Experimental Study of Anderson Localization in Thin Wires

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The electrical properties of wires with cross-sectional areas (A) in the range 1×10^{-11} to 3×10^{-10} cm^2 have been studied. At temperatures below about 10 K the resistance of the wires increases with decreasing temperature. The size of the increase varies as A^{-1} and becomes larger as the impurity resistance is made larger, in qualitative agreement with recent theoretical predictions by Thouless. The size of the increase is in order-of-magnitude agreement with the theory but the temperature dependence is not.

In the past few years there has been a great deal of interest in Anderson localization, and it has been studied both theoretically and experimentally in a number of two- and three-dimensional systems.[1] While the theory also predicts very interesting behavior in one dimension, this case did not appear to be experimentally accessible until very recently when Thouless[2,3] argued that all systems regardless of their cross-sectional area will behave one-dimensionally insofar as localization is concerned provided only that they are sufficiently long. More specifically, Thouless predicted that localization will cause all one-dimensional systems (i.e., wires) with impurity resistances greater than about 10 kΩ to exhibit thermally activated conduction at low temperatures and to be insulators at absolute zero. The temperature at which this effect becomes observable, T_L, is predicted to increase both as the cross-sectional area, A, of the wire is decreased and as the amount of randomness in the wire (i.e., the impurity resistance) is increased.[2] For macroscopic size wires T_L is predicted to be unattainably low, but for very random wires with $A=2.5\times10^{-11}$ cm^2 (a radius of order 250 Å) T_L is predicted[2] to be of order 1 K. Attempts to observe this effect experimentally have so far been somewhat ambiguous. Garland, Gully, and Tanner[4] found no effect in percolative mixtures of Ag particles in KCl. Dolan, Osheroff, and Tsui[5] have observed a null result in silicon metal-oxide-semiconductor field-effect transistors and unexpected temperature-dependent nonlinear effects in "wires" composed of granular metal films. Unfortunately, the samples studied in these experiments were rather different from the continuous metallic structures which were considered theoretically,[2] and it is therefore not clear if the observed discrepancies are due to a failure of the theory or simply its inapplicability to the types of samples which were studied. We have searched for the effect of localization in continuous metallic wires. We find that the effect does occur and that the behavior of T_L is in qualitative agreement with the theory.[2] There do seem to be some quantitative discrepancies, however, and these will be described below.

The wires studied in the present work were fabricated with use of a novel lithographic technique which is described in Fig. 1. A glass slide which is half covered with a metal film [Fig. 1(a)] is bombarded at normal incidence with Ar^+ ions which "mill" into the surface [Fig. 1(b)]. The metal film is then removed chemically leaving a step in the glass [Fig. 1(c)]. A second metal film is next deposited in such a way that the step is coated. The surface is then milled again with Ar^+ ions but this time at an angle such that the metal on the side of the step is in the "shadow" of the step [Fig. 1(d)]. The result is a wire which runs along the step [Fig. 1(e)]. Examination with a scanning electron microscope shows that the wires are continuous strips with uniform cross sections. Useful steps can be as small as a few hundred angstroms in height, and it is thus possible to make extremely thin wires using this technique.[6] The wires used in this work were fabricated from $Au_{60}Pd_{40}$ films which were deposited in two different ways: sputtering, which produced films with resistivities of 3.7×10^{-4} Ω cm and resistivity ratios[7] of 1.03; and evaporation, which produced films

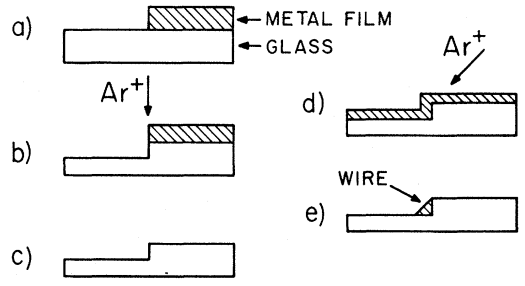

FIG. 1. Description of the lithographic process used to make the wires studied in this work.

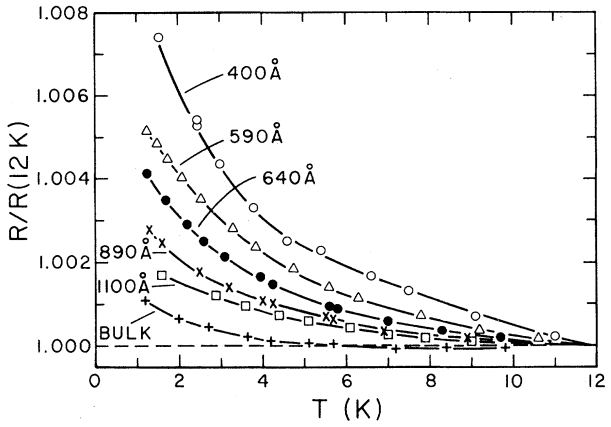

FIG. 2. Resistance as a function of temperature for dirty wires of various sizes and a dirty bulk film. The resistance of each sample has been normalized by its value at 12 K. The numbers given in the figure are $\sqrt{A}$ for each wire.

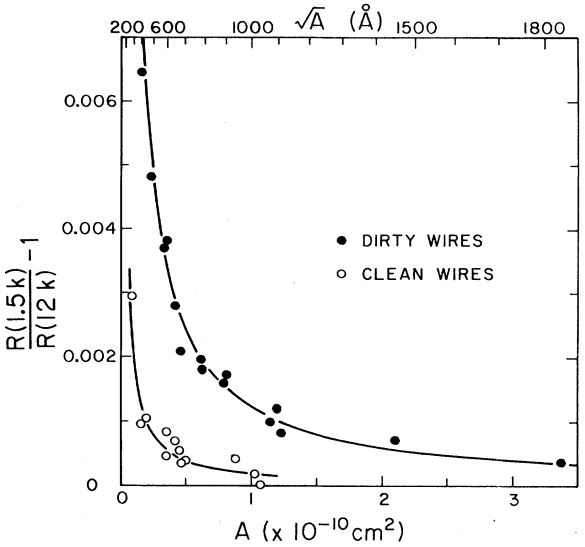

FIG. 3. Magnitude of the resistance rise, as measured by the difference between the resistances at 1.5 and 12 K normalized by the value at 12 K, as a function of cross sectional area for the dirty wires (filled circles) and the clean wires (open circles). The resistance rise found in the bulk has been subtracted so that zero resistance rise corresponds here to bulk behavior. The solid lines are proportional to A^{-1}.

with resistivities of 1.0×10^{-4} Ω cm and resistivity ratios of 1.06. The difference between the sputtered and evaporated films enabled us to study the effect of changing *both* the amount of randomness and the cross-sectional area. Wires made from the sputtered films will in the following be referred to as "dirty," while those made from the evaporated films will be referred to as "clean." Wires with A in the range from 1×10^{-11} to 3×10^{-10} cm^2 were studied. The values of A were determined from the measured lengths and resistances, and the known resistivity, and were in agreement with, but more accurate than, the values expected from the known step heights and film thicknesses. The $Au_{60}Pd_{40}$ films were between 200 and 1000 Å thick prior to ion milling. The wires had resistances in the range 15 to 500 kΩ and were from 90 to 450 μm long. They had resistivity ratios equal to the bulk values and could be cycled between room temperature and low temperatures with no ill effects except for small, typically a few parts per thousand, changes in resistance.

Figure 2 shows results for the resistance as a function of temperature for dirty wires of various sizes. For purposes of comparison we have normalized the resistance of each wire by its value at 12 K. Also shown is the behavior of a "bulk" film[8]; its resistance increases slightly with decreasing temperature as expected from previous studies of Au-Pd alloys.[9] However, the increase in the bulk resistivity is seen to be small compared to the increase found in the wires. Figure 3 shows a plot of the magnitude of the resistance increase at 1.5 K relative to that at 12 K as a function of A for both dirty and clean wires. Here we have subtracted the increase found in the bulk so that zero increase corresponds to bulk behavior. The resistance rise is seen to vary as A^{-1} for both the clean and dirty wires. The results are not consistent with either an A^{-2} or an $A^{-1/2}$ dependence. The rise is larger in the dirty wires than in the clean wires by approximately a factor of 6. To within the combined uncertainties this is equal to the ratio of the impurity resistances of the dirty and clean materials. Both of these results are in qualitative agreement with the theory.[2]

The temperature dependence of the resistance of a typical wire is shown in more detail in Fig. 4. The variation is seen to be approximately logarithmic with temperature although the data are also consistent with a $T^{-1/2}$ dependence. While the size of the increase is in order-of-magnitude agreement with the theory,[2] the results do not appear to be consistent with the predicted T^{-2} dependence. This discrepancy will be discussed further below.

The results described above are qualitatively consistent with the theoretical predictions based

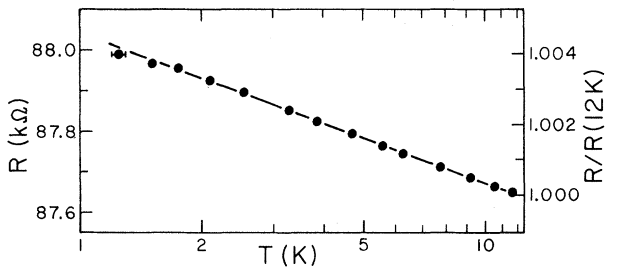

FIG. 4. Resistance as a function of the logarithm of the temperature for a dirty wire with $A = 3.5 \times 10^{-11}$ cm^2 ($\sqrt{A} = 590$ Å). The variation of the bulk resistivity has been subtracted, so that here a resistance independent of temperature corresponds to bulk behavior.

on Anderson localization. However there are other mechanisms which can cause an increase in resistance as the temperature is lowered, and we have therefore performed a number of additional tests in order to rule out explanations other than localization. (1) The resistance measurements were made with two-terminal dc, four-terminal dc, and two-terminal ac (100 Hz) arrangements. All gave the same result. At high currents (10^{-6} A) and low temperatures Joule heating was clearly visible, while at low currents (below about 10^{-7} A) the resistance was independent of the current to within the experimental error. (2) Measurements on wires with the same cross-sectional area but different resistances and with different areas but the same resistance showed that the effect depends on the area and not the resistance.[10] (3) Measurements on bulk films showed only a small increase in resistance as the temperature was lowered (see Fig. 2). (4) Bulk films which were thinned by Ar^+-ion milling exhibited behavior identical to the unmilled bulk films. (1) and (2) rule out instrumental artifacts. (3) rules out any mechanism intrinsic to bulk $Au_{60}Pd_{40}$, while (4) rules out any mechanisms associated with the Ar^+-ion milling. Moreover, Kondo or similar impurity effects are excluded by the fact that the clean wires show a smaller effect than the dirty ones. We therefore conclude that the increase in resistance which is observed is a real effect that depends on both the area of the wire and the amount of randomness. To our knowledge, localization is the only mechanism which can account for such behavior.

While the theory[2] is in qualitative agreement with our results, there are a number of quantitative discrepancies. The most serious discrepancy involves the temperature dependence of the resistance. The theory[2] predicts a T^{-2} dependence, whereas a much slower, approximately logarithmic increase is observed experimentally (see Fig. 4).[11] However, an important quantity which enters into the calculation of the resistance is the inelastic scattering time,[2] and this discrepancy could simply be due to shortcomings in the present understanding of inelastic processes and not to inadequacies in the theory of localization. This conjecture is supported by preliminary measurements at high temperatures (15–30 K) which seem to indicate that the inelastic scattering time *increases* as the impurity resistance is decreased, whereas the theory[2] predicts that the inelastic time should either remain constant or decrease as the randomness is decreased. As noted above, the experimental results for the dependence of the resistance rise on impurity resistance and cross sectional area are qualitatively consistent with the theory. However, since any quantitative theoretical predictions depend crucially on the form of the inelastic scattering time and this quantity is not at present understood, it is not possible to make further quantitative comparisons with the theory at this time.

It is interesting to compare our results with those of other workers. If we use our observed dependences on impurity resistance, area, and temperature to extrapolate to the parameter values appropriate to the experiment of Garland, Gully, and Tanner,[4] we find a resistance rise which is *smaller* than their experimental resolution. The behavior reported by Dolan and Osheroff[5] is very different from what we observe; in particular, we see no evidence for the nonlinearities in the I-V characteristics which these workers report.[12] One possible explanation for these differences is that the discontinuous nature of their samples is playing an important role.[13]

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[1] See, for example, D. J. Thouless, Phys. Rep. 13C, 93 (1974), and in Metal Non-Metal Transition in Disordered Systems, Proceedings of the Nineteenth Scottish

Universities Summer School in Physics, 1978, edited by L. R. Friedman and D. P. Tunstall (to be published); N. F. Mott, M. Pepper, S. Pollitt, R. H. Wallis, and C. J. Adkins, Proc. Roy. Soc. London, Ser. A 345, 169 (1975), and references contained therein.

[2]D. J. Thouless, Phys. Rev. Lett. 39, 1167 (1977).

[3]C. J. Adkins, Philos. Mag. 36, 1285 (1977), has put forth arguments similar to those of Thouless (Ref. 2), although he finds somewhat different results for the conditions under which the effects of localization should be observable.

[4]J. C. Garland, W. J. Gully, and D. B. Tanner, Bull. Am. Phys. Soc. 24, 280 (1979), and to be published.

[5]G. J. Dolan, D. D. Osheroff, and D. C. Tsui, Bull. Am. Phys. Soc. 24, 233 (1979); G. J. Dolan and D. D. Osheroff, preceding Letter [Phys. Rev. Lett. 43, 721 (1979)]. These workers have reported results on two types of samples. One type was interpreted as behaving two-dimensionally, while the other type may have exhibited one-dimensional behavior. In all of our discussions of the results of Dolan and Osheroff, we refer *only* to the latter type of sample. The behavior of the two-dimensional samples can be understood in terms of the theory of P. W. Anderson, E. Abrahams, and T. V. Ramakrishnan, second preceding Letter [Phys. Rev. Lett. 43, 718 (1979)].

[6]N. Giordano, M. D. Feuer, and D. E. Prober, to be published.

[7]We define the resistivity ratio here as the ratio of the resistance at room temperature to that at 12 K.

[8]By this we mean a thin-film sample whose width (typically 1 mm) is sufficiently large that it should not be affected by localization.

[9]The resistance rise we observe is slightly larger than that reported by previous workers [L. R. Edwards, C. W. Chen, and S. Legvold, Solid State Commun. 8, 1403 (1970)]; however, our films have much higher resistivities than those studied by Edwards, Chen, and Legrold and this may affect the mechanism proposed by those workers. It is also possible that our films are exhibiting "two-dimensional" localization. However, the resistance increase does not appear to scale inversely with the sheet resistance as would be expected for this mechanism (Ref. 5).

[10]This result also indicates that the effect is independent of the length of the wire. Although the theory (Ref. 2) predicts that at low temperatures the resistance will vary exponentially with the length of the wire, this is expected to be observable only when the inelastic mean free path is longer than the wire, and this is not the case in our samples.

[11]Recent theoretical work by Abrahams *et al.* [E. Abrahams, P. W. Anderson, D. C. Licciardello, and T. V. Ramakrishnan, Phys. Rev. Lett. 42, 673 (1979)] predicts a logarithmic variation in the case of localization in two dimensions. However, in one dimension this theory appears to predict a temperature dependence which is identical to that given by Thouless (Ref. 2).

[12]The current-voltage characteristics of our samples were linear to within the experimental error at currents down to 5×10^{-10} A corresponding to an electric field strength of approximately 3×10^{-3} V/cm. These limits were set by our electronics.

[13]After this work was completed we have learned that P. Chaudhari and H.-U. Habermeier (to be published) have studied continuous wires made using a different method and have obtained results somewhat similar to ours.

Surface Magnetization of Ferromagnetic Ni(110): A Polarized Low-Energy Electron Diffraction Experiment

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The magnetic field dependence (hysteresis curve) and the temperature dependence of the magnetization at a Ni(110) surface was measured by polarized low-energy electron diffraction. The diffracted intensities are spin dependent by a few percent. The temperature dependence of the surface magnetization measured in the range $0.5<T/T_c<0.8$, is significantly different from that of the bulk.

The magnetic moments, and even the magnetic order at the surface of a ferromagnet, may be different from that of the bulk.[1-6] This is a result of the lack of translational invariance perpendicular to the surface and the reduced number of neighbors of surface atoms compared to the bulk. The surface magnetization, its temperature dependence, and the transition temperature at the surface have been described by a number of theoretical models using mean-field theory,[1,2] scal-

