Phase-Slip and Localization Diffusion Lengths in Amorphous W-Re Alloys

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With application of the notion of phase-slip centers, the quasiparticle charge-diffusion length in amorphous W-Re wires of cross-sectional dimension of 250 Å wide by 100 Å thick has been measured. The normal electron-diffusion length deduced from this data is in good agreement with values obtained from the application of localization theory on the same materials. This result provides the first quantitative support for the theory of localization in one-dimensional metallic wires.

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The temperature dependence of the resistance of metallic wires has been measured by a number of investigators.[1-6] In the case of polycrystalline Au-Pd (Refs. 1-3) and amorphous W-Re (Ref. 4) alloys the temperature dependence changes as the cross section of the wire approaches 10^{-11} cm^2. In contrast no evidence for localization was obtained in experiments carried out on Bi whiskers[5] and on colloidal Ag particles[6] dispersed in KCl. All of these experimental investigations were prompted by Thouless's suggestion that in disordered metallic systems there is a maximum metallic resistance of the order of 10 kΩ and above which all such metallic systems are unable to transport an electric current across the entire length of the specimen at 0 K.[7] This behavior is associated with Anderson localization.

At finite temperatures inelastic scattering events can delocalize the electrons and hence lead to finite resistance. The temperature dependence of the extra resistance associated with localization is determined by the temperature dependence of inelastic scattering. Experimental results show that the extra resistance is inversely proportional to the square root of temperature leading to the conclusion that the inelastic scattering time constant is inversely proportional to temperature.[3,4] Based on Landauer's[8] ideas about the relation between the conductance and transmission coefficient across barriers in a linear chain, Anderson *et al.*[9] have derived an expression for the temperature dependence of the one-dimensional wire. With use of this expression[9,10] [see Eqs. (8) and (11) of Ref. 10] and the experimental data, the value of the inelastic-scattering time constant or the corresponding diffusion length can be extracted. In amorphous W-Re alloys the diffusion length is estimated to be approximately 250 Å at 4.2 K. A similar value is obtained for the polycrystalline Au-Pd alloys.

Although the temperature dependence of the inelastic scattering can be explained in terms of two-level scattering, the magnitude of the scattering is two orders of magnitude larger than the available theoretical estimates.[11] In fact, there is currently no published theory that can explain these short inelastic-scattering time constants. This situation has brought into question the validity of interpretation of the experimental data in terms of localization theory. Lee and co-workers[12] have shown that a theory based on Coulomb interaction between electrons gives the same expression as localization theory without running into the difficulty of explaining the values of inelastic-scattering times. Our data agree quantitatively with the Coulomb interaction theory. Given this situation it is desirable to measure the inelastic-scattering time by some independent technique that does not involve localization. We have carried out such a measurement on the same alloy on which we perform the localization experiments. Our method is based on the notion of phase-slip centers in superconducting wires.[13-15] We find that the value of the inelastic scattering time is comparable to that deduced using localization theory. These results lend support to the ideas of localization and pose a theoretical puzzle on the mechanism of such short inelastic-scattering times.

Amorphous W-Re films with approximately 60 at.% Re were prepared by electron-beam evaporation. The superconducting transition temperature (approximately 4 K) and normal-state resistivity of the evaporated films were very similar to those reported in the localization experiments. Using high-resolution electron-beam lithography with the contamination resist, we fabricated wires with a width of approximately 250 Å and larger. The thickness of the wires was a nominal 100 Å. We were forced to use narrow wires as the zero-temperature coherence length of amorphous superconductors, as determined from

critical-field measurements, is usually less than 100 Å.[16] The zero-temperature coherence length of amorphous W-Re alloys was found in the same experiment to be approximately 60 Å. In order to apply the one-dimensional approximation our wires must be narrow and thin and the data taken not far from the superconducting transition temperature where the temperature-dependent coherence length is comparable to the thickness or the width of our samples. We note, parenthetically, that these W-Re wires have the smallest cross section of any wires on which any physical measurement has been made to data. The details of the tecnhiques necessary to fabricate such wires have been described elsewhere.[15] The length of the wire was varied and was typically between 0.5 and 1 μm. We have examined a number of samples prepared in different runs, i.e., different evaporation and subsequent fabrication series. The results are generally similar. We have found that the yield, i.e., the number of successful samples to the number of attempts, is low. The samples burn out, presumably because of electrical discharges, even though we worked in a shielded room and with protective ciruitry. We also found that the superconducting transition temperature broadened when the films were cut into wires. We have therefore used the variation of critical current with temperature to identify the transition temperature with zero critical current. For example, in one of the samples we found that the critical current measurements gave a transition temperature of approximately 3.5 K in contrast to the film value of approximately 4 K.

The quasiparticle-charge–diffusion length has to be corrected to obtain a normal electron-diffusion length. Calculations describing such corrections have been carried out for electron-phonon inelastic processes.[17,18] One simple model (see Ref. 11) which gives the inelastic-scattering time of conduction electrons an inverse temperature dependence is a two-level system with a flat distribution of the excitation energy. Using this model, we obtain the quasiparticle-charge-relaxation rate, $\tau_{Q^*,T}^{-1}(E)$, for quasiparticles of energy E in the superconducting state as

$$\tau_{\mathrm{in},T_c}\,\tau_{Q^*,T}^{-1}(E) = 0.41(T/T_c)\int_{-\infty}^{\infty} d(E'/k_BT)\rho_\Delta(E-E')[\Delta^2E'/E(E-E')^2] \times\{1+\tanh(E'/2k_BT)\tanh[(E-E')/2k_BT]\}/2,$$

where τ_{in,T_c} is the electron inelastic scattering time at T_c, Δ is the superconducting gap, and

$$\rho_\Delta(E-E') \equiv \Theta(|E-E'|-\Delta)\,|E-E'|/[(E-E')^2-\Delta^2]^{1/2}$$

is the BCS density of states. Because the electron elastic mean free path is very short, the normalized quasiparticle-charge–diffusion length, $\lambda^*(T)/\lambda(T-T_c)$, is equal to $[\tau(E)_{Q^*,T}/\tau_{\mathrm{in},T}]^{1/2}$.[1] In Fig. 1 the dashed and the dotted lines correspond to $\tau_{Q^*,T}^{-1}(2\Delta_0)$ and $\tau_{Q^*,T}^{-1}(3\Delta_0)$, respectively, and the solid line corresponds to an averaged $\tau_{Q^*,T}^{-1}(E)$ over a quasiparticle distribution which represents a small shift in the chemical potential,[19] i.e., $\delta f = (-\partial f_T/\partial E)[(E^2-\Delta^2)^{1/2}/E]\,\delta\mu/2$. The averaged value is independent of the amount of the chemical-potential shift as long as the first-order expansion of the quasiparticle distribution with respect to $\delta\mu$ is adequate.

As we approach a temperature of $0.9T_c$, the calculated curves merge and yield similar values. This then is the temperature range over which we can reliably translate the quasiparticle-charge–diffusion length to the normal electron-diffusion length. Of interest to note here is that the correction factor at this temperature for electron-phonon inelastic scattering is also close to 2.[18]

An I-V curve of one of the samples is shown in

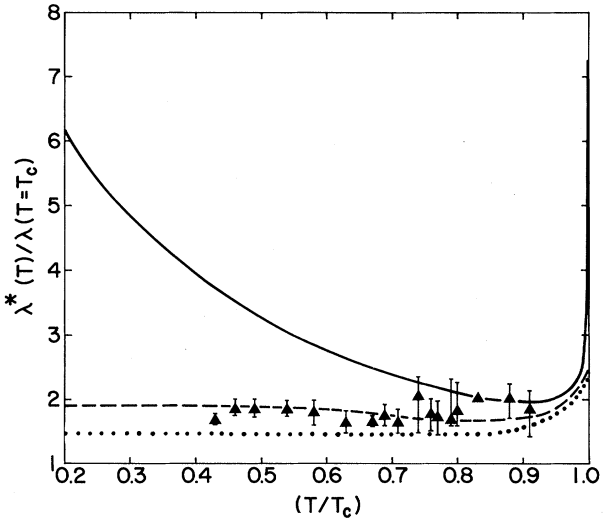

FIG. 1. Ratio of the quasiparticle-charge–diffusion length λ^* to the normal electron-diffusion length λ measured at T_c as a function of the reduced temperature. The dashed and dotted lines correspond to $\tau_{Q^*,T}^{-1}(2\Delta_0)$ and $\tau_{Q^*,T}^{-1}(3\Delta_0)$, respectively, and the solid line is for an averaged $\tau_{Q^*T}^{-1}(E)$.

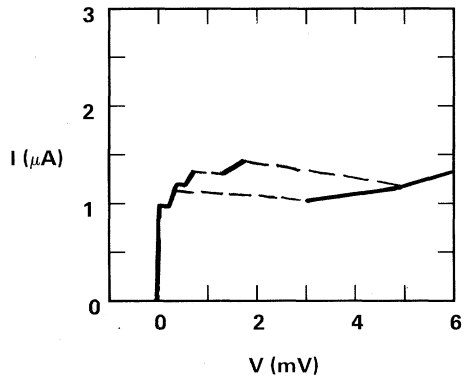

FIG. 2. An I-V curve of one of the samples showing three steps associated with two, three, and four phase-slip cavities. Other samples prepared from nominally the same material and fabrication process showed one or two phase-slip cavities.

Fig. 2. The sequence of steps in this curve could be associated with two, three, and four phase-slip centers. We deduce these to be two, three, and four rather than one, two, and three phase-slip centers from the constancy of the extracted value of the quasiparticle-charge–diffusion length λ^*. If our assignment is wrong the value of the quasiparticle-charge–diffusion length averaged over the three steps is in error by approximately 33% on the low side as it is obtained from the relation $\lambda^* = LR_n/2nR_L$, where L is the length of the wire, R_L its normal-state resistance, n the number of phase-slip centers, and R_n the normal-state resistance associated with those centers.[14]

The normal electron-diffusion length deduced from experiments carried out to verify one-dimensional localization theory was found for these alloys to be 260 ± 40 Å at 4.2 K. At 3.5 K this has an average extrapolated value of 285 Å. Using this number we have normalized all of our measured values of the quasiparticle-charge–diffusion length. The results are shown in Fig. 1 for one of the samples. Very similar values were obtained for three other samples which have slightly different transition temperatures and were not measured over as great a temperature span as this sample. The agreement between theory and experiment is good near the transition temperature where we can reliably compare the two. At lower temperatures, theory and experiment cannot be compared in a meaningful way even though the agreement appears to be good because we do not know the average excitation energy of quasiparticles in the phase-slip center. We have also not included the effect of heating in our measurements which increases as the critical-current increases with decreasing temperature. However, the agreement near the transition temperature leads us to conclude that the inelastic-scattering times deduced from the localization model are comparable to those obtained from phase-slip measurements.

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