Crossover between Dissipative and Nondissipative Electron Transport in Metal Wires

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Electron transport in one-dimensional metal wires of different length is shown to change from dissipative to nondissipative when the electron-phonon relaxation length becomes equal to the wire length. The crossover provides the first direct measurement of the energy relaxation length in metal wires which is found to have an inverse cube temperature dependence. In the dissipationless regime the electron energy is shown to be linearly related to the voltage applied across the wire.

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Over the past decade there have been many measurements of transport in mesoscopic systems that have length L less than the phase breaking length l_ϕ [1]. Most of these measurements have been performed close to equilibrium. Another length scale associated with transport is the inelastic length l_i. Many scattering processes are inelastic, for example, electron-electron scattering which relaxes energy within the electron system [2] and electron-phonon scattering which relaxes energy from the electron system. Since inelastic scattering processes also relax phase, in general, $l_\phi \leq l_i$. In disordered metals at low temperatures the phase breaking length is dominated by the quasielastic electron-electron scattering so that $l_\phi < l_i$ in these systems [3]. To study carrier energy relaxation, far-from-equilibrium transport experiments in which the electrons are heated above the lattice temperature have been performed in the dissipative regime $L > l_i$; in this case l_i is the inelastic scattering length associated with energy loss from the electron system [4–7]. Far-from-equilibrium measurements have also been used to study the phase coherence length in the mesoscopic regime $L < l_\phi$ [8], but the region $L \approx l_i$ has so far not been explored. In this Letter we report far-from-equilibrium transport measurements in the regime $L \approx l_i$, and we demonstrate the crossover from dissipative to nondissipative transport as the sample length L is changed from $L > l_i$ to $L < l_i$. This provides the first direct measurement of the energy relaxation length in nanometer scale wires. In the regime $L < l_i$, the energy is dissipated in the contacts, and the electron temperature T_e in the wire is shown to be proportional to the applied voltage V. In the dissipative regime, $L > l_i$, energy is relaxed in the system itself and, in agreement with previous work, the electron temperature $T_e \propto (V/L)^{2/5}$ [5,9,10].

The experiments were performed on $Au_{60}Pd_{40}$ alloy wires that were defined by electron-beam lithography and were thermally evaporated onto a silicon substrate at room temperature and at a pressure of 5×10^{-6} Torr. Three sets of wires were investigated: 82 parallel wires 20 nm thick, 40 nm wide, and 85 μm long; 45 parallel wires 20 nm thick, 90 nm wide, and 30 μm long; and 6 parallel wires 20 nm thick, 30 nm wide, and 4.8 μm long. The lengths of the wires are designated as L_{85}, L_{30}, and $L_{4.8}$, respectively. The samples were comprised of many parallel wires for two reasons: First, the number of wires reduces universal conductance fluctuations by increasing the ensemble averaging, and, second, the parallel wires made the sample resistance match the minimum noise contour of the measurement apparatus. The samples were fabricated with four wide contacts to facilitate four-terminal resistance measurements and were mounted in a vacuum inside a dilution refrigerator so that the substrate temperature T_s could be controlled to better than 1 mK in the range 0.05 and 1.5 K. A low frequency four-terminal bridge and signal averaging were used to measure the resistance. To minimize electron heating by the ac sensing current at the lowest temperatures, the sensing voltage was kept below 5 μV rms, which is equivalent to the thermal energy of the electrons at the lowest temperatures used. The low temperature resistivity of all sets of wires was $\rho \approx 40\ \mu\Omega$ cm, giving an elastic scattering length $l_e \approx 2.1$ nm.

When the substrate temperature was reduced below 1.5 K, the temperature dependence of the equilibrium resistance change, $(R - R_i)/R_i = \Delta R/R_i$, for each set of wires increased as $T^{-1/2}$. Here R_i is the impurity limited resistance. A $T^{-1/2}$ dependence of the low temperature resistance of AuPd wires is expected from interaction corrections [11,12] when the Thouless length $l_T = (D\hbar/k_BT)^{1/2}$ becomes greater than the width and thickness of the wires. The electronic diffusion constant $D = v_F^2\tau_e/3$, where v_F is the Fermi velocity which is estimated to be 1.4×10^6 ms^{-1} and τ_e is the elastic scattering time. For the present samples D is 0.98×10^{-3} m^2 s^{-1} so that l_T is greater than the cross-sectional dimensions of the 85 and 4.8 μm long wires over the entire temperature range studied and is greater than the cross-sectional dimension of the 30 μm long wire at temperatures below 900 mK. At the lowest temperatures, $l_T < L_{4.8}$, meaning that for all three sets of wires the electrons remain in the one-dimensional regime over the entire temperature range. The equilibrium resistance change for all three samples was well described by the

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interaction model [13],

$$\frac{\Delta R}{R_i} = \frac{\rho e^2}{Ah}\left(4 - \frac{3}{2}F\right)\sqrt{\frac{D\hbar}{2k_BT}}, \quad (1)$$

where A is the cross-sectional area of the wire, using a screening parameter $F \approx 0.8$.

A constant dc voltage was applied across the wires to heat the electrons. The steady-state resistance change $[R(E) - R_i]/R_i = \Delta R(E)/R_i$ as a function of the electric field $E = V/L$, where L is either L_{85}, L_{30}, or $L_{4.8}$, is shown in Figs. 1 and 2 for the 85 and 4.8 μm long wires, respectively, for several different substrate temperatures. Similar behavior was found in the 30 μm long wires. At low electric fields $\Delta R(E)/R_i$ is independent of E, but at higher fields $\Delta R(E)/R_i$ falls as E is increased. The point at which $\Delta R(E)/R_i$ changes from being independent to being dependent on E occurs when the electrons gain enough energy from the dc electric field to cause them to heat above the lattice temperature [5]. For each set of wires at the lowest substrate temperatures, above the electric field independent region the steady-state resistance change had a dependence on E that became weaker above a certain value of E, as indicated by the intersection of the two lines in the inset to Fig. 2. This feature is strikingly different from other electron heating measurements on much longer wires [5,11]. The electric field at which the weakening of the dependence on E occurred was different for each set of wires. At higher substrate temperatures the steady-state resistance change was found to have a simpler behavior, going directly from the field independent region to the regime that had the weaker dependence on E. The substrate temperature at which this change in behavior occurs is seen in Figs. 1 and 2 to be approximately 300 and 800 mK for the 85 and 4.8 μm long wires, respectively.

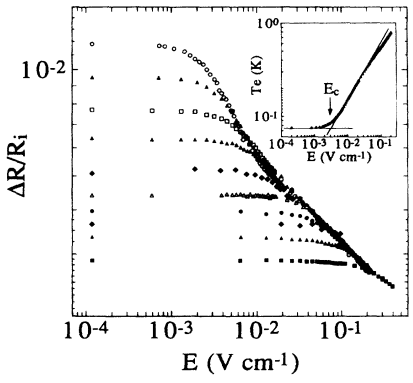

FIG. 1. The steady-state resistance change as a function of the electric field for an 85 μm long wire for different starting substrate temperatures. From top to bottom the substrate temperatures are 75, 115, 175, 250, 400, 530, 655, 775, 915, and 1250 mK. The inset shows the electron temperature as a function of the electric field for the starting substrate temperature of 75 mK.

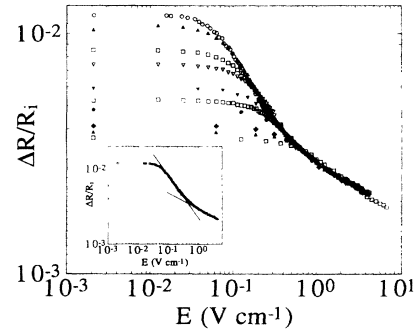

FIG. 2. The steady-state resistance change as a function of the electric field for a 4.8 μm long wire for different starting substrate temperatures. From top to bottom the substrate temperatures are 95, 125, 190, 250, 410, 500, 595, 815, 915, and 1030 mK. The inset shows two lines drawn on the 95 mK data to indicate where the field dependence weakens.

For the 30 μm long wires the change occurred at about 400 mK. All the equilibrium and nonequilibrium features remained unchanged after thermal cycling the wires to room temperature, and no dependence on the polarity of V was found.

The crossover from a stronger to a weaker E dependence of $\Delta R(E)/R_i$ has not been previously reported in metal wires. To analyze this effect $\Delta R(E)/R_i$ was converted to the equivalent electron temperature using the equilibrium resistance change. This was achieved by calculating the corresponding dc value of the measured ac resistance using an integration procedure [14,15]. Following integration, a critical electric field E_c was defined at each substrate temperature as indicated in the inset to Fig. 1. At E_c the electrons have an energy that is about 10% above k_BT_s. The values of E_c for all three sets of wires are plotted as a function of T_e in Fig. 3. For the 4.8 μm long wires, a least squares fit to the values of E_c below 800 mK gives a slope of 0.95 ± 0.1, as shown by the solid curve in Fig. 3. Therefore, to within the accuracy of the experiment $E_c = \alpha T_e$. For the 30 and 85 μm long wires, below the substrate temperatures of 400 and 300 mK the critical fields are empirically found to lie close to the linear relationship $E_c = (\alpha/B)T_e$, where B is 6.25 and 17.7, respectively. The linear relationships for the 30 and 85 μm long wires are indicated by the dotted and dashed lines in Fig. 3. The numerical scaling factors B that relate the linear relationships of the three wires are simply the ratio of the wire lengths; that is, $L_{85}/L_{4.8} = 17.7$ and $L_{30}/L_{4.8} = 6.25$. The relationship between E_c and temperature becomes stronger at higher temperatures where a least squares analysis gives $E_c \propto T_e^{5/2}$ for all three sets of wires, as shown in Fig. 3. At these higher temperatures scaling by the length ratio of the wires is not found.

At low lattice temperatures the scaling between the linear dependencies of E_c with T_e by the ratio of the wire lengths implies that electron heating is determined by the

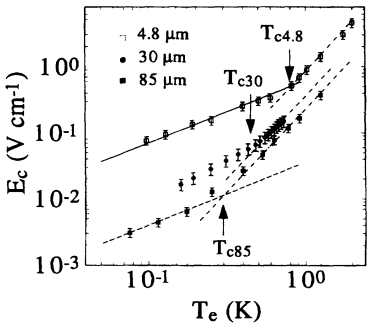

FIG. 3. The values of critical field, E_c, plotted as a function of the electron temperature for the 4.8, 30, and 85 μm long wires. The solid curve is a least squares fit to the 4.8 μm data below $T_{c4.8}$. The dotted (dashed) curve is the solid curve scaled in magnitude by the ratio $L_{30}/L_{4.8}$ ($L_{85}/L_{4.8}$). The dash-dotted curves show the power law dependence $E_c \propto T_e^{5/2}$.

applied voltage, not the electric field. In Fig. 4 we show a plot of the critical voltage, $V_c = E_c/L$, as a function of T_e for all three sets of wires. The linear region has a slope of about $3k_B/e$, where e is the electron charge. This slope is in close agreement with the value obtained from a more complete calculation that accounts for the nonequilibrium distribution of hot electrons [10]. At temperatures where $V_c \propto T_e$, the electron transport must be elastic with respect to energy loss from the electron system as a whole; that is, no dissipation occurs in the wires themselves.

Under the influence of an electric field the electron energy distribution will be a non-Fermi distribution, but will be relaxed toward a Fermi distribution by electron-electron scattering. By equating the internal energy of the nonequilibrium energy distribution to that of a Fermi distribution, it has been shown that in the limit of $l_i < L$ and in the presence of electron-electron scattering an effective temperature describes the electron system well [16]. At the lowest temperatures of the present experiment, $l_i > L$, and we estimate that the electron-electron scattering length approaches $L_{4.8}$ [3]. In this regime the electrons lose no energy in the wire, gain an energy eV from the applied bias, and yet probably do

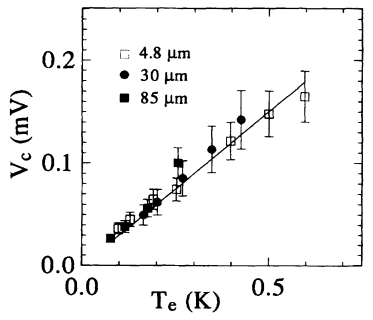

FIG. 4. The critical voltage as a function of the electron temperature in the linear region for all three sets of wires.

not come to internal equilibrium. In this situation the voltage dependence of the resistance must originate from the energy dependence of the electron transmittance in the wire. Therefore, in our discussion and analysis of the transition between dissipative and nondissipative transport we have used only the onset of the resistance change with field where the energy distribution of the electrons likely remains close to a Fermi distribution.

At higher lattice temperatures the dependence $E_c \propto T_e^{5/2}$ is characteristic of dissipative transport. In this regime inelastic scattering causes energy loss from the electron system, and the power developed in the wire can be expressed as [9]

$$\frac{E^2}{\rho} = \int \frac{\gamma T}{\tau_i(T)} dT, \tag{2}$$

where γ is the electronic specific heat and $\tau_i(T)$ is the energy loss lifetime. Thus, in each set of wires at high temperatures we find $\tau_i \propto T^{-3}$. At the crossover point between the nondissipative and dissipative transport regimes we expect that $l_i(T_c) = L$, where T_c is a characteristic temperature of the crossover, as indicated in Fig. 3. Furthermore, at the temperature T_c we expect $l_i(T_c) = v_F \tau_i(T_c)$ since at this point inelastic electron diffusion does not dominate the transport. It follows that $L_m/L_n = (T_{cm}/T_{cn})^{-\beta}$, where the subscripts m and n refer to either 4.8, 30, or 85. For self-consistency β should equal 3. From Fig. 3 we estimate that $T_{c85} = 295$ mK, $T_{c30} = 410$ mK, and $T_{c4.8} = 807$ mK, and we find that $\beta = 2.8 \pm 0.3$. The temperature dependence of the energy loss lifetime is therefore in agreement with the observed temperatures at which the transport changes from one regime to the other.

In the low temperature regime where $V_c \propto T_e$, dissipation must occur in the large contact pads over a length scale characterized by the energy relaxation length appropriate to the pads. In the high temperature regime where dissipation occurs in the wires themselves, we find the energy loss lifetime has a cubic temperature dependence. The dominant phonon wavelength is estimated to be $q_D = 6.2 \times 10^7$ m^{-1} K^{-1}; therefore at the highest temperatures the wires approach the clean limit, $q_D l_e \approx 0.2$. In the clean limit, and with a three-dimensional phonon spectrum, the electron-phonon relaxation time has been calculated by Reizer [17] who finds $\tau_i \propto T^{-3}$, which agrees with the data. However, it is surprising that this temperature dependence is found to extend down to 300 mK in the longest wires since this temperature is about an order of magnitude below the lowest longitudinal acoustic subband energy [18]. At this low temperature the wires are in the dirty limit and a one-dimensional phonon spectrum is expected. In this situation it has been predicted that the energy relaxation time has a temperature dependence $\tau_i \propto T^{-2}$ [19]. Since the geometry of the samples seems to preclude the possibility of two-dimensional phonons for

which $\tau_i \propto T^{-3}$ has been suggested [20], the origin of the T^{-3} dependence of the energy loss lifetime in the wires is uncertain. One possibility is that phonon coupling between the wire and the substrate modifies the relationship between E and T_e, as has been shown for thin films [21].

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