# Drag-related thermo-emf in metallic systems containing a point contact

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A thermoelectric circuit which has no heterogeneous metals and which is interrupted in one place by a point contact whose diameter is smaller than the inelastic length of the mean free path of an electron makes it possible to measure the absolute thermo-emf of the drag of electrons by phonons. The contribution of the point contact to the total voltage of this circuit contains information about the electron-phonon interaction $g^T(\omega)$ with the thermoelectric $K$ factor, $K^T(\mathbf{p}, \mathbf{p}')$.

The methods of point-contact spectroscopy have clearly demonstrated that a wealth of information can be obtained from a current-voltage characteristic of point contacts connecting massive conductors. Since the resistance of point contacts is governed by the current density near the contact, and since the heat is released over considerably greater distances, a nonlinear current regime can be attained relatively easily in normal metals. The energy dependence of the electron and phonon relaxation lengths in the conductors, the phonon state density and the electron-phonon-interaction function can be reconstructed from the shape of the $I$-$V$ curve.[1] The nonequilibrium state of a contact has been customarily attributed in experiments to the electric field. In this letter we consider a case in which, in addition to creating a potential difference, the sides of a contact are held at different temperatures. In this case the electronic and phonon systems are the nonequilibrium systems. We will study the drag of electrons caused by nonequilibrium phonons due to the thermoelectromotive force of the point contacts and we will show that point contacts can, in principle, be used to measure the absolute thermo-emf responsible for the drag produced in the bulk metal.

The particular point-contact model that we will study is a hole in a flat dia-

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phragm which is opaque to electrons and phonons. The hole diameter $d$ is assumed to be small on one side in comparison with the mean free paths of electrons and phonons (ballistic regime) and large on the other side in comparison with the scale lengths of the electron and phonon waves. The massive sides of the contact to which the potential difference $V$ is applied are held at different temperatures $T_1$ and $T_2$. The system of kinetic equations for the distribution functions of electrons $f_{\mathbf{p}}(\mathbf{r})$ and phonons $N_{\mathbf{q}}^{\alpha}(\mathbf{r})$ is

$$\mathbf{v}\frac{\partial f_{\mathbf{p}}}{\partial \mathbf{r}} + e\mathbf{E}\frac{\partial f_{\mathbf{p}}}{\partial \mathbf{p}} = I_{e-\mathrm{ph}}\{f_{\mathbf{p}}, N_{\mathbf{q}}^{\alpha}\}\ , \tag{1}$$

$$\mathbf{w}_{\alpha}(\mathbf{q})\frac{\partial N_{\mathbf{q}}^{\alpha}}{\partial \mathbf{r}} = I_{\mathrm{ph}-e}\{N_{\mathbf{q}}^{\alpha}, f_{\mathbf{p}}\}\ , \tag{2}$$

where $\mathbf{E} = -\nabla V; \mathbf{v} = \partial\epsilon(\mathbf{p})/\partial\mathbf{p}$, $\mathbf{w}_{\alpha}(\mathbf{q}) = \partial\omega^{\alpha}(\mathbf{q})/\partial\mathbf{q}$; $\epsilon(\mathbf{p})$, and $\omega^{\alpha}(\mathbf{q})$ are the dispersion laws for electrons and phonons, respectively, and $I_{e\text{-ph}}\{\cdots\}$ and $I_{\text{ph-}e}\{\cdots\}$ are the electron-phonon and phonon-electron standard collision integrals. Far from the contact, the distribution functions, which are equilibrium functions, satisfy the following boundary conditions (the $z$ axis is perpendicular to the contact plane):

$$f_{\mathbf{p}}(z\to\infty) = n_F\left(\frac{\epsilon-\mu_1}{T_1}\right),\quad f_{\mathbf{p}}(z\to-\infty) = n_F\left(\frac{\epsilon-\mu_2}{T_2}\right); \tag{3}$$

$$N_{\mathbf{q}}^{\alpha}(z\to\infty) = n_P\left(\frac{\hbar\omega_q^{\alpha}}{T_1}\right),\quad N_{\mathbf{q}}^{\alpha}(z\to-\infty) = n_P\left(\frac{\hbar\omega_q^{\alpha}}{T_2}\right), \tag{4}$$

where $n_F(x) = (e^x+1)^{-1}$, and $n_P(x) = (e^x-1)^{-1}$. The electric field can be found from the condition of electrical neutrality, and the chemical potentials $\mu_1$ and $\mu_2$ are determined by the temperatures of the contact sides, $T_1$ and $T_2$. In zeroth approximation, we find from the collision integrals the following expressions for the electric current **I** and for the electronic entropy flux $\Pi$[1]:

$$I = -\frac{V^*}{R_v} + K(T_2^2 - T_1^2), \tag{5}$$

$$\Pi = -K(T_1+T_2)V^* + \frac{1}{R_T}(T_2 - T_1). \tag{6}$$

Here $V^* = V + (1/e)(\mu_1 - \mu_2)$, $R_v = 2\pi^2\hbar^3/e^2 m\epsilon_F\Sigma$, $R_T = R_v 3e^2/\pi^2$, $K = em\Sigma/12\hbar^3$, and $\Sigma$ is the area of the contact. Let us consider the conditions under which the Onsager principle and the Wiedemann-Franz law hold. For the thermoelectromotive force produced in the circuit, $\mathscr{E}_T^{(0)}$, from (5) we find the expression

$$\mathscr{E}_T^{(0)} = \frac{\pi^2}{6e\epsilon_F}(T_2^2 - T_1^2), \tag{7}$$

which in the linear approximation leads to a standard thermo-emf $S = \pi^2 T/6e\epsilon_F$.

The interaction of electrons with nonequilibrium phonons produces a drag-related thermo-emf in the point contact, $\mathscr{E}_T^{(\mathrm{ph})}$, which is similar to the known Gurevich volume effect.[3] Here $\mathscr{E}_T^{(\mathrm{ph})}$ may be greater than $\mathscr{E}_T^{(0)}$. Using $I_{\text{e-ph}}\{\cdots\}$ in accordance with the perturbation theory, we find

$$\mathscr{E}_T^{(\mathrm{ph})} = \frac{2^8\hbar^2 d}{3ev_F}\int_0^\infty g^T(\omega)\left[n_P\left(\frac{\hbar\omega}{T_1}\right) - n_P\left(\frac{\hbar\omega}{T_2}\right)\right]\omega d\omega, \tag{8}$$

where $g^T(\omega)$ is the electron-phonon interaction

$$g^T(\omega) = \sum_\alpha \int \frac{dS_{\mathbf{p}}}{v_\perp}\int \frac{dS_{\mathbf{p}'}}{v'_\perp(2\pi\hbar)^4} W^\alpha_{\mathbf{p}-\mathbf{p}'}\,\delta(\omega-\omega^\alpha_{\mathbf{p}-\mathbf{p}'})K^T(\mathbf{p},\mathbf{p}')/\int\frac{dS_{\mathbf{p}}}{v_\perp} \tag{9}$$

with the $K$ factor (cf. Ref. 4)

$$K^T(\mathbf{p},\mathbf{p}') = \frac{v_z w^z_{\mathbf{p}-\mathbf{p}'}}{|\mathbf{v}w^z_{\mathbf{p}-\mathbf{p}'} - \mathbf{w}_{\mathbf{p}-\mathbf{p}'}v_z|}, \tag{10}$$

for which the following expression holds after symmetrization over $\mathbf{p}$ and $\mathbf{p}'$ and averaging over the angles under the assumption that the vector of the group velocity of a phonon, $\mathbf{w}_{\mathbf{q}}$, is directed along $\mathbf{q}$:

$$K^T(\theta) = \frac{\pi}{16}\tan\frac{\theta}{2}, \qquad \theta = \arccos\left(\frac{\mathbf{p}\mathbf{p}'}{pp'}\right). \tag{11}$$

If the condition $T \ll \Theta_D$ holds ($\Theta_D$ is the Debye temperature), we will have $\mathscr{E}_T^{(\mathrm{ph})} \sim (1/e)(d/l_\epsilon)(T_4/\Theta_D^3)$ ($l_\epsilon$ is the inelastic relaxation length of the electrons); i.e., the drag-related thermo-emf of the point contact has an additional small term $d/l_\epsilon$ in comparison with that of the bulk metal.[5]

In actuality, we measured experimentally (see Fig. 1) the difference between the

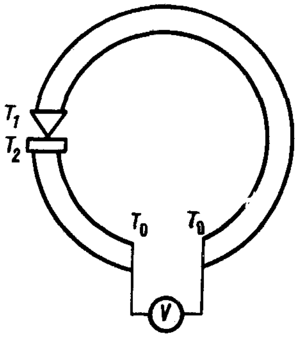


FIG. 1. Thermoelectric circuit for the point contact between two identical metals.

thermoelectromotive forces:

$$\Delta \mathcal{E} = \mathcal{E}_T - \int_{T_1}^{T_2} S dT \,, \tag{12}$$

where $\mathscr{E}_T = \mathscr{E}_T^{(0)} + \mathscr{E}_T^{(\mathrm{ph})}$, and $S$ is the absolute differential thermo-emf of the bulk metal. Since the diffusive thermo-emf of the bulk metal is the same as that of the point contact, and since the drag-related thermo-emf of the point contact is small, we have a unique opportunity to measure the absolute drag-related thermo-emf of the bulk metal over a broad temperature interval.

At $T \gg \Theta_D$ expression (8) does not apply, since the phonon-phonon collision length $l_{\text{ph-ph}}$ is shorter than the phonon-electron scattering length $l_{\text{ph-}e}$. The contribution of the bulk metal to thermo-emf (12) remains in force, however, as long as $l_{\text{ph-ph}}$ is larger than $d$.

The drag-related thermo-emf in a homogeneous circuit containing a point contact has recently been studied experimentally by O. I. Shklyarevskiĭ, A. Jansen,[2)] and P. Wieder.[2)] The results of these experiments are well described by the theory proposed by us in the temperature range $T < \Theta_D$.

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[1)]The contribution of phonons to Π (Ref. 2) in metallic point contacts is small in comparison with (6).
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