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ENERGY RELAXATION OF HOT ELECTRONS AND INELASTIC COLLISION TIME IN THIN METAL FILMS AT LOW TEMPERATURES

S.I. Dorozhkin*, F. Lell and W. Schoepe

Institut für Angewandte Physik, Universitat Regensburg D-8400 Regensburg, West Germany

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In a sandwich consisting of a thin Au film and a thin Bi film insulated by a 500 Å SiO layer the electrons of one film are heated above the lattice temperature while in the other film they are kept in thermal equilibrium with the phonons. By measuring the magnetoresistance of both films we obtain the temperature difference between electrons and phonons from which we imply the energy-relaxation time τ_ϵ from 0.3 K to 2 K. We find that electron–phonon scattering determines τ_ϵ and, above 5 K, also the inelastic collision time τ_i obtained from weak localization theory in thermal equilibrium.

WEAK LOCALIZATION PHENOMENA in thin metal films have revealed detailed information about the dynamics of the electron gas because they are sensitive to various scattering mechanisms which break the phase coherence of the electrons [1]. Especially from the magnetoresistance (MR) these scattering times can easily be determined. A particularly simple situation exists in the limit of strong (or negligible) spin-orbit scattering where the MR is almost exclusively governed by inelastic collisions of the electrons [2]. Therefore, the MR in thin Au or Bi films, e.g., provides a direct measurement of the inelastic scattering time τ_i [3–7]. From the temperature dependence of τ_i one usually concludes that at high temperatures ($T \gtrsim 2$ K) τ_i is caused by electron–phonon collisions. At lower temperatures, however, τ_i is thought to be given by inelastic electron–electron scattering. This now offers the interesting possibility of heating the electron gas to a temperature T_e above the low phonon temperature T_p. While T_e is established on a time scale of the order of τ_i the energy relaxation is slower because it requires collisions between electrons and phonons to cool the electron gas. Overheating of the electrons therefore is possible up to a temperature where electron–phonon collisions become as frequent as electron–electron collisions. If both temperatures T_e and T_p can be measured simultaneously one can determine the *energy-relaxation time* τ_ϵ which has not been accessible under equilibrium conditions where τ_i ($\ll \tau_\epsilon$) sets the limit for phase coherence.

As a thermometer for the electron gas we use the MR of thin Au and Bi films. Both films are thermally tightly coupled by a 500 Å insulating SiO layer so that they have a common phonon bath because the phonon wavelength in our temperature regime (0.3 to 2 K) is larger than 500 Å [8]. Driving one film at successively higher d.c. current levels results in a reduction of its MR because of an increase of T_e. Simultaneously we measure the MR of the other film at a sufficiently low current level to ensure equilibrium between electrons and phonons and obtain the common phonon temperature T_p. From T_e–T_p we can infer the energy relaxation rate of the electrons which has a temperature dependence indicative of electron–phonon scattering. Furthermore we find that τ_ϵ extrapolates to the high temperature τ_i curve, consistent with dominant electron–phonon scattering above 5 K. Thus, our method provides a first direct comparison of τ_ϵ and τ_i in thin metal films.

Our sample is fabricated by first depositing a 75 Å Au film onto a glass substrate. Except for the two current and three voltage connections this film is covered by the SiO layer on top of which we deposit a 200 Å Bi film. The length between the voltage probes is 3 mm and the width of the films is 1 mm. Typical convenient resistivities are about 300 Ω/□ for either film. Homogeneity is checked by interchanging voltage connections and comparing resistivities in different sections of the films. Insulation between the films is usually better than 20 MΩ. The sample is mounted inside the ^{3}He pot of our cryostat and is completely immersed in the liquid in order to keep the lattice temperature as low as possible. A transverse magnetic field up to 3.5 tesla can be applied for MR measurements, which are performed with a four-terminal a.c. bridge at low frequencies (32 Hz) and low current levels (~ 5 μA). Heating of the electron gas of one film is achieved by applying a d.c. current I of up to 1 mA and measuring the voltages with a high resolution

*Permanent address: Institute of Solid State Physics, Academy of Sciences of the USSR, Chernogolovka, Moscow district, USSR.

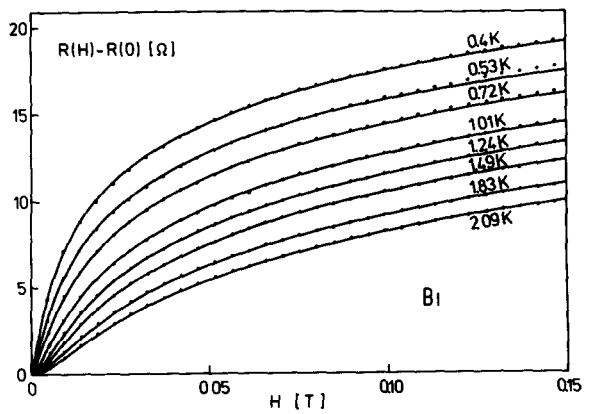

Fig. 1. Magnetoresistance of the Bi film at different temperatures. Solid lines are the measurements, dots are from a fit of weak localization theory.

d.c. voltmeter while the other film is being monitored at low a.c. levels as before. The power I^2R delivered to the electron gas heats up T_e and to a lesser extent also T_p and ultimately the ^{3}He bath.

We first measure the equilibrium MR of both films at various temperatures between 0.3 and 20 K. These data not only provide us with the temperature calibration of the MR but in addition enable us to evaluate the inelastic scattering time $\tau_i(T)$ by fitting the standard theory of weak localization ot the data. Fig. 1 shows a typical set of MR data at low fields where the MR is determined by weak localization only (at higher fields effects from electron–electron interaction may contribute). In the limit of strong spin-orbit scattering the MR is described simply by [2]

$$\frac{R(H)-R(0)}{R(0)} = \frac{e^2}{2\pi^2\hbar}\cdot R_\square \cdot \frac{1}{2} f\left(\frac{H}{H_i}\right),$$

where $f(x) = \psi(1/2 + 1/x) + \ln x$ and ψ is the digamma function. The "inelastic field" H_i is related to τ_i by

$$H_i\tau_i = \hbar/4eD,$$

with the diffusion coefficient D being given by the Einstein relation $D = (e^2 R_\square dN(\epsilon_F))^{-1}$; d is the film thickness and $N(\epsilon_F)$ is the density-of-states at the Fermi level. Equation (1) may be extended to allow for finite spin-orbit scattering times [2]. These corrections, however, are not essential here. From a fit to the data we obtain H_i from which we calculate τ_i by using published values for the density-of-states $N(\epsilon_F)$ [9]. The results are depicted in Figs. 2 and 3.

Application of a large d.c. current then heats the electrons in one film to a temperature T_e above the phonon temperature T_p. Both temperatures can now be determined from the temperature calibration of the MR as measured before. For small temperature differences

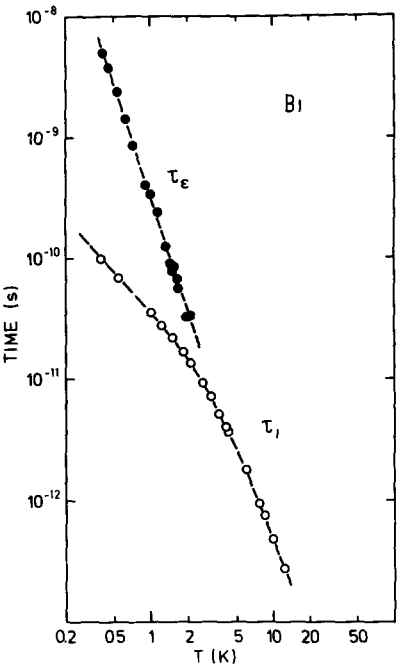

Fig. 2. Energy-relaxation time τ_ϵ and inelastic collision time τ_i in bismuth.

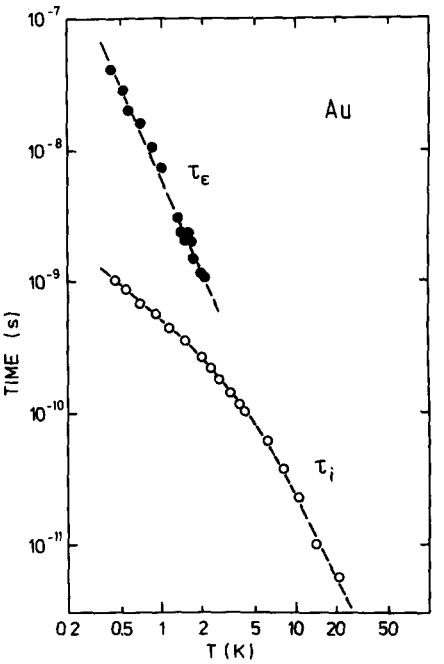

Fig. 3. Energy-relaxation time τ_ϵ and inelastic collision time τ_i in gold.

$\Delta T = T_e - T_p$ we calculate τ_ϵ from a simple heating model [10]:

$$I^2R\tau_\epsilon(T) = V_0 C_{el}(T)\Delta T, \qquad (2)$$

where V_0 is the volume of the film and $C_{el}(T) = \gamma_{el}T$ is the electronic specific heat at the average temperature $T = (T_e + T_p)/2$. It is interesting to note that the density-of-states is a common scaling factor for both τ_i and τ_ϵ (via γ_{el}) and does not affect their ratio. By varying the current from 10 μA to 1 mA (i.e. four orders of magnitude in power) we obtain the data shown in Figs. 2 and 3.

Analyzing our results we find that in both metals $\tau_i \propto T^{-p}$ has two distinct regimes: $p = 1.0$ below 2 K for both Au and Bi, and above 5 K $p = 2.0$ for Au and $p = 2.5$ for Bi, although the temperature intervals outside of the transition regime are rather short for a precise determination of the power laws. We attribute the low temperature behavior of τ_i to inelastic electron–electron scattering, where in fact a T^{-1} law has been calculated [11,12]. Our measured values at 1 K are a factor of 4 smaller for Bi and a factor of 2 larger for Au when compared with [12]. The high temperature part reflects electron–phonon processes for which the predicted power laws depend on the purity and dimensionality of the sample [13]. With regard to phonons we consider our sample to be three-dimensional because of the coupling to the substrate. The purity is given by $q_p \cdot l_0$, where q_p is a typical phonon wavevector and l_0 is the elastic mean free path. Estimating l_0 from the diffusion coefficient and the Fermi velocity and setting $q_p \sim k_B T/\hbar c$, where c is the velocity of sound, we find that our Au film is "dirty" at all of our temperatures ($q_p l_0 \ll 1$), whereas our Bi film may be "clean" above 0.5 K ($q_p l_0 \gtrsim 1$). For the clean case a T^{-3} law is expected [14, 15]. For the dirty case, however, the situation is unclear since both a T^{-2} law or a T^{-4} law have been predicted [1, 13, 14].

Comparing our τ_i data with the earlier experiments [3–5] on Bi, we note good agreement in temperature dependence as well as absolute values. As for the Au film the published work [1, 6, 7] gives a less clear picture. Obviously the investigated samples are difficult to compare. This might be related to the more granular structure of the Au film.

The essential result of our work is the determination of the energy relaxation time τ_ϵ. In Bi we find $\tau_\epsilon \propto T^{-3.0}$, which gives clear evidence of electron–phonon scattering. In Au we get $\tau_\epsilon \propto T^{-2.2}$ which may be consistent with the dirty limit. Furthermore, it is most remarkable that in both films τ_ϵ clearly coincides with a low temperature extrapolation of the τ_i data from above 5 K. This proves that electron–phonon scattering limits phase coherence at high temperatures. The absolute values of τ_ϵ at 1 K are $3.4 \cdot 10^{-10}$ s in Bi and $7.2 \cdot 10^{-9}$ s in Au, which is of the expected order when compared with theory [15] or with measurements of electron–phonon scattering rates by resonance methods at higher temperatures [16].

Earlier experiments on electron heating in thin films [17, 7] have been analyzed by use of equation (2) under the assumption $T_e \gg T_p$ and by replacing the equilibrium temperature T by T_e in the $\ln T$-divergence of the zero field resistance. From a comparison of the measured voltage dependence of the resistance with the equilibrium temperature dependence on can imply τ_ϵ to scale as $T^{-p'}$ with $p' = 3$ in Au–Pd films [18] and $p' \simeq 0.4$–0.8 in Au films [7]. Obviously, our method of separately measuring T_e and T_p does not rely on the above assumption.

By employing a completely different technique Roukes *et al.* [19] recently measured $\tau_\epsilon \propto T^{-3}$ in thick Cu films at very low temperatures. T_e and T_p were determined by noise thermometry on two separate films on the same substrate. In that work τ_i was not measurable.

In summary, our method yields a direct comparison of τ_ϵ and τ_i by use of weak localization. Electron – electron scattering governs τ_i at low temperatures and hence limits the phase coherence time, whereas electron–phonon scattering determines τ_ϵ and, at higher temperatures, also τ_i.

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