to samples with $N=1$, and it should be less than this for other samples. From Fig. 1 we see that the data are quite consistent with this sort of behavior. The solid line is a guide to the eye, which is drawn so as to pass through the points with the largest values of ρ_{RT}/N, and hence it describes the behavior of samples with only one wire. Data which lie below this line correspond to samples with more than one wire. From this result it is possible to determine both the sample resistivity and the number of wires in a given sample.

The value of the resistivity and its behavior as a function of d will be discussed shortly. However, we should first mention that the results shown in Fig. 1 correspond to *only* the "well-behaved" samples. There were other samples (the results for which are not shown in Fig. 1)

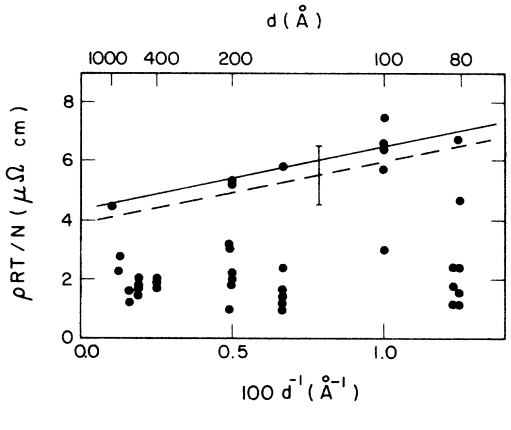

FIG. 1. Room-temperature resistivity, ρ_{RT}, divided by the number of wires in the sample, N, as a function of d^{-1}, where d is the diameter of the wires, for a number of samples. The solid line is a guide to the eye which corresponds to samples which contain one wire ($N=1$), as described in the text. The dashed line, which also corresponds to $N=1$, was obtained from the measured resistance ratio Γ and the known contribution of the phonons to the resistivity, as discussed in the text.

which did, on occasion, give results significantly above the line in Fig. 1, and hence appeared to contain fewer than one wire. However, these samples always became discontinuous upon thermal cycling to low temperatures. This presumably indicates that the wires in these samples were not uniform in cross section, but had constrictions due to impurities (dust, etc.) which found their way into the tracks during the fabrication process. Such constrictions would cause the sample to have a much higher resistance than a corresponding uniform wire, and also make it much more susceptible to developing a discontinuity under the stress developed during thermal cycling. For this reason, we discarded all results for samples which did not survive thermal cycling, and as noted above, data from such samples are not shown in Fig. 1. There were also cases in which the sample resistance increased significantly after thermal cycling, although it did not become infinite. This suggests that some, but not all, of the wires in the sample became discontinuous, and hence that the sample had a potential problem of the sort described above. While most of these "marginal" samples exhibited behavior which was very similar to that of the well-behaved samples, we nevertheless decided to discard the results for such samples. To do this in an objective way, we discarded the results for all samples whose resistance changed by more than 20% after thermal cycling. The results for only about 25% of the samples which survived thermal cycling had to be disregarded for this reason.

Returning to Fig. 1, the solid line corresponds to samples which contained only one wire, and hence this line also gives the resistivity of the Au. The resistivity is seen to increase with decreasing sample diameter. This is not surprising as it is due to simple boundary scattering. The room-temperature resistivity, ρ_{RT}, can, assuming the validity of Matthiesson's rule, be written as a sum of three terms,

$$\rho_{RT} = \rho_{ph} + \rho_i + \rho_b \ , \tag{5}$$

where ρ_{ph} is the contribution from electron-phonon scattering, ρ_i the contribution from bulk impurity scattering, and ρ_b the contribution from boundary scattering. In the large-d limit, ρ_b vanishes. From Fig. 1 we find $\rho_{RT} \sim 4.4\ \mu\Omega$ cm in this case. Using the handbook value[32] of 2.2 $\mu\Omega$ cm for ρ_{ph}, we then find $\rho_i \sim 2.2\ \mu\Omega$ cm, corresponding to an elastic mean free path of approximately 400 Å at low temperatures (i.e., when ρ_{ph} is negligible). From Fig. 1 we also see that for the smallest wires, $\rho_b \sim 2.4\ \mu\Omega$ cm. Using Sondheimer's theory[33] for the effect of boundary scattering, this yields a specularity parameter of about 0.5, which is quite reasonable. The residual resistivity which enters the theory, and which was denoted as ρ in Sec. II, includes all sources of elastic scattering, and thus is equal to the sum of ρ_i and ρ_b. We therefore conclude that ρ is a function of wire size, and varies from $\sim 2.2\ \mu\Omega$ cm for the largest wires to $\sim 4.6\ \mu\Omega$ cm for the smallest wires.

An independent check on this analysis can be obtained from a consideration of the resistance ratio, Γ. Here Γ is taken as the ratio of the room-temperature resistivity to the low-temperature value, $\rho_i + \rho_b$ (since ρ_{ph} is negligible at low temperatures). The latter can be obtained from measurements at 4.2 K, since at this temperature the contributions to the resistance from localization and interaction effects is negligible for our purposes here. Hence Γ is given by

$$\Gamma = \frac{\rho_{RT}}{\rho_i + \rho_b} = \frac{\rho_{ph} + \rho_i + \rho_b}{\rho_i + \rho_b} \ , \tag{6}$$

which yields

$$\rho_{RT} = \rho_{ph} \left[\frac{\Gamma}{\Gamma - 1} \right] . \tag{7}$$

The measured values of Γ were in the range 1.4—1.9, and decreased as the wire diameter was decreased. Using $\rho_{ph} = 2.2\ \mu\Omega$ cm, and the measured values of Γ, (7) yields the dashed line in Fig. 1. The error bar indicates the approximate (maximum) scatter of the individual values (which for purposes of clarity are not shown) from the dashed line. We see that the values of ρ_{RT} derived from the measured resistance ratios are in very reasonable agreement with those found in the first analysis described above. This provides an important independent check on our determination of ρ_{RT}, ρ_i, and ρ_b.

B. Results

Figure 2 shows some typical results for the resistance as a function of temperature for samples of several different sizes. These samples, and all other samples discussed in this section, were 5 μm long. We see that the resistance increases as the temperature is decreased, and that the resistance increase becomes larger as the sample is made smaller. This is in qualitative accord with the theory,[5,18–20] and with previous experiments.[6,7,10,11,13–17] At the highest temperatures shown there is a slight resistance increase. This increase continues above 10 K, and is due to ordinary inelastic processes, such as electron-phonon scattering, which become increasingly important in this range. The results shown in Fig. 2 were reproducible to approximately the size of the symbols, provided that the sample was kept at low temperatures. The reproducibility after thermal cycling was not as good, presum-

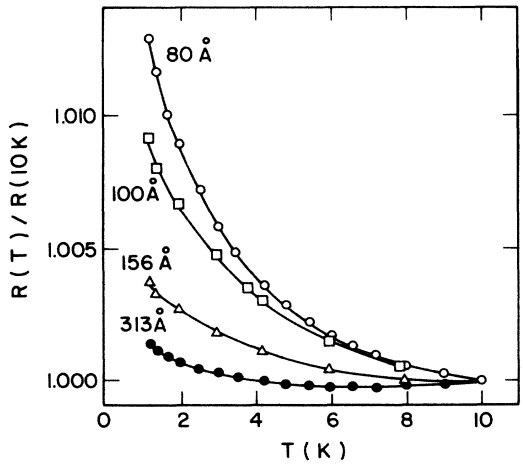

FIG. 2. Resistance as a function of temperature for several samples. The wire diameters for the different samples are indicated in the figure.

ably because the sample could lose one or more wires (while still passing the "20%" test described above). This could have a small effect on the average wire size, and hence also the fractional resistance increase.

The overall magnitude of the resistance increase is illustrated in Fig. 3, which shows the fractional resistance increase from 4.2 to 1.2 K as a function of A^{-1}, where A is the cross-sectional area of the sample. The data in Fig. 3 were obtained from measurements on 11 different samples; about 30% of the samples were remeasured after thermal cycling, and in these cases both results are shown. The sample-to-sample scatter is seen to be consistent with the 10% uncertainty in the wire diameter (and hence 20% uncertainty in A). A notable feature of Fig. 3 is that the resistance increase does not vanish as A^{-1} goes to zero, i.e., in the bulk limit, as would have been expected from (2) and (3). This is presumably due to the Kondo effect. It is well known that relatively small concentrations of magnetic impurities yield a sizable Kondo effect in Au. For example, only about 0.003 at. % Fe is necessary[34] to produce the resistance rise observed in Fig. 3 when $A^{-1}=0$. The impurity concentration of our electroplating deposit was, according to the manufacturer,[35] as much as three times larger than this, so it seems quite reasonable to suppose that magnetic impurities are the cause of the bulk resistance rise seen in Fig. 3. Since this effect should be present in all of the samples, and moreover it is fairly small compared to the resistance rise found in the smallest wires, it can easily be accounted for in our comparison with the theory in the following.

According to the theory, and also previous experiments, the fractional resistance rise should vary as A^{-1}. The dashed line in Fig. 3 corresponds to this form, and it is seen that while this prediction is in qualitative agreement with our results, there are some slight systematic deviations. However, we should note that this dependence on A is found only when quantities such as τ_i and ρ [see (2) and (3)] are independent of A. We have seen in connection with Fig. 1 that this is not the case for the residual resistivity, ρ. According to the theory, $\Delta R/R_0$ should vary as $\rho^{1/2}/A$ (this follows directly from interaction theory, or from localization theory if one assumes that τ_i is independent of A). The dependence of this quantity on A, using the measured dependence of ρ on A, is shown by the solid line in Fig. 3, and is seen to be in somewhat better agreement with our results than the simple A^{-1} dependence. We therefore conclude that our results are consistent with the theory provided that the area dependence of ρ is taken into account. This has not been necessary in the analysis of previous experiments, since in those cases the contribution of boundary scattering to ρ has been negligible, and hence ρ has been independent of A. We should note that our results are not accurate enough to provide a stringent test of the dependence on ρ in the present case. That is, we cannot rule out a dependence of the form $\rho^{1/4}/A$ or ρ/A. However, we can conclude that a $\rho^{1/2}/A$ dependence is in better agreement with our results than a simple A^{-1} form.

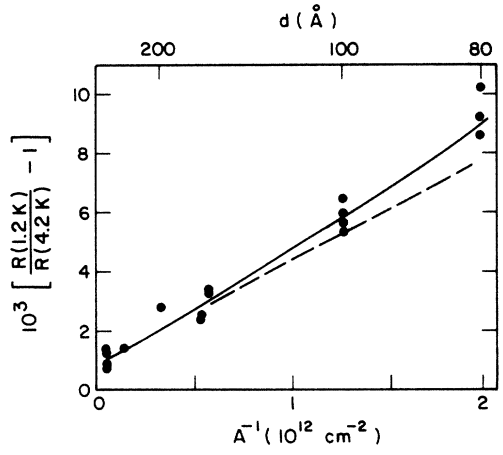

FIG. 3. Fractional resistance rise from 4.2 to 1.2 K as a function of A^{-1}, where A is the cross-sectional area of the wires. The dashed line is drawn proportional to A^{-1}, while the solid line is proportional to $\rho^{1/2}/A$, where ρ is the low-temperature resistivity.

C. Comparison with theory

We will first compare our results with the two theories, interactions and localization, separately. We will find that neither theory, by itself, can describe all of the important features of our data. However, we will see that with some fairly plausible assumptions, the two mechanisms together can account for our results.

As discussed in Sec. II, interaction theory predicts that the fractional resistance rise will vary as $T^{-1/2}$. Figure 4 shows the data from Fig. 2 replotted so as to compare with this temperature dependence. We see that it is consistent with our results at the lowest temperatures, but above about 3 K there are substantial deviations toward lower values of $\Delta R/R_0$. One would expect there to be deviations at high temperatures due to ordinary inelastic processes such as electron-phonon scattering, etc., but

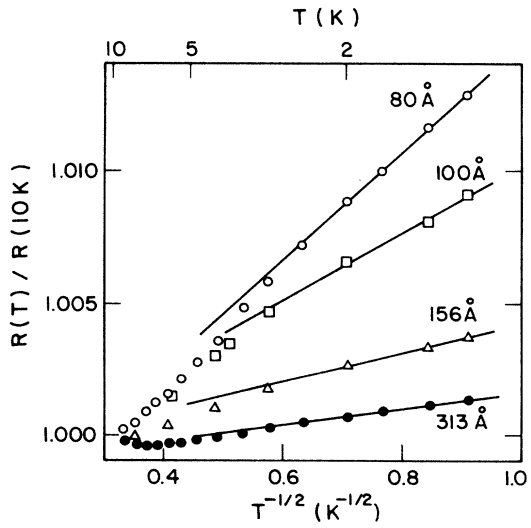

FIG. 4. Resistance as a function of $T^{-1/2}$, for the same samples as considered in Fig. 2. The solid lines are guides to the eye.

these deviations should be towards *higher* values of $\Delta R/R_0$, in contrast to what is seen in Fig. 4. Our results are thus not consistent with electron-electron interactions alone, since this mechanism yields a $T^{-1/2}$ dependence with only positive deviations at high temperatures. It is nevertheless useful to compare the overall size of the rise we observe with the prediction of interaction theory, (3). Using the measured value of ρ together with known data for Au, we estimate an elastic mean free path of 200 Å for our smallest wires. Assuming a Fermi wave vector of 1.2×10^8 cm^{-1} then yields[36] a diffusion constant of $D=80$ cm^2/s. If we demand that the theory, (3), fit the results for our smallest wires, we find that the screening factor F is approximately 0.9. Since according to the theory F must lie between 0 and 1, this result is quite reasonable,[37] and we conclude that except for the problem with the negative deviations mentioned above, interaction theory is quantitatively consistent with our results.

The temperature dependence of the resistance change predicted by localization theory is, as discussed in Sec. II, determined by the inelastic scattering time, while the sign of the resistance change depends on the strength of the spin-orbit scattering. Possible inelastic scattering mechanisms and their temperature dependences have been discussed elsewhere.[2,5,10,15] Previous experiments have observed a resistance rise which varies as $T^{-1/2}$, and if this is due to localization,[38] then the inelastic scattering time τ_i must vary as T^{-1}. As noted in connection with Fig. 4, our results are consistent with a $T^{-1/2}$ dependence at the lowest temperatures. However, this dependence is consistent with the data over only a rather small temperature range, and it is therefore worthwhile to consider other possible temperature dependences. Since τ_i will generally vary as a power of T, we expect ΔR to also vary as a power of T. In Fig. 5 we replot the data of Fig. 4, but now as a function of $T^{-1/4}$. This temperature dependence is seen to be somewhat more consistent with our results than a $T^{-1/2}$ dependence, as the data follow this

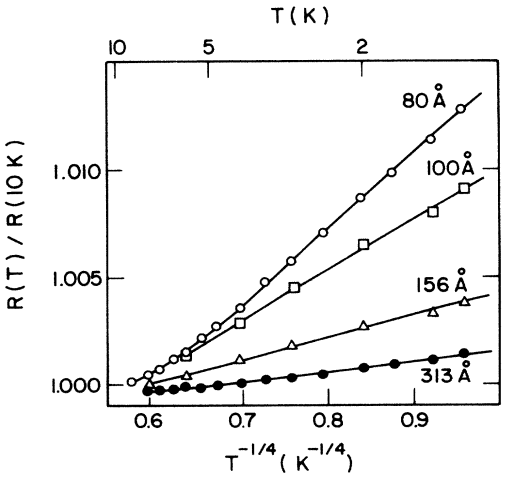

FIG. 5. Resistance as a function of $T^{-1/4}$, for the same samples as considered in Fig. 2. The solid lines are guides to the eye.

form over a larger temperature range. In addition, the deviations at high temperatures are now positive, as would be expected from ordinary electron-phonon scattering, etc. Other temperature dependences, such as a $\log(T)$ dependence, do not describe the data as well as found in Fig. 5. From these observations, one might be tempted to conclude that the observed resistance rise is due to localization with an inelastic scattering time which varies[38] as $T^{-1/2}$. So far as we know, the only inelastic scattering mechanism which could be applicable in our case, and for which τ_i has a temperature dependence which is close to this, is one-dimensional electron-electron scattering in the presence of disorder.[39] While this scattering time also depends on the cross-sectional area of the wire, A, it may still be consistent with our results for the dependence of the resistance change on A. However, a serious problem with this explanation is that the strong spin-orbit scattering in Au should make the contribution to $\Delta R/R_0$ from localization negative, which clearly is not what we observe. For this reason we are forced to conclude that localization is not responsible for the resistance increase we observe, unless for some (unexplained) reason the effects of spin-orbit scattering are negligible in this case.

In the preceding discussion we have seen that neither localization alone nor electron-electron interactions alone can account for all of our results, and we now consider the possibility that both are important. Assuming that the two effects are simply additive, it is possible to account for our results in the following manner. The behavior at the lowest temperatures could be due predominantly to interactions; as we have seen, both the temperature dependence and overall magnitude of $\Delta R/R_0$ are in good quantitative agreement with interaction theory in this range. The deviations observed in Fig. 3 towards lower values of $\Delta R/R_0$ above about 3 K would then be due to localization with the spin-orbit scattering being sufficiently weak so as to make its contribution to ΔR negative at this relatively high temperature (although its contribution would still become positive at lower temperatures). It is also necessary to assume that below 3 K the effects of localization vary fairly slowly with temperature so as not to "interfere" with the $T^{-1/2}$ dependence due to interactions. This would be the case if τ_i varies only slowly with temperature, if magnetic impurity scattering[2,4] is important in this range,[38] or if the spin-orbit scattering time is approximately equal to the inelastic time at 3 K (as this would make the contribution from localization become positive at lower temperatures). With these assumptions we can account, at least qualitatively, for all of our results. A quantitative check on these assumptions, particularly regarding the strength of the spin-orbit scattering, would clearly be desirable. Such a check could be made if magnetoresistance measurements were available, but unfortunately such experiments have not yet been performed.

D. Comparison with previous experiments

Our main results are that at the lowest temperatures the fractional resistance rise, $\Delta R/R_0$, varies in a manner consistent with a $\rho^{1/2}/AT^{1/2}$ dependence. We hasten to add that our evidence for the dependence on ρ is fairly weak in

that the precise power of ρ is not determined very accurately. This dependence on A and T is in good agreement with the results of previous workers.[6,7,10,11,13,14,16,17] Moreover, the overall magnitude of the resistance rise is also in reasonable agreement. A detailed comparison of the magnitude of $\Delta R/R_0$ observed in the different experiments (including the present work), with particular attention to the behavior as a function of ρ, is given elsewhere.[17] There it has been shown that wires made of low-resistivity materials, such as our Au samples, exhibit a dependence of $\Delta R/R_0$ on ρ that is consistent with a $\rho^{1/2}$ form, as would be expected from interaction theory, or from localization theory if τ_i is independent of ρ. This is consistent with our conclusion discussed above that the behavior we observe at the lowest temperatures is due predominantly to interactions. As for the deviations we find at high temperatures, such behavior has not been widely observed in previous experiments. Some indications of such deviations were noted in early experiments on AuPd wires,[10] but they do not appear to be present in other low-resistivity materials such as the Cu wires studied by White *et al.*[13] The reason why these deviations are so large in our case and apparently not in other similar low-resistivity samples[13] is not clear, although it is possible that the quantity τ_i, which controls the temperature dependence of the contribution from localization, and which is expected to be nonuniversal, is simply different in the two cases. We feel that in spite of these deviations our findings allow a very important conclusion. Namely that in all major respects our wires exhibit properties very similar to those of wires made in other ways. Since our samples are the first, and so far only, "nonlithographic" wires in which one-dimensional localization and/or interaction effects have been observed, this implies that the effects observed in thin wires are not dependent on fabrication technique (i.e., on the substrate, etc.).

V. LENGTH DEPENDENCE

As discussed in Sec. II, both localization and interactions lead to a resistance increase which can be written in the form

$$\frac{\Delta R}{R_0} = \frac{L}{L_{\rm loc}}, \tag{8}$$

where $L_{\rm loc}$ is the localization length, and L is a characteristic length scale. For localization, L is the inelastic mean free path, while for interactions, L is proportional to the cutoff which enters the perturbation calculation. Both theories predict that the behavior will be different from (8) if the system is probed on a length scale smaller than L. The most straightforward way to accomplish this in our case is to make the sample length comparable to, or smaller than, L, and experiments of this type with lithographically produced wires have been reported previously.[14] There it was suggested that when the length of the sample, L_w, is comparable to L, one would expect the resistance rise to be given by

$$\frac{\Delta R}{R_0} = \frac{L_{\rm eff}}{L_0}, \tag{9}$$

where $L_{\rm eff}$ is an effective length which is a function of L and L_w. Further, one would expect $L_{\rm eff}$ to approach L when $L \ll L_w$, and to approach L_w in the opposite limit. This sort of behavior has been observed previously with lithographically produced wires,[14] and we have attempted to observe it with our samples. All of our results discussed in the previous section concerned wires approximately 5 μm long. Using the results in Fig. 2 together with (8), we find $L \sim 0.9$ μm. Note that if, as we concluded above, the resistance rise is due predominantly to interactions, this implies a cutoff length, L_c, of 0.3 μm, since $L = 2(2-3F/4)L_c$ [see (3)].

We have made wires as short as 1.5 μm by simply varying the thickness of the mica. We were able to make mica substantially thinner than this, but it was unable to withstand the entire fabrication process without cracking, etc. Some typical results for the fractional resistance rise as a function of temperature are shown in Fig. 6, where for comparison we also show the results for long wires with the same cross-sectional areas. We see that both the temperature dependence and the magnitude of the resistance rise are essentially independent of sample length. This is also illustrated in Fig. 7, which shows the fractional rise as a function of A^{-1} for wires of various lengths. To within the uncertainties, the resistance rise is independent of the length. The shortest samples are somewhat longer than the estimates for L, so it is necessary to consider how large a length dependence one would expect in this case. The only guide we have here is the experiment of Masden and Giordano.[14] If we use their result for the length dependence for a sample with the *same* value of L as estimated from (8), then we find that our 1.5 μm samples should exhibit a resistance rise that is approximately 30% smaller than that found with the 5 μm samples. This is illustrated in Fig. 7, where the solid curve is simply a guide to the eye which follows the data and the dashed curve is drawn 30% lower. Hence we would have

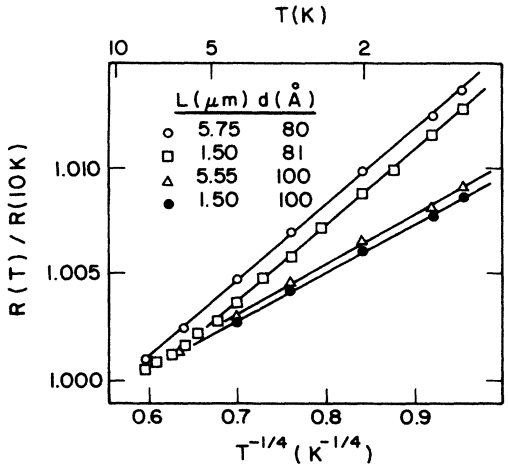

FIG. 6. Resistance as a function of $T^{-1/4}$ for several samples of various lengths and cross-sectional areas. The lengths and cross-sectional areas of the different samples are indicated in the figure.

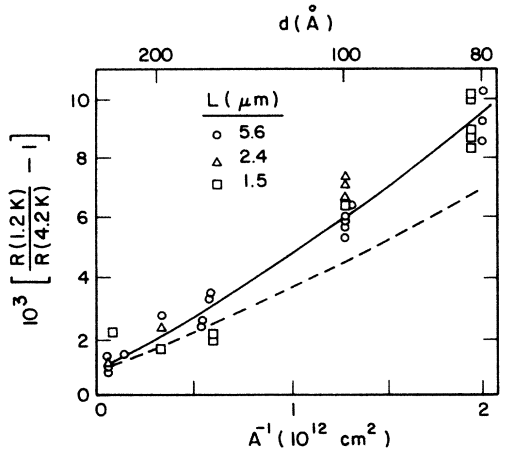

FIG. 7. Fractional resistance rise from 4.2 to 1.2 K as a function of A^{-1} for wires of various lengths. The solid curve is a guide to the eye, and the dashed curve is drawn proportional to the solid curve, but 30% lower; see text for discussion.

expected the results for our 1.5 μm samples to fall this far below the results for the 5.5 μm samples, and we see that this is clearly not the case.[40] We therefore conclude that the dependence of the resistance rise on length for our Au wires is substantially different from that found by Masden and Giordano.[14] It is important to emphasize that this comparison of the two experiments is essentially model independent. That is, we have assumed only that experiments with similar values of L, as estimated using (8), should behave similarly. We have made *no* assumptions concerning the precise values of the characteristic length scales for localization or interactions. It is not at all clear why the two experiments find different magnitudes for the length dependence, especially as recent work[41] has shown that the behavior of the AuPd wires studied in Ref. 14 was dominated by interactions, as appears also to be the case for our samples.

VI. CONCLUSIONS

We have studied the electrical behavior of thin Au wires made using a process which is completely different from those used in past investigations of this kind. Our wires, which are smaller than any studied previously, display behavior which is very similar to that found in past experiments, and thus lends strong support to the prediction that this behavior is an intrinsic property of thin wires. The detailed behavior that we observe cannot be explained in terms of interactions or localization alone, but can be accounted for if one assumes that interactions dominate at low temperatures and that localization becomes important (although not dominant) at high temperatures. We have searched for a dependence of the resistance rise on the length of the sample, but such effects are smaller than our resolution, which implies that they are also much smaller than found in previous work. The reason for this is not clear at this time.

ACKNOWLEDGMENTS

We thank J. T. Masden, D. M. Fleetwood, D. E. Beutler, J. J. Lin, and G. Ascarelli for many useful discussions. We wish to also thank L. D. McCabe and N. Otsuka for performing the electron microscopy, and R. L. Fleischer, C. P. Bean, and M. V. Doyle for much useful advice concerning nuclear tracks in mica. This work was supported in part by the National Science Foundation through Grants Nos. DMR 79-06716 and DMR 84-03995, and through the use of central facilities of the Purdue Materials Research Laboratory supported by Grant No. DMR 80-20249.

*Present address: NASA Lewis Research Center, 21000 Brookpark Road, Cleveland, OH 44135.

[1]For recent reviews of this subject see Refs. 2—4, and references contained therein.
[2]G. Bergmann, Phys. Rep. **107**, 1 (1984).
[3]*Localization, Interaction, and Transport Phenomena,* B. Kramer, G. Bergmann, and Y. Bruynseraede, edited by (Springer, Berlin, 1984).
[4]P. A. Lee and T. V. Ramakrishnan, Rev. Mod. Phys. **57**, 287 (1985).
[5]D. J. Thouless, Phys. Rev. Lett. **39**, 1167 (1977).
[6]N. Giordano, W. Gilson, and D. E. Prober, Phys. Rev. Lett. **43**, 725 (1979).
[7]P. Chaudhari and H.-U. Habermeier, Phys. Rev. Lett. **44**, 40 (1980); P. Chaudhari and H.-U. Habermeier, Solid State Commun. **34**, 687 (1980).
[8]J. C. Garland, W. J. Gully, and D. B. Tanner, Phys. Rev. B **22**, 507 (1980).
[9]D. R. Overcash, B. A. Ratnam, M. J. Skove, and E. P. Stillwell, Phys. Rev. Lett. **44**, 1348 (1980)
[10]N. Giordano, Phys. Rev. B **22**, 5635 (1980).
[11]N. Giordano, in *Physics in One Dimension,* edited by J. Bernasconi and T. Schneider (Springer, Berlin, 1981), p. 310.
[12]A. C. Sacharoff, R. M. Westervelt, and J. Bevk, Phys. Rev. B **26**, 5976 (1982); **29**, 1647 (1984).
[13]A. E. White, M. Tinkham, W. J. Skoçpol, and D. C. Flanders, Phys. Rev. Lett. **48**, 1752 (1982).
[14]J. T. Masden and N. Giordano, Phys. Rev. Lett. **49**, 819 (1982).
[15]P. Santhanam, S. Wind, and D. E. Prober, Phys. Rev. Lett. **53**, 1179 (1984).
[16]J. C. Licini, G. J. Dolan, and D. J. Bishop, Phys. Rev. Lett. **54**, 1585 (1985).
[17]J. T. Masden and N. Giordano, Phys. Rev. B **31**, 6395 (1985).
[18]D. J. Thouless, Solid State Commun. **34**, 683 (1980).
[19]P. W. Anderson, D. J. Thouless, E. Abrahams, and D. S. Fisher, Phys. Rev. B **22**, 3519 (1980).
[20]E. Abrahams, P. W. Anderson, D. C. Licciardello, and T. V. Ramakrishnan, Phys. Rev. Lett. **42**, 673 (1979).
[21]We should note however that experiments with effectively one-dimensional metal-oxide-semiconductor field-effect transistor (MOSFET) devices have been performed in the re-

gime in which the conduction is dominated by hopping; see, e.g., A. B. Fowler, A. Hartstein, and R. A. Webb, Phys. Rev. Lett. **48**, 196 (1982).

[22]See also the discussion in Ref. 17.

[23]B. L. Al'tshuler, A. G. Aronov, and P. A. Lee, Phys. Rev. Lett. **44**, 1288 (1980); B. L. Al'tshuler, D. Khmelnitsky, A. I. Larkin, and P. A. Lee, Phys. Rev. B **22**, 5142 (1980).

[24]A. M. Finkel'stein, Zh. Eksp. Teor. Fiz. **84**, 168 (1983) [Sov. Phys.—JETP **57**, 97 (1983)].

[25]G. E. Possin, Rev. Sci. Instrum. **41**, 772 (1970).

[26]W. D. Williams and N. Giordano, Rev. Sci. Instrum. **55**, 410 (1984).

[27]W. D. Williams, thesis, Purdue University, 1983 (unpublished).

[28]R. L. Fleischer, P. B. Price, and R. M. Walker, *Nuclear Tracks in Solids* (University of California Press, Berkeley, 1975).

[29]C. P. Bean, M. V. Doyle, and G. Entine, J. Appl. Phys. **41**, 1454 (1970).

[30]Our electron microscope studies are consistent with previous work [R. E. Beck, thesis, University of Michigan, 1969 (unpublished)] which has shown that the etched tracks in mica have a range of sizes, with the variation in the diameter being about $\pm 10\%$. Note also that the etched tracks, and hence the wires, have rhombic rather than circular cross sections (see Ref. 28). Here we take the effective track diameter d to be the diameter of the circle which has the same area as the corresponding rhomboid.

[31]See, for example, E. Frank, *Electrical Measurement Analysis* (McGraw-Hill, New York, 1959).

[32]*American Institute of Physics Handbook,* 3rd ed., edited by D. E. Gray (McGraw-Hill, New York, 1972).

[33]E. H. Sondheimer, Adv. Phys. **1**, 1 (1952).

[34]See for example, D. K. C. MacDonald, W. B. Pearson, and I. M. Templeton, Proc. R. Soc. London, Ser. A **266**, 161 (1962).

[35]The electroplating solution was obtained from Technic, Inc., P.O. Box 965, Providence, RI 02901.

[36]Here we use free-electron theory to estimate the Fermi wave vector, and the diffusion constant D, through $D=v_f^2\tau_e/3$, where v_f is the Fermi velocity, and τ_e is the elastic scattering time. See, for example, N. W. Ashcroft and N. D. Mermin, *Solid State Physics* (Holt, Rinehart, and Winston, New York, 1976).

[37]A rough theoretical estimate for F can be made using Thomas-Fermi theory to evaluate the screening integral which is involved. This gives $F\sim 0.5$.

[38]Here it is assumed that magnetic impurity scattering is unimportant. If this is not the case, the temperature dependence will be affected. In particular, even though this scattering is not temperature dependent, it can change the way in which the temperature dependence of τ_i affects $\Delta R/R_0$, and if the magnetic scattering time is much less than τ_i, $\Delta R/R_0$ will be nearly temperature independent.

[39]B. L. Al'tshuler, A. G. Aronov, and D. E. Khmelnitsky, Solid State Commun. **39**, 619 (1981); B. L. Al'tshuler, A. G. Aronov, and D. E. Khmelnitsky, J. Phys. C **15**, 7367 (1982). Note that for this inelastic scattering mechanism we expect $\tau_i\sim T^{-2/3}$; this exponent is close enough to 0.5 that it is consistent with the observed temperature dependence.

[40]We note that if the resistance rise is instead due to localization, then the relevant length is the inelastic length, which as derived from (8) is larger than the corresponding L_c by a factor of $2(2-3F/4)\sim 2.7$. Since this is closer to the length of our shortest wires, this would lead us to expect the length dependence to be larger than discussed in the text (see also Fig. 7). Hence, this cannot explain the difference between our results and those for AuPd wires (Ref. 14).

[41]J. J. Lin and N. Giordano, Phys. Rev. B **33**, 1519 (1986).