Thermal correction to resistivity of 2D electron (hole) gas in low-temperature measurements at $B = 0$

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Abstract

We calculate the zero magnetic field resistivity, taking into account the degeneracy of the 2D electron (hole) gas and the thermal correction due to the combined Peltier and Seebeck effects. The resistivity is found to be universal function of temperature, expressed in units of $\frac{h}{e^2}(k_F l)^{-1}$.

Key words: Thermoelectric effects, metal-insulator transision

1. Introduction

Recently, a great deal of interest has been focussed on the anomalous behaviour of 2D electron(hole) systems,[1] whose resistivity unexpectedly decreases as the temperature is lowered, exhibiting a behaviour generally associated with metals, rather than insulators. Although numerous theories have been put forward to account for this effect, the origin of this metallic behaviour is still the subject of a heated debate.

We report on a study of low-T transport in 2DEG at zero magnetic field, taking into account both the electron degeneracy and the Peltier-effect-induced correction to resistivity.[2,3] Usually, the ohmic measurements are carried out at low current density in order to prevent Joule heating. In contrast to the Joule heat, the Peltier and Thomson effects are linear in current. As shown in [2],[3], the Peltier effect influences ohmic measurements and results in a correction to a measured resistance. When current is flowing, one of the sample contacts is heated, and the other cooled, because of the Peltier effect. The established temperature gradient is proportional to the current. Then, the voltage drop across the circuit includes the thermoelectromotive force induced by the Peltier effect, which is linear in current. Finally, there exists a thermal correction $\Delta\rho$, to the ohmic resistivity, ρ, of the sample. As was demonstrated in [3], for degenerate electrons, $\Delta\rho/\rho \approx (kT/\mu)^2$, where μ is the Fermi energy. Hence, the above correction may be comparable with the ohmic resistance of a sample when $kT \sim \mu$. We discuss the features of thermal correction within 2D electron-density-modulated low-temperature ohmic measurements.

2. Analytical approach

Let us consider a 2DEG sample(Fig.1, inset) and dc current flowing in it. The 2DEG structure is arbitrary, electrons are assumed to occupy the first quantum-well subband with isotropic energy spectrum $\varepsilon(k) = \frac{\hbar^2 \mathbf{k}^2}{2m}$. Here, m is the electron effective mass, $\mathbf{k}$ is the wave vector. The sample is connected by means of two identical leads to the current source. Both contacts are assumed to be ohmic. The voltage is measured between the open ends ("c" and "d") kept at the temperature of the external thermal reservoir. The sample is placed in a sample chamber with mean temperature T_0. With the temperature gradient term included, the current density $\mathbf{j}$ and the energy flux density $\mathbf{q}$ are given by

$$\mathbf{j} = \sigma(\mathbf{E} - \alpha\nabla T), \ \mathbf{q} = (\alpha T - \zeta/e)\mathbf{j} - \kappa\nabla T, \qquad (1)$$

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Here, $\mathbf{E} = \nabla\zeta/e$ is the electric field, $\zeta = \mu - e\varphi$. Then, $\sigma = Ne^2\tau/m$ is the conductivity, N the 2DEG density, τ the momentum relaxation time, κ the thermal conductivity, and α the thermopower.

We recall that the electron-phonon coupling known is weak below ~1K. Thus, the cooling of 2DEG with respect to bath could predominately occur through the contacts of the sample. However, the experiments[4] demonstrate that the electron gas is, in fact, the dominant thermal resistance in this problem. The cooling is provided by thermal conductivity of 2DEG alone and found to follow Wiedemann-Franz law. Thus, we neglect further the contact heat leak assuming adiabatic cooling conditions. Then, we omit the Joule heating.

It is well known that the Peltier heat is generated by current flowing across the interface between two different conductors. At the contact "a" the temperature $T_{\rm a}$, electrochemical potential ζ, normal components of the current $I = jd$, and energy flux qd are continuous. Here, d is the sample width. Then, there exists a difference of thermopowers $\Delta\alpha = \alpha_{\rm me} - \alpha$, where $\alpha_{\rm me}$ is the thermopower of the metal lead. For $\Delta\alpha > 0$ and the current direction depicted in Fig.1, contact "a" is heated, and contact "b" is cooled. The amount of the Peltier heat, $Q_{\rm a} = I\Delta\alpha T_{\rm a}$, evolved at contact "a" and that absorbed at contact "b" are equal. Thus, the contacts are at different temperatures($T_{\rm a,b} \approx T_0$) and $T_{\rm a} - T_{\rm b} = \Delta T > 0$. Since the energy flux is continuous at each contact, the difference of the contact temperatures is given by $\Delta T = I\Delta\alpha T_0 l_0/\kappa d$, where l_0 is the sample length. Following Ref. [2],[3], there exists a thermal correction to resistivity associated with thermoelectromotive force $\epsilon_{\rm T} = \Delta\alpha\Delta T \sim I$. Finally, the total resistivity of the 2DEG-sample is given by

$$\rho^{\rm tot} = \rho\left(1 + \alpha^2/L\right), \qquad (2)$$

where α and $\rho = 1/\sigma$ are 2DEG thermopower and ohmic resistivity, $L = \frac{\pi^2 k^2}{3e^2}$. Using Gibbs statistics and isotropic energy spectrum we obtain $N = N_0\xi F_0(1/\xi)$, where $N_0 = \frac{m\mu}{\pi\hbar^2}$ is the density of strongly degenerate 2DEG, $F_{\rm n}$ is the Fermi integral, $\mu = kT_{\rm F}$ is the Fermi energy, $\xi = T/T_{\rm F}$ is the dimensionless temperature. Following Boltzman equation formalism, 2DEG thermopower (for 3D case, see Pisarenko, 1940) yields $\alpha = -\frac{k}{e}\left[\frac{2F_1(1/\xi)}{F_0(1/\xi)} - \frac{1}{\xi}\right]$, where the momentum relaxation time assumed to be energy-independent. In Fig.1, we plot $\rho^{\rm tot}(T)$ at different Fermi energies. Within low-temperature $\xi \ll 1$ metallic region $N = N_0$, thus $\rho^{\rm tot} = \rho_0(1 + \frac{\pi^2\xi^2}{3})$. Here, $\rho_0 = \frac{h}{e^2}(k_{\rm F}l)^{-1}$ is the ohmic resistivity at $T \to 0$, $k_{\rm F}$ is the Fermi vector, and l is the mean free path. Then, for the high-temperature $\xi \gg 1$ insulating region we obtain the asymptote $\rho^{\rm tot} = \rho_0\frac{2.18}{\xi\ln 2 + 1/2}$. These results are confirmed by recent experiments[5−7] shown that for the metallic region data obey a scaling law where the disordered parameter $k_{\rm F}l$ and dimensionless temperature ξ appear explicitly. Our predictions may be confirmed by ac measurements since the thermal correction disappears above some critical frequency.[2,3]

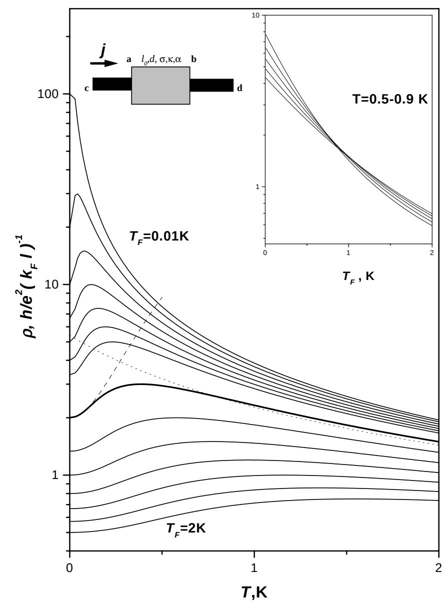

Fig. 1. T-dependence of the 2DEG resistivity, given by Eq.(2) for $T_F = 2; 1.75; 1.5; 1.25; 1; 0.75; 0.5; 0.3; 0.25; 0.2; 0.15; 0.1; 0.05; 0.01$K. Asymptotes: $\xi \ll 1$ - dashed line, $\xi > 1$ - dotted line for $T_F = 0.5$K. Inset: the experimental setup(left); density dependence of the 2DEG resistivity within the T =0.5-0.9K range(right).

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