Quantum Localization in Amorphous W-Re Alloys

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The resistance of amorphous W-Re wires between 2 and 20°K has been measured. Wires with a resistance of approximately 10 kΩ show a different temperature dependence from that of wires with a resistance of over 200 kΩ. The latter show a relative increase in resistance as the temperature is decreased or the magnetic field is increased. These wires also show an anomalous dependence of resistance on width and length. These results are discussed in the perspective of Thouless's suggestion of maximum metallic resistance.

Thouless[1] has proposed that the temperature and length dependence of the conductance of a metallic wire deviates from its usually expected behavior when the resistance of the sample exceeds some critical value. This value ranges from 10 to 30 kΩ. Similar ideas have been advanced byAdkins,[2] Licciardello and Thouless,[3] and Abrahams *et al.*[4] Several authors have searched for quantum localization in wires[5,6] and in composite materials.[7] We have carried out a series of electrical resistance measurements on amorphous W-Re alloys. Our samples show, qualitatively, the deviations predicted by Thouless. In addition, we have measured the temperature dependence of the resistance in a magnetic field and find enhanced magnetoresistance below 20 K. The magnetic-field dependence of quantum localization in metallic wires has not been predicted theoretically.

We chose the amorphous alloys for a number of reasons. Because of positional disorder, we expect localization to be present. The resistivity of the amorphous samples is usually high. This has significant advantages in the fabrication of high-resistance metallic wires. The temperature dependence of the resistivity is generally small, so that small changes can be followed readily. In addition, the amorphous films can be deposited to yield relatively smooth films with little or no granularity that is characteristic of polycrystalline films. We chose the amorphous W-Re alloys for their stability to crystallization and general ability to withstand handling during the fabrication of the wires. These alloys have a superconducting-transition temperature which can be varied with composition. We used the superconducting transition temperature as a monitor of our film quality. Our films are nominally only 50 Å thick and we were concerned about oxidation or other deleterious effects during the fabrication of the relatively high-resistance wires. Observing the same superconducting transition temperature in the high- and low-resistance films was therefore a reassuring sign that the quality of the high-resistance wire had not been changed during fabrication.

The films were grown by electron-beam evaporation onto oxidized silicon substrates.[8] The details of the microstructure and growth technique have also been discussed in Ref. 8. With electron-beam lithography and ion milling[9] the films were cut into wires with two types of widths. In one case, the width was varied between approximately 700 to 5000 Å and in the other it was 20 μm. The resistivity of the films measured at room temperature is approximately 4×10^{-4} Ω cm and was found, within 10%, to be the same for the low- and high-resistivity samples. This small difference was attributed to variations in the width of the narrow wire and to our inability to measure this width precisely. The wire was tapped nine times, two for current leads and seven for resistance measurements. In the high-resistance wires, each of these segments was at least 200 kΩ and exceeded the upper limit of 30 kΩ. At the point of contact the probes were of the same geometrical dimension as the thin wire. The silicon chips containing the samples were mounted on a ceramic header. With standard semiconductor joining technology, aluminum wires were ultrasonically bonded to the large W-Re pads and the header pins. In order to provide mechanical support for the contacting wire to the W-Re pad the photoresist, used for fabricating the sample, was left on the wire. This photoresist, which was typically a few thousand angstroms thick, also provided protection against environmental attack. The sample was then enclosed in an aluminum cap and mounted on a copper block which was a part of the Dewar system.

The I-V curves of the low- and high-resistance samples were linear. The maximum current through the high-resistance samples was usually

10 nA and the measurements carried out in 1-nA steps. In a few cases the current was increased to 100 nA and the measurements were then made after 5-nA intervals. In the low-resistance samples the current was usually varied between 100 and 1000 nA in ten or twenty steps. There was, therefore, considerable overlap in the current densities used for measuring the high- and low-resistance samples. A least-squares fit was used to obtain the resistance from this data set. Linear regression analysis showed that the coefficient of determination was better than one part in 10^5.

The temperature and magnetic field dependence of a set of low- and high-resistance samples are shown in Fig. 1. We note that the low- and high-resistance samples behave quite differently although both were prepared in the same run and, in fact, on the same wafer. In order to bring out the differences between the two samples, all of the data were normalized to the resistance measured at 13 K. The temperature and magnetic field dependence of another high-resistance sample in a parallel field is shown in Fig. 2. Above 20 K there appears to be little change in resistance with magnetic field. This sample has a different composition from that of the sample whose data are shown in Fig. 1. The superconducting-transition temperature is lower and the temperature dependence of the resistivity somewhat larger. Both of these samples, although of different composition, show extra resistance associated with a decrease in cross section of the wire.

The length dependence of the resistance was measured at room temperature and again at 4.2 K. As we had seven taps, we obtained a matrix of measurements, R_{ij}, where the suffix indicates that the resistance was measured between points i and j. The change in resistance with length is shown in Fig. 3. This composite plot is obtained by subtracting, say, from R_{17} the sum of the resistances of the individual segments $R_{12}+R_{23}+R_{34}+\ldots+R_{67}$. Instead of length, we have plotted our result as a function of the resistance of the segment R_{ij}. We examined also the length dependence of one of the samples in a parallel magnetic field and found the data to be indistinguishable from the zero-field data.

The temperature dependence of resistance in the low- and high-resistance samples is measurably different. Before considering this difference in terms of localization we examine the possibility that our samples have changed during the fabrication of the narrow wires. In particular, we are concerned about the possibility that the material may have become granular and what we

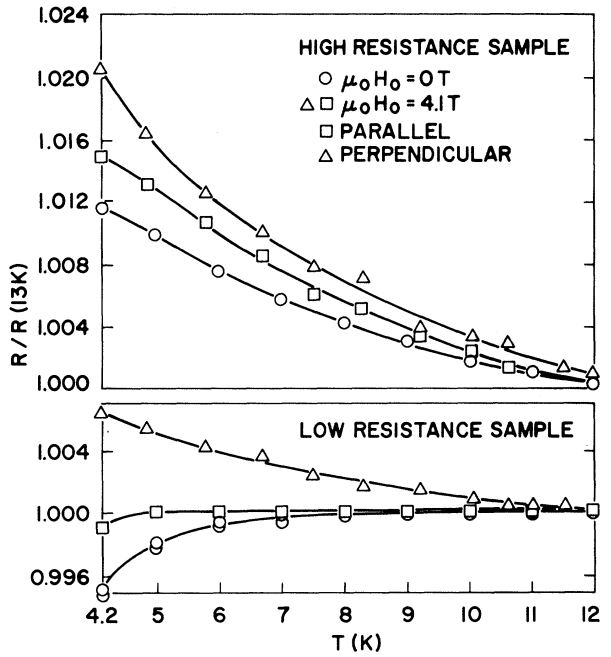

FIG. 1. The temperature and magnetic field dependence of one set of low- and high-resistance samples. The width of the high-resistance sample is approximately 700 Å and its thickness 50 Å. The width of the low-resistance sample is approximately 20 μm and its thickness is 50 Å.

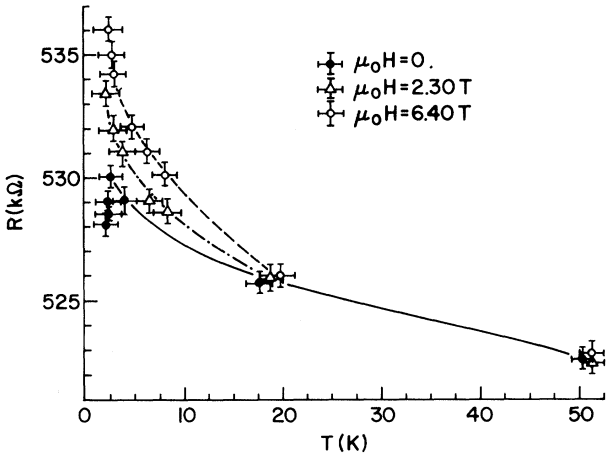

FIG. 2. The temperature and magnetic field dependence of one of the high-resistance W-Re samples. For clarity of presentations not all of the data points are shown. In particular the data points between 5 and 17 K are not included. The drawn lines represent the data. The width of this sample is approximately 5000 Å and its thickness 50 Å.

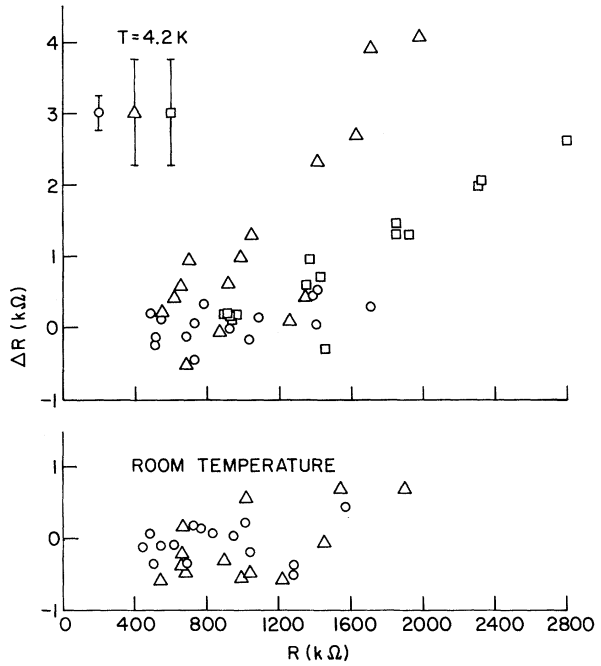

FIG. 3. The length dependence of resistance of the high-resistance samples measured at room temperature and at 4.2 K. The data are for three different samples which had different widths but the same length and thickness. The room-temperature data shows the usually expected behavior from metallic systems but the same samples measured at 4.2 K show an unexpected length dependence. The data have been corrected for instrumental loading which was found to be appreciable when the resistance of the sample exceeded 1 MΩ. The change in resistance of the samples between room temperature and 4.2 K was approximately 5%.

are observing is the temperature dependence of conduction across a thermally activated barrier such as an oxide. We do not believe that this has occurred for the following reasons. The resistivity deduced from the measured resistance and geometry is unchanged in going from a wide to a narrow line. Similarly, the superconducting-transition temperature was unchanged. This is usually sensitive to changes in the properties of materials. Paraconductivity, associated with superconducting fluctuations, also changes when the films become granular.[10] We find that the nature of the paraconductivity has not changed in going from a wide to a narrow line. We deduce this from our magnetic field data. If we subtract from our high-resistance samples a background resistance as measured in the low-resistance sample, we find that the temperature dependence of the residual resistance is the same with and without a perpendicular magnetic field. Finally, as we have emphasized in the introduction, we took considerable care to ensure that the films were protected from environmental attack by leaving the photoresist on and also by using ion milling rather than conventional chemical etching to prevent possible attack of the film from the sides by the etchant. As the films are amorphous, possible attack along the kinetically preferred grain boundaries by air or airborne contaminants is also not a possibility. This is to be contrasted with the polycrystalline Au-Pd alloys studied by Dolan and Osheroff and by Giordano *et al.* where grain boundaries are present and where the possibility of preferential change in properties along the boundary cannot be ruled out unambiguously. It is for these reasons we believe that the behavior of our narrow wires is not to be associated with a change in the material. This then leaves us with Anderson localization.

If localization has set in, the extra resistance associated with this phenomenon is expected to increase inversely with the cross section of the sample and square root of temperature.[11] We find that the extra resistance does indeed increase inversely with the cross-sectional area of the sample. This has also been reported by Giordano *et al.* on the Au-Pd alloys and, in fact, their data overlap with ours.[12] The temperature dependence of our data spans less than a decade of temperature variation. Within this qualification we find that the temperature dependence of the high-resistance samples, after correcting for superconducting fluctuations, measured on the low-resistance samples, is well described by a $\ln T$ or $T^{-1/2}$ dependence. The latter is consistent with Thouless's recent suggestion.[11] We conclude that both the width and the temperature dependence are in accord with the notion of localization in one-dimensional wires. Using the expression proposed by Thouless and free-electron theory to estimate the diffusion constant we find that the inverse of the inelastic-scattering time constant for our samples is between 0.8 and $8.7\times10^{10}T$ sec^{-1}.

The results on the length dependence of extra resistance are, however, puzzling. The minimum length between any two of our voltage probes is approximately ten to fifteen times the localization length of our samples. The inelastic-scattering length deduced from our estimated inelastic time constants is smaller than the localization length. There should therefore be negligible length dependence. Typically a segment of our

high-resistance samples shows an extra resistance of few kilohms per 300 kΩ of resistance. If the extra resistance, measured as a function of length, was exponentially dependent on length the observed values are an order of magnitude smaller. Another possibility is to assume that the amount of localization measured in our experiment decreases as the length of the wire decreases. The measuring probes perturb the quantum localization.[13] The smaller the segment the lower the relative value of the extra resistance associated with that segment. If we assume that each probe decreases the extra resistance by a value Δ, the length dependence shown in Fig. 3 can be explained by assuming that Δ is of the order of 0.7 kΩ per probe. This value is comparable to the extra resistance measured as a function of temperature and would suggest that the effect of measuring probes is quite significant.

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[13]Professor D. J. Thouless has pointed out to us that the dependence on length may not be measurable experimentally since the measuring apparatus, including the pads, can be a source of electrons. We are carrying this argument one step further by suggesting that this perturbation decays from the point of contact of the probe with the wire and that far enough away from the probe localization is not disturbed.

Electronic Structure of Hydrogenated Amorphous Silicon

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Calculations of the electronic states and total energies of various bonding conformations in hydrogenated amorphous Si are presented. Various surprising results emerge, including identification of peaks in photoemission spectra as signatures of *nearest-neighbor* SiH configurations, a gap increasing with increasing H content while the conduction band remains essentially unchanged, and localized states in the gap arising from various defects whose energies are in sharp contrast to recently proposed simple model estimates.

The exciting possibilities of substitutionally doping hydrogenated amorphous Si (*a*-Si:H) and the subsequent construction of a solar cell have inspired a large number of experimental investigations of the structural, electronic, vibrational, and transport properties of this material.[1] Several interesting experimental observations include a much lower mobility for holes than for electrons,[2,3] an optically induced spin signal,[4,5] apparently two peaks in the gap as observed in field-effect measurements,[6] a valence band (VB) which recedes with increasing H content,[7] and photoemission spectra[7] for the high-temperature modification with structure which has been identified as that observed in Si(111):H and Si(100):H. Several theoretical models, in-