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 \(1 \times 10^{-11}\) to \(5 \times 10^{-10}\) 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.\(^4\) For macroscopic size wires \(T_L\) is predicted to be unattainably low, but for very random wires with \(A = 2.5 \times 10^{-11}\) cm\(^2\) (a radius of order 250 Å) \(T_L\) is predicted\(^5\) 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-Pd films which were deposited in two different ways: sputtering, which produced films with resistivities of \(3.7 \times 10^{-4}\) Ω cm and resistivity ratios of 1.03; and evaporation, which produced films

![FIG. 1. Description of the lithographic process used to make the wires studied in this work.](https://example.com/fig1.png)
with resistivities of $1.0 \times 10^{-4} \, \Omega \cdot \text{cm}$ 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 $1 \times 10^{-11}$ to $3 \times 10^{-10} \, \text{cm}^2$ 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$_{80}$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; its resistance increases slightly with decreasing temperature as expected from previous studies of Au-Pd alloys. 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.

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, 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
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. (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 unthinned 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 predicts a $T^{-2}$ dependence, whereas a much slower, approximately logarithmic increase is observed experimentally (see Fig. 4). However, an important quantity which enters into the calculation of the resistance is the inelastic scattering time, 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 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, we find a resistance rise which is smaller than their experimental resolution. The behavior reported by Dolan and Osheroff 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. One possible explanation for these differences is that the discontinuous nature of their samples is playing an important role.

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See, for example, D. J. Thouless, Phys. Rev. 13C, 93 (1974), and in Metal Non-Metal Transition in Disordered Systems, Proceedings of the Nineteenth Scottish
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.\textsuperscript{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,\textsuperscript{1,2} scal-