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Localization and interaction effects in two-dimensional W-Re films

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In this Communication we report our findings on two-dimensional amorphous W-Re films of various compositions in which we have studied superconducting fluctuations, the superconducting transition temperature T_c, and the magnetoresistance. We have also measured the dependence of T_c on sheet resistance. The T_c data fit well with the predictions of Maekawa and Fukuyama which are based on localization and Coulomb-interaction effects. Inelastic-scattering times derived from these measurements agree with data from phase-slip phenomena.

There are by now a number of metallic systems in which a logarithmic increase in resistivity as the temperature is decreased has been reported. This effect is observed at low temperatures and has been attributed to localization[1] and/or Coulomb-interaction[2,3] effects. Recently, Larkin[4] and Maekawa and Fukuyama[5,6] have examined theoretically the role of localization and interaction effects in determining the superconducting fluctuation and the transition temperature (T_c). The fluctuation effects are particularly interesting in theories of localization for they enable us to determine the inelastic-scattering times. These times can be compared with data obtained either from measurements based on localization theories or from phase-slip measurements.[7–15] A consistency between the times obtained from a variety of measurements would lend support not only to theories of localization but also provide a test of recent models for inelastic scattering in "dirty" systems.[16,17]

In this Communication, we report our findings on two-dimensional amorphous W-Re alloys in which we have measured fluctuation effects and the change in transition temperature as a function of the sheet resistance of the film. This alloy system[8,18] is particularly interesting for it is the only system in which the magnitude and temperature dependence of the inelastic-scattering time has been described and found to agree with theories of one-dimensional localization[19] and phase-slip measurements.[9]

Amorphous W-Re alloys with a composition ranging from 30 to 50 at.% W and thickness from 30 to 1200 Å were prepared by electron beam evaporation onto oxidized silicon substrates held at room temperature. The details of the sample preparation procedure, their composition analysis, structural and superconducting properties are to be reported elsewhere.[20] The resistivity of the films was found to be a function of film thickness and generally ranged between 160 and 360 $\mu\Omega$ cm except for a film with a nominal thickness of 30 Å which had a resistivity of 1300 $\mu\Omega$ cm. The resistance ratio, i.e., $R\,(300\text{ K})/R\,(15\text{ K})$ was less than but close to unity—between 0.95 and 0.99. Again the 30-Å film was different with a resistance ratio of 0.8.

The superconducting transition temperature was obtained from resistance measurements and determined by the intersection of the linear portion of the curve with the temperature axis. For films with a thickness less than 100 Å there is a marked rounding of the upper part of the transition curve due to superconducting fluctuations and a tail in the lower part—characteristic of two-dimensional superconducting systems. The superconducting transition temperature T_c is plotted in Fig. 1 as a function of film thickness and sheet resistance. The variation in T_c with thickness has been observed in a number of systems.[21–24] It has often been interpreted on the basis of proximity effects. However, we find that the dependence of T_c on sheet resistance can be explained rather well with localization models. The data, along with the theoretical fit using the model of Maekawa and Fukuyama,[5,6] are shown in Fig. 1(b). In this model, the Coulomb interaction between electrons is enhanced by localization effects resulting in a depression of T_c as ex-

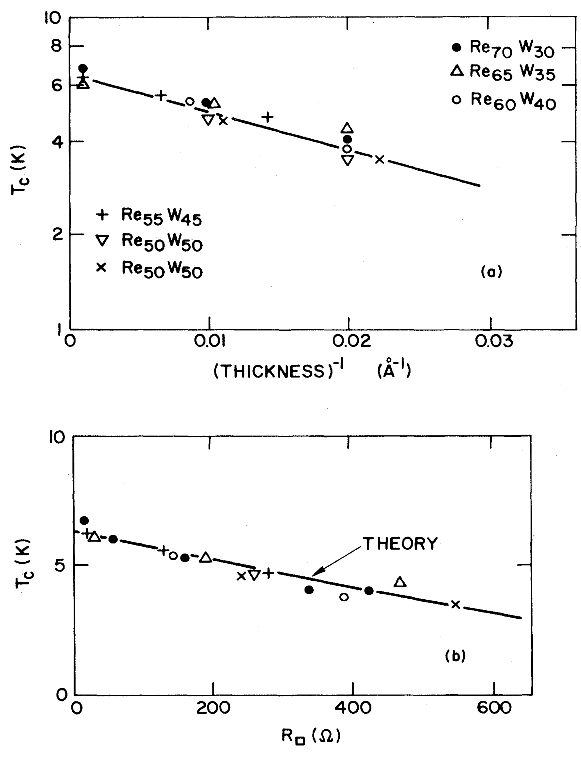

FIG. 1. Superconducting transition temperature T_c plotted as a function of the inverse of the thickness for a variety of alloy compositions. The solid line is a best fit to the data. Data replotted as a function of sheet resistance $R_{\square}$. Theory curve is that of Maekawa or Fukuyama (Ref. 5).

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pressed in Eq. (1):

$$\ln\left(\frac{T_c}{T_{c0}}\right) = -\frac{\lambda_s}{2}\left[\ln\left(5.4\frac{\xi_0}{l}\frac{T_{c0}}{T_c}\right)\right]^2 - \frac{\lambda_s}{3}\left[\ln\left(5.4\frac{\xi_0}{l}\frac{T_{c0}}{T_c}\right)\right]^3 , \quad (1)$$

where

$$\lambda_s = \frac{g_l N(0)\hbar}{2\pi\epsilon_F\tau_0} . \quad (2)$$

T_c and T_{c0} are the superconducting transition temperatures of the film with and without impurity scattering. ξ_0 is the zero-temperature coherence length corresponding to T_{c0}, and l is the mean free path associated with elastic scattering. The constant g_1 is a coupling constant associated with the Coulomb interaction and is positive. $N(0)$ is the density of states, ϵ_F the Fermi energy, and τ_0 the elastic scattering time. The sheet resistance $R_\square$ is given by $R_\square = \pi\hbar^2/e^2\epsilon_F\tau_0$, $e^2/\pi\hbar = 7.54\times10^{-5}\ \Omega^{-1}$. In Eq. (1), the first term on the right-hand side is due to the correction to the density of states and the second to enhancement of the Coulomb repulsion between electrons due to impurities. Note that the second correction is much stronger than the first. We rewrite Eq. (2) in the form

$$\lambda_s = 1.2\times10^{-5} R_\square(\Omega) g_1 N(0) , \quad (3)$$

and adjust $g_1N(0)$ and ξ_0/l to fit the experimental data. The solid curve shown in Fig. 1(b) is obtained with the parameter values of $T_{c0}=6.3$ K, $g_1N(0)=1.19$, and $\xi_0/l=30$. This value of T_{c0} is to be compared with the maximum value of 6.4 K obtained experimentally. The value of $g_1N(0)$ may be compared with that of the screened Coulomb interaction[2] in the limit of long wavelength, which gives $g_1N(0)=1$. The zero-temperature coherence length in amorphous alloys is generally of the order of 100 Å and the elastic mean free path of the order of interatomic spacing. The ratio ξ_0/l is therefore expected to be around 30.

In films with the lowest T_c we were able to measure the change in resistance with temperature (Fig. 2) and obtain the logarithmic dependence of resistance on temperature. When temperature is high enough compared with T_c, the conductance due to localization, interactions, and their interplay is written as[1-3]

$$\sigma = R_\square^{-1} + \frac{e^2}{2\pi^2\hbar}\tilde{\alpha}\ln(k_BT\tau_0/\hbar) , \quad (4)$$

$$\tilde{\alpha} = \alpha p + (g_1 + 3|g_{BCS}|)N(0) , \quad (5)$$

where σ is the conductance of the film and p is the exponent in the temperature dependence of inelastic scattering rate ($\tau_{in}\propto T^{-p}$). α is a constant; $\alpha=1$ when spin-orbit scattering is neglected and $\alpha=-\frac{1}{2}$ when the scattering is relatively strong; g_{BCS} is the BCS coupling constant. Since g_{BCS} is an attractive interaction (negative), this also increases the resistance, which is in contrast with the simple screened-Coulomb-interaction model.[2] From the experimental data, we find $\tilde{\alpha}$ to be 0.95. From the analysis of T_c, we have obtained that $g_1N(0)=1.19|g_{BCS}|N(0)$ is of the order of 0.1. In our films, as shown below, $p\approx1$, leading to the conclusion that in the W-Re films spin-orbit scattering is quite strong. This conclusion is also derived from the following analysis of the magnetoresistance data. The magnetoresistance for a particular alloy composition $Re_{50}W_{50}$ is shown in Fig. 3 at various temperatures. Larkin[4] has examined the Maki-Thompson (MT)[25] mechanism for the superconducting fluctuation conductance and derived an expression for magnetoresistance in two-dimensional (2D) films at temperatures not too close to T_c and in a weak magnetic field:

$$\Delta R(H) = -R_\square^2\frac{e^2}{2\pi^2\hbar}[\alpha-\beta(T)]Y\left(\frac{4D\tau_{in}eH}{\hbar}\right) . \quad (6)$$

$$Y(x) = \ln x + \psi\left(\frac{1}{2}+\frac{1}{x}\right) , \quad (7)$$

where D is the diffusion constant and $\psi(z)$ is the di-gamma function. $\beta(T)$ is a parameter that is independent of spin-orbit scattering and has been tabulated in Ref. 4. Note that in this temperature range, the resistance deviates from the $\ln T$ dependence because of fluctuations. In bulk amorphous materials, the MT mechanism gives only small contribution

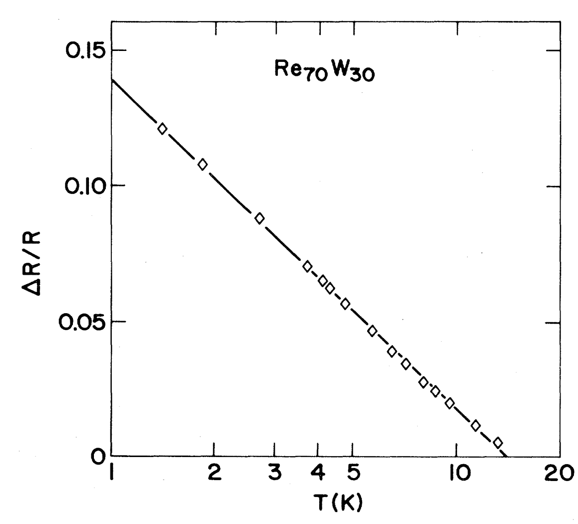

FIG. 2. Change of resistance $\Delta R/R$ vs temperature for a particular alloy composition. The film thickness was 30 Å.

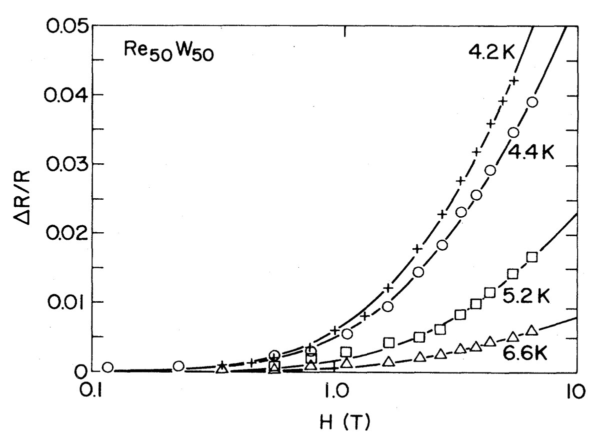

FIG. 3. Magnetoresistance for a particular alloy composition at various temperatures. The solid curves are theoretical estimates using the Larkin theory, Eq. (6).

on the fluctuation conductance.[26] However, in our particular thin amorphous films,[20] the Larkin theory fits the magnetoresistance quite well for $T/T_c > 1.2$. Using Eq. (6), we fit our data as shown, for example, in Fig. 3 and then obtain $[\alpha - \beta(T)]$ and $L_{in} = (D\tau_{in})^{1/2}$. We have plotted in Fig. 4 the experimental $[\alpha - \beta(T)]$ and the theoretical value of $\beta(T)$. Although $[\alpha - \beta(T)]$ is sensitive to the choice of T_c, we can clearly conclude that α is negative. Hence the spin-orbit scattering dominates in our samples, which is consistent with the above conclusion as obtained from the $R_\square(T)$ measurements. This is not surprising as both W and Re are high-atomic-number elements.

The value of L_{in} was determined from the data over rather small temperature range $2.5 > T/T_c > 1.2$. The upper limit is determined by the signal to noise in our measurements and the lower by the onset of superconductivity. Over this narrow temperature range, we find the temperature dependence of L_{in} to be consistent with the result of Abrahams *et al.*[16] This is shown in the inset in Fig. 4. The value of D was determined from the superconducting critical magnetic field to be ~ 0.46 cm^2/sec. The experimental values of $\tau_{in}^{-1} = D/L_{in}^2$ can be compared with the values found by phase-slip[9] and one-dimensional localization measurements,[18] e.g., at $T \sim 4.2$ K, τ_{in} from phase slip in about 12 ps in good agreement with a value of 9 ps obtained from the above magnetoresistance. The detailed dependences[14] of τ_{in} on sample size (both 1D and 2D) and temperature for the W-Re films will be given in a future publication.[27]

In summary, we have studied the superconducting transition temperature T_c and the magnetoresistance in two-dimensional amorphous W-Re alloy films. The dependence of T_c on $R_\square$ appears to fit a single theoretical curve [Fig. 1(b)] independent of alloy composition, indicating that the localization is also independent of composition. Both the resistance and magnetoresistance indicate the presence of strong spin-orbit scattering effects. The data also provide a consistency check with recent theories of localization and Coulomb interaction and their role in superconducting phenomena. The inelastic-scattering time deduced from the analyses of the influence of superconducting fluctuations on magnetoresistance agrees with the theory[16] and the phase-slip measurements.[9]

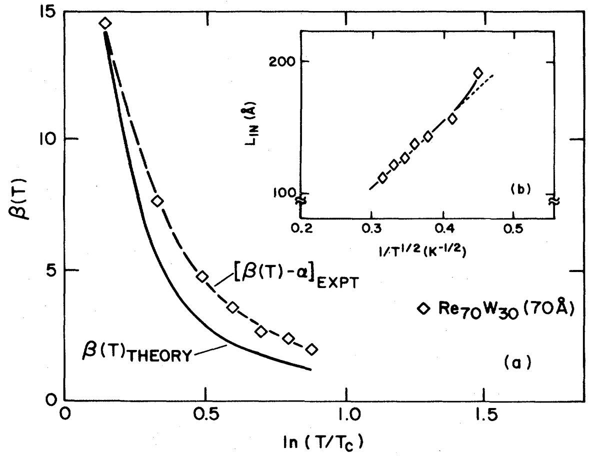

FIG. 4. Comparison of experimental value of $\beta(T) - \alpha$ and the theoretical $\beta(T)$ for the alloy $Re_{70}W_{30}$ at a thickness of 70 Å. Inset shows the temperature dependence of the inelastic-scattering length derived from the magnetoresistance data.

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