Magnetoresistance and non-Ohmic conductivity of thin platinum films at low temperatures

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The electrical conductivity of thin Pt films is measured as a function of temperature T, magnetic field B, and electric field E. A logarithmic temperature dependence is observed. The magnetoresistance is positive and anisotropic, increasing as B^2/T in small perpendicular fields and logarithmically in high $B_\perp$. The electric field causes the resistance to drop proportional to E^2 at low E and logarithmically at high E, in agreement with localization theory. Our data on the magnetoresistance, however, disagree with theory.

Electron localization in thin metal films and inversion layers leads to a logarithmic correction to the temperature dependence of the conductivity.[1,2] Alternatively, rather similar behavior is predicted from a completely different model based on electron-electron interaction.[3] Strikingly different phenomena are expected only if a magnetic field is applied (magnetoresistance, Hall effect).[4–6] Experiments have shown either negative[7–10] or positive[11] magnetoresistance, or both (Refs. 12–14). Though some of the observed phenomena may be described either by localization or by interaction effects a detailed understanding is still far from being complete.

In our work we have measured the resistance of thin Pt films at temperatures down to 0.33 K and in fields up to 3.4 T. In addition, we have investigated deviations from Ohmic behavior by varying the current through the films. An analysis of our data on the temperature and electric field dependencies shows quantitative agreement with localization theory and yields both the elastic and the inelastic electron scattering rates. On the other hand, our data on the magnetoresistance disagree with available calculations.

Pt was chosen mostly because of its favorable properties for making thin and homogeneous films.[15] At pressures below 10^{-9} mbar, Pt was evaporated onto glass substrates at room temperature. At a thickness of 0.7 nm, typically, films became continuous, and evaporation was stopped at thicknesses between 1.2 and 2.5 nm, resulting in resistances per square between 5000 and 600 Ω. The samples were cooled in a ^{3}He cryostat and the resistance was measured in a four-terminal method both with dc current and an ac bridge at 32 Hz. A split coil magnet in the ^{4}He bath produced a magnetic field up to 3.4 T with a homogeneity of better than 1% across the sample. The field axis was either perpendicular to the film surface or parallel, if desired.

Upon cooldown, the measured resistances passed through a minimum at temperatures ranging from 150 to 8 K, depending on film thickness. If the current was kept sufficiently low, the well-known logarithmic increase of the resistance was observed at lower temperatures with a coefficient of $(1.01 \pm 0.07)e^2/2\pi^2\hbar$ (Fig. 1), in agreement with earlier work at higher temperatures.[16] Excessive currents ($\gtrsim 1$ μA) resulted in a considerable deviation from Ohm's law and a decrease below the $\ln T$ divergence, especially at our lowest temperatures. In Fig. 2 a typical non-Ohmic behavior of the resistance is shown as a function of the electric field E across the sample. The data indicate an increase of the conductivity (resistance drop) proportional to E^2 at low fields and a logarithmic dependence on E at high fields, the characteristic field which separates the E^2 regime from the $\ln E$ law being strongly decreasing with decreasing temperature. The coefficient A of the E^2 law, i.e., $-\Delta R/R = AE^2$, increases as $T^{-2.90 \pm 0.07}$ between 4.2 and 0.33 K (see Fig. 3). In the $\ln E$ regime the resistance was found to be independent of the substrate temperature which varied with the duration of the current pulses applied to the film. It is interesting to note the slopes of the $\ln E$

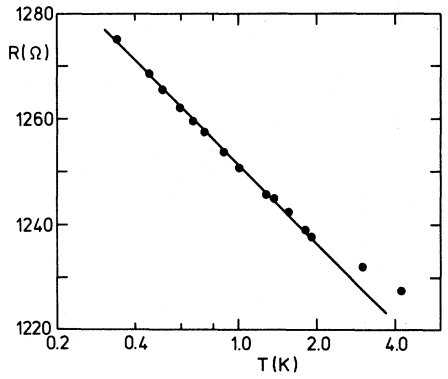

FIG. 1. Typical temperature dependence of a film resistance measured at $B = 0$ in the Ohmic regime (R independent of current). Below 2 K the logarithmic increase is observed.

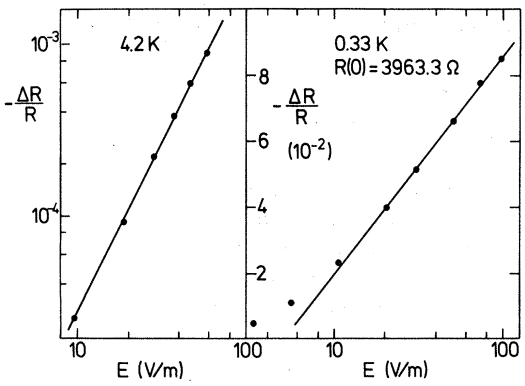

FIG. 2. Non-Ohmic behavior of the resistance. Left: E^2 law (solid line) at 4.2 K. Right: $\ln E$ law at 0.33 K; at this temperature the E^2 law exists only at much lower fields (not shown here).

dependence of all of our films have a value of $(0.62 \pm 0.05)e^2/2\pi^2\hbar$.

A typical magnetoresistance (MR), as a function of the magnetic induction B, is shown in Fig. 4. Data from all of our films have the following features. The MR is positive, anisotropic, and temperature dependent. In the perpendicular geometry at small $B_\perp$ we find $\Delta R \propto B^x$, with x between 1.7 and 2.0. With increasing field, ΔR then varies linearly and, at

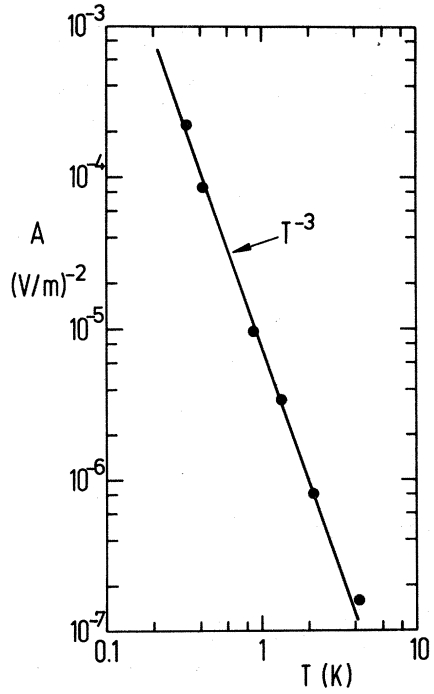

FIG. 3. Temperature dependence of the coefficient A of the E^2 law.

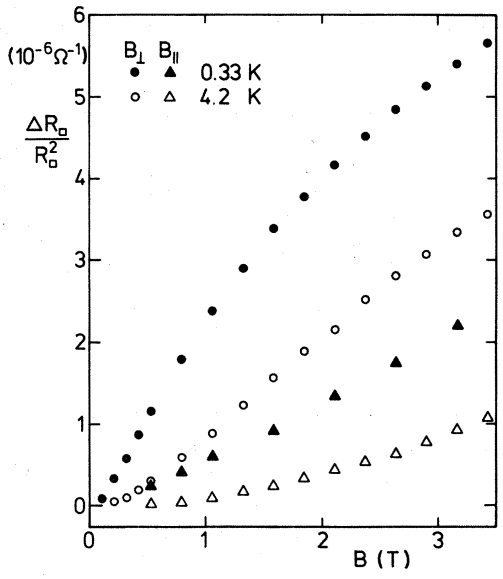

FIG. 4. Magnetoresistance at 4.2 and 0.33 K with B parallel and perpendicular to film surface ($R_\square$ is the resistance per square).

low temperatures, approaches a logarithmic behavior having a coefficient of $(0.30 \pm 0.03)e^2/2\pi^2\hbar$. Our thinnest films have a wider power-law regime and less tendency to saturate, insufficient to evaluate a logarithmic behavior unambiguously. At 4.2 K the MR has less variation with B, but the general features of the low-temperature behavior are still visible. In the parallel geometry (B parallel to the surface, but perpendicular to the current) and MR at a given temperature is smaller and may be fitted to a power law B^y over the entire field range with y between 2.0 at 4.2 K and 1.2 at 0.34 K. We note that our data are different from those of Ref. 14 where, under conditions similar to ours, a negative MR is observed. It will be interesting to find out the cause of this difference.

We may compare our experimental results with current theoretical models based either on electron localization or on electron-electron interaction. In the localization picture our coefficient of the $\ln T$ increase of the resistance indicates $P = 1.0$, where P determines the temperature dependence of the inelastic scattering rate $\tau_{in}^{-1} \propto T^P$. Contributions to the $\ln T$ dependence resulting from interaction effects are expected to be small because the screening length of the static Coulomb interaction in our case should be shorter than the Fermi wavelength.[3] We estimate this contribution to the prefactor to be between 0.1 and 0.2. It seems reasonable to assume that the scattering rate $\tau_{in}^{-1} \propto T$ results from inelastic electron-electron collisions. In fact, recent calculations[17] indicate $\tau_{in}^{-1} \propto T \ln T$ for two-dimensional metal films,

quite similar to the linear behavior deduced from our data.

Further information can be obtained by comparing the electric field dependence of the resistance with calculations by Tsuzuki.[18] The coefficient A of the E^2 law is then given by $A = (e^2/3\pi\hbar m)\tau_{in}^3$ and hence $P = 0.97$, in agreement with the above conclusions drawn from the $\ln T$ dependence. At 1.0 K, τ_{in} has a value of 8.3×10^{-11} sec if m is taken to be twice the free-electron mass. Furthermore, the slope of the $\ln E$ dependence of 0.62 compares well with the theoretical result of $\frac{2}{3}$. Also our observation that, in the $\ln E$ regime, the resistance is independent of the lattice temperature agrees with the calculation. In addition, the elastic electron scattering time τ can be determined easily from the absolute values of the resistance drop shown in Fig. 2 (right). We find values of τ being around 5×10^{-15} sec, corresponding to an elastic mean free path of about twice the film thickness. Having obtained both $\tau_{in}(T)$ and τ the complete, (T,E) dependence of the nonmetallic conductivity due to electron localization is determined.[18]

Concerning the discussion of the observed magnetoresistance we note that our data disagree, however, with presently available calculations based either on localization or interaction theory. The first one predicts a negative MR except for strong spin-orbit scattering.[4,19] In this case, though, the MR in weak fields is expected to scale as $B^2\tau_{in}^2$, whereas our data scale approximately as B^2/T, which is over an order of magnitude less than B^2/T^2 between 4.2 and 0.34 K. Furthermore, if the spin-orbit scattering rate is larger than the inelastic one, the temperature dependence of the zero-field data should be reduced or even have the opposite sign. On the other hand, interaction effects should lead to an isotropic positive MR scaling as $(B/T)^2$ in small fields.[6] Obviously this result also does not describe our data.

In summary, we may state that both the temperature and the electric field dependencies of our data can be consistently interpreted in terms of localization theory with $\tau_{in}^{-1} \propto T$. An understanding of the observed magnetoresistance, however, must await further theoretical progress.

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