Effect of an electron–electron interaction on the conductivity of ultrathin metal films

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(Submitted 1 June 1981)
Pis'ma Zh. Eksp. Teor. Fiz. **34**, 32–35 (5 July 1981)

Study of the effects of a constant magnetic field and of microwave radiation on the conductivity of ultrathin films shows that the logarithmic growth of the resistance exhibited by such films with decreasing temperature results from a Coulomb interaction of electrons in the presence of impurity scattering.

PACS numbers: 73.50.Dt

Several important new results have been obtained recently in the physics of disordered systems. In particular, a logarithmic growth of the resistance with decreasing temperature T has been observed in two-dimensional systems.[1,2] There are two mechanisms which might be responsible for this behavior: a localization of noninteracting electrons[3] and a Coulomb interaction of electrons in the presence of impurity scattering.[4] As Altshuler *et al.*[5,6] have shown, the effects of these two mechanisms can be distinguished experimentally by applying a constant magnetic field or microwave radiation to the disordered system.

In this letter we are reporting measurements of the resistance R of thin copper and niobium films, which exhibit a logarithmic dependence $R(T)$ at $T \lesssim 20$ K, as the films are subjected to a magnetic field H and to microwave radiation. The experimental results seem to show that the observed temperature dependence $R(T)$ is governed by a Coulomb interaction.

The copper and niobium films studied in these experiments had a thickness $d = 30$–40 Å, a width of 2 mm, and a length ~7 mm; they were synthesized by rf sputtering. The films were cooled at a rate of 5–10 Å/*s* on room-temperature glass substrates on which contact areas had been deposited beforehand. The surface resistivity $R_\square$ of the samples lay in the range 100–500 Ω. The dc resistance was measured within ~2×10^{-5}. In the microwave measurements, carried out at a frequency of 10 GHz, the sample was held at the center of a waveguide with the plane of the film oriented parallel to the microwave electric field vector.

Similar results on the behavior $R(T)$ were obtained in dc measurements for the copper and niobium films; one set of data points is shown in Fig. 1. (At thicknesses $d = 30$–40 Å, the niobium films do not go superconducting at temperatures as low as $T \approx 2$ K). At $T < 20$ K we observe a behavior $\Delta R \sim \ln T$, in accordance with the theoretical results obtained from the model of a localization of noninteracting electrons[3] and the Coulomb-interaction model[4] for the two-dimensional case:

$$\frac{\Delta R_\square}{R_\square^2} = \frac{Ae^2}{2\pi^2\hbar} \ln T. \tag{1}$$

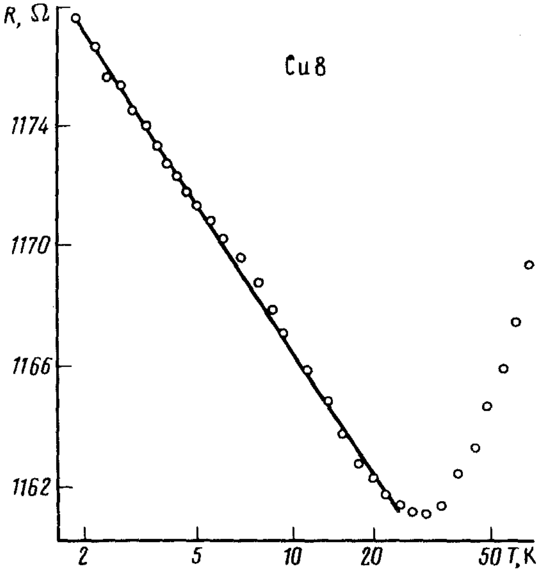

FIG. 1. The temperature dependence $R(T)$ for a copper film (sample #Cu8) with $R_\square$(300 K) = 363 Ω and R(300 K)/R(20 K) = 1.062. The solid line corresponds to $A = 1.22$.

The coefficient A in the electron-localization model is the same as the exponent P in the temperature dependence of the inelastic scattering time for electrons, $\tau_{\text{in}} \sim T^{-p}$, while for the Coulomb-interaction model this coefficient is approximately unity for large screening lengths. Experimentally, the only parameter which affects $\Delta R/R$ is $R_\square$, as would follow from Eq. (1), and the coefficient A lies in the range 0.9–1.1 for the niobium films and 0.95–1.3 for the copper films. Corresponding results have been obtained previously[1,7] for thin films of $Au_{60}Pd_{40}$. Since the behavior $\tau_{\text{in}}(T)$ for dirty, thin films (with $l \approx d \gg \lambda_{\text{ph}}$, where l is the electron mean free path and λ_{ph} is the wavelength of a thermal phonon) may be affected by many factors which are difficult to take into account (for example, the acoustic matching of the film and the substrate), measurements of $R(T)$ for such films cannot reveal a distinction between electron-localization and Coulomb effects.

The effect on the film conductivity of a magnetic field oriented perpendicular to the plane of the film was studied over the range $H = 0$–3000 Oe at $T \leqslant 4.2$ K. The niobium films exhibited a weak, temperature-independent, approximately quadratic increase in the resistivity with increasing field, $\Delta R/R = (5 \times 10^{-5}\ \text{kOe}^{-2}) \cdot H^2$, while the copper films exhibited a slight decrease, $\Delta R/R = (2-30) \times 10^{-5}$ at $H = 3$ kOe. The change ΔR decreases with decreasing temperature in the case of the copper. If we are seeing electron-localization effects, there should be a significant negative magnetoresistance at fields $H \gtrsim 20$ Oe for both the copper and the niobium films, because of a suppression of localization at fields $H > H_c = \hbar c/4eD\tau_{\text{in}}$ (Ref. 5). (For our samples the diffusion coefficient is $D \cong 10\ \text{cm}^2/s$, and $\tau_{\text{in}} \cong 10^{-10} s$.) On the other hand, if we are seeing Coulomb-interaction effects, the influence of the magnetic field on the the conductivity should be very slight over the filed range studied, and this is what we see in the experimental results. Giordano[7] has also reported the absence of a negative magnetoresistance.

Figure 2 shows the effect of a constant electric field E and of microwave radiation (at a power P_{mw}) on the film conductivity. During the microwave irradiation the film resistivity was measured with a current corresponding to $E = 2 \times 10^{-2}$ V/cm. The theory derived by Altshuler *et al.*[6] shows that the effect of microwave radiation at a frequency ω—a suppression of the localization corrections to the conductivity—depends on two parameters: the product $\omega\tau_\phi$ (τ_ϕ is the time over which phase coherence is lost[6]) and the dimensionless quantity $\alpha = 2e^2E_\sim^2D/\hbar^2\omega^3$, where $E_\sim$ is the microwave electric field. The values $\omega\tau_\phi = 3 - 10$ and $\alpha_{\max} = 5\text{–}10$ found experimentally should correspond to substantial changes in the resistivity: by more than 3%, for example, in Fig. 2 for $\log P_{\mathrm{mw}} = 0.4$. A constant electric field, on the other hand, should not have any direct effect on electron localization.[6] Experimentally, however, we find that a constant electric field does in fact affect these films, as does the microwave radiation, and thus we conclude that the logarithmic behavior $R(T)$ is not a consequence of localization effects.

The observed changes $R(E)$ and $R(P_{\mathrm{mw}})$ are not caused by heating; estimates put the lattice and electron heating at no more than 1 K for our samples. Furthermore, we observed $\min R(P_{\mathrm{mw}}) < \min R(T)$ for several of the samples, as can be seen clearly from a comparison of Figs. 1 and 2. The field dependence of the conductivity of these films is apparently caused by their granular structure. The granularity should not affect the dependence $R(T)$ caused by Coulomb effects or by localization effects,

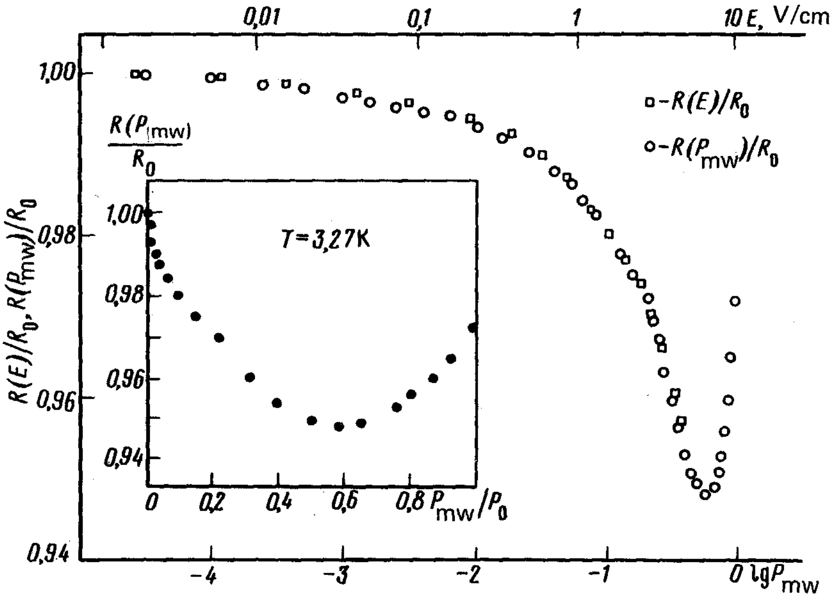

FIG. 2. The results on $R(E)/R_0$ and $R(P_{\mathrm{mw}})/R_0$ for film sample #Cu8. The inset shows $R(P_{\mathrm{mw}})/R_0$ in a scale linear in the power. R_0—Resistivity of the sample measured at a low measurement current in the absence of the microwave signal; P_0—maximum microwave power.

since the grain size (comparable to the film thickness) is far smaller than the characteristic lengths of these models: $\sqrt{\hbar D/kT}$ for the Coulomb interaction and $\sqrt{D\tau_{\text{in}}}$ for the electron localization. On the other hand, small metal grains and tunneling barriers in the films can give the conductivity complicated field dependence.

These experiments show that the logarithmic dependence $R(T)$ observed in thin metal films with $R_\square \gtrsim 100\ \Omega$ is a consequence of an electron–electron interaction. It should be noted that for thicker and purer films (and thus, presumably, with a better measurement accuracy), it is apparently possible to observe Coulomb-interaction and electron-localization effects simultaneously.[8] At present, the question of the mechanism for the suppression of localization in dirty, thin films remains open.

We thank B. L. Al'tshyler, A. G. Aronov, and D. É. Khmel'nitskiĭ for a useful discussion of these questions.

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Translated by Dave Parsons

Edited by S. J. Amoretty