Comment on "Crossover Between Dissipative and Nondissipative Electron Transport in Metal Wires"

Recent experiments [1] have studied electron heating in metal wires at low temperatures, $T < 1$ K. The electrons are heated above the temperature of the phonons in the wire, which remain close to the substrate temperature. The authors report a result for the scaling of the critical electric field, E_c, with wire length L and electron temperature T, where E_c is the field at which the electrons are heated by an amount $\Delta T = 0.1T$. At low temperatures E_c is found to obey the relation

$$E_c \approx 3\,(k_B/e)\,T/L\,, \tag{1}$$

with e the electron charge and k_B the Boltzmann constant. (At higher temperatures, E_c is proportional to $T^{5/2}$ and does not depend on L, as expected for phonon cooling.) At the temperatures where Eq. (1) applies, the power produced in the wire is dissipated (i.e., converted into phonons) in the leads, not in the wire.

Kanskar and Wybourne explain the result in Eq. (1) by an earlier theoretical paper [2]. However, that theory paper dealt solely with phonon cooling of the electrons, not electron diffusion out of the wire, which dominates the cooling process at low temperatures [3,4]. Reference [2] also did not include the fact that the electrons share energy among themselves rapidly. It is now know that in such dirty metals the electron-electron energy sharing time, τ_{ee}, is much shorter than the electron phonon time [5]. These two important aspects of the experiment were considered previously for wires in two different contexts: a superconducting microbridge used as a THz heterodyne mixer [3], and heating experiments on a long strip of GaAs two-dimensional electron gas below 1 K [4].

We propose a physically appropriate explanation for the observations in Ref. [1] regarding E_c. Heat flow within the electron gas is governed by the Wiedemann-Franz relation when electron-electron scattering is rapid enough to ensure a local electron temperature. For the wire geometry the spatial dependence of the temperature rise, for a small temperature increase, is an inverted parabola [4]. Taking ΔT to be the average temperature increase and defining the thermal conductance out of the wire via the electron gas to be G_e, we find [4]

$$G_e = (12\mathcal{L}\,T)/R\,, \tag{2}$$

with R the electrical resistance of the wire and $\mathcal{L}$ the Wiedemann-Franz constant, $\mathcal{L} \approx 3(k_B/e)^2$. Note that heat is able to diffuse out of both ends. For a temperature increase of $0.1T$,

$$\Delta T = 0.1T = P/G_e\,. \tag{3}$$

P is the power produced in the wire, given by $V^2/R = (E_cL)^2/R$ for $\Delta T = 0.1T$. Thus,

$$E_c \approx 2(k_B/e)\,T/L\,. \tag{4}$$

Equation (4) gives a result like the experiment, Eq. (1), but with a somewhat different prefactor. This difference may result from the specific definition of E_c. The scaling of E_c inversely with L is simply due to the fact that longer wires provide poorer cooling of the electrons in the center. The scaling with T is due to the Wiedemann-Franz relation. In any case, at low temperatures electron cooling dominates. We agree with the authors' conclusion that phonon cooling operates at higher temperatures.

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