Anomalous temperature profiles in solids associated with the electron-phonon drag

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The classification of current carriers according to the energies based on the electron-phonon drag is predicted. This drag may cause the electron temperature drop to be much greater than the temperature difference between the heater and the refrigerator.

Bass *et al.*[1] have shown that if the inequality $\nu_{pp} \gg \nu_{pe}$, where ν_{pe} and ν_{pp} are the frequencies of collisions of the phonons with electrons and among themselves, is satisfied, the expressions for the electron heat flux $\mathbf{Q}_e$ and the phonon heat flux $\mathbf{Q}_p$ may be written

$$\mathbf{Q}_e = -\kappa_e \vec{\nabla} T_e - \kappa_{ep} \vec{\nabla} T_p, \qquad (1)$$
$$\mathbf{Q}_p = -\kappa_p \vec{\nabla} T_p - T_e \kappa_{ep} \vec{\nabla} T_e / T_p,$$

where T_e and T_p are the electron and phonon temperatures. The terms in (1) containing κ_{ep} correspond to the electron-phonon drag which affects both κ_e and κ_p. The parameter which determines the degree of the electron-phonon drag is ν_{pd}/ν_{pe} (ν_{pd} is the phonon-impurity collision frequency). Calculations show that the drag can be ignored in the case of n-GaAs, for example, with an electron density $n \sim 10^{16}$ cm^{-3} ($|\kappa_{e_p}| \ll \kappa_e, \kappa_p$) when $\nu_{pd}/\nu_{pe} > 10^4$, which corresponds to a defect density $n_d \sim 10^{20}$ cm^{-3}. In actual situations we therefore have $\kappa_e \lesssim |\kappa_{ep}| \ll \kappa_p$; if $\nu_{pd} \ll \nu_{pe}$, then $\kappa_e/|\kappa_{ep}| \sim 10^{-4}$ and $|\kappa_{ep}|/\kappa_p \sim 10^{-5}$.

Interestingly, in the case of the scattering mechanisms corresponding to the increase in the frequency of electron-phonon collisions (ν_{ep}) with the electron energy, we have $\kappa_{ep} > 0$ (the scattering of electrons by the deformation potential of acoustic phonons—the *DA* scattering). In the case of scattering of electrons by the polarization potential of acoustic phonons—the *PA* scattering (ν_{ep} decreases with increasing energy), we have $\kappa_{ep} < 0$. Since the phonons drag most efficiently the electrons with energies corresponding to large ν_{ep} frequency, this drag should be accompanied by a classification of electrons according to the energies in the direction of the phonon flux. If the phonon flux is caused by the temperature gradient T_p, then in the case of the *PA* scattering primarily the carriers with an energy higher than the average energy will remain at the heated end of the sample because of the drag-related classification of electrons. As a result, the electron subsystem will have a temperature gradient T_e in the same direction as the gradient T_p. An important point here is that this gradient is not directly linked to external heating and cooling of the electron gas, but instead is determined by the phonon flux and by the intensity of the electron-phonon drag. The electron temperature gradient, in general, can therefore be much higher than the gradient T_p. The phenomenon examined above should also occur in the *DA* scattering of electrons, except that the gradient T_e in this case will be in the direction opposite to the gradient T_p.

The most favorable conditions for observing the drag-related classification of the carriers apparently occur when there is an ideal heat transfer between the phonons and the heater with a temperature T_1 and between the phonons and the refrigerator with a temperature T_2. The maximum phonon flux occurs under these conditions. The electrons, however, must be thermally insulated from the heater and the refrigerator in order to eliminate the thermalization of the carriers at the walls. These conditions can easily be attained experimentally.[2]

The arguments advanced above are completely confirmed by calculations. Let us solve the energy-balance equations for electrons and phonons (see Ref. 1),

$$\operatorname{div} \mathbf{Q}_e = P(T_e - T_p),$$
$$\operatorname{div} \mathbf{Q}_p = P(T_p - T_e) \qquad (2)$$

with the boundary conditions corresponding to the situation described above,

$$T_p\big|_{x=\pm a} = T_{2,1}, \quad Q_{ex}\big|_{x=\pm a} = 0. \qquad (3)$$

Here P is the parameter of the electron-phonon energy interaction ($P \sim n\nu_{pe}$), and $2a$

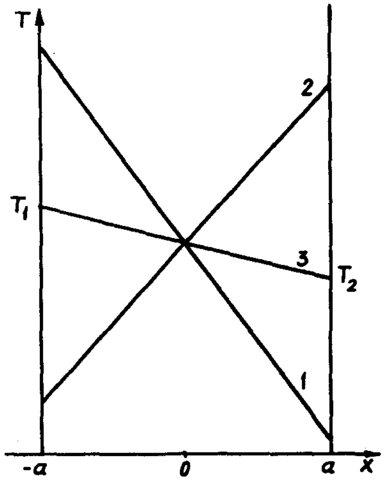

FIG. 1.

is the length of the sample along the x axis; the side walls of the sample are thermally insulated.

In short samples ($ka \ll 1$, $k = \sqrt{P/\kappa_e}$ is the reciprocal of the cooling length) we have

$$T_e = \frac{T_1 + T_2}{2} - \frac{T_2 - T_1}{2}\,\frac{x}{d}\,\frac{\kappa_{ep}}{\kappa_e},$$

$$T_p = \frac{T_1 + T_2}{2} - \frac{T_2 - T_1}{2}\,\frac{x}{a}. \tag{4}$$

Equation (4) implies that if $\kappa_{ep}/\kappa_e < -1$ ($\kappa_{ep} < 0$), the electron temperature gradient will be $|\kappa_{ep}|/\kappa_e$ times larger than the phonon gradient and will have the same sign (curve 1 in Fig. 1). In the case of a total drag, we have, as indicated above, $|\kappa_{ep}|/\kappa_e \sim 10^4$ and hence $|\vec{\nabla} T_e| \sim 10^4 |\vec{\nabla} T_p| = 10^4 (T_2 - T_1)/2a$. If, on the other hand, $\kappa_{ep}/\kappa_e > 1$, then $\vec{\nabla} T_e$ will again be larger than $\vec{\nabla} T_p$ in absolute value, but its direction will be reversed (curve 2 in Fig. 1). The phonon temperature profile is represented by curve 3 in Fig. 1.

In long samples ($ka \gg 1$) we have

$$T_e = \frac{T_1 + T_2}{2} + \frac{T_2 - T_1}{2}\left[\frac{x}{a} - \frac{1 + (\kappa_{ep}/\kappa_e)}{ka}\,\frac{\sinh kx}{\cosh ka}\right], \tag{5}$$

and the phonon temperature is again given by Eq. (4). Here, as in short samples, for $\kappa_{ep}/\kappa_e < -1$ or $\kappa_{ep}/\kappa_e > 2ka$ we would have $|T_e(a) - T_e(-a)| > T_1 - T_2$. In the case of a total drag, we would have $(|\kappa_{ep}|/\kappa_e \sim 10^4)|T_e(a) - T_e(-a)|$

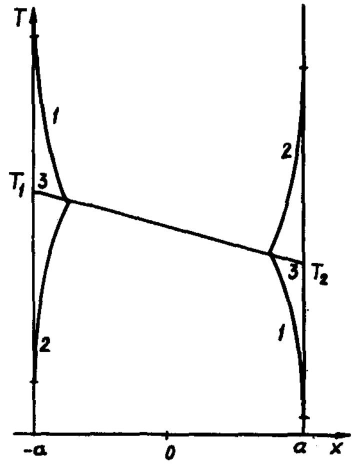

FIG. 2.

$\sim 10^4(T_1 - T_2)/ka$; the effect is ka times smaller than that in the short samples. Even in this case, however, we would have $|T_e(a) - T_e(-a)| \sim 10(T_1 - T_2)$ even in 1-cm-long samples, since $k^{-1} \sim 10^{-3}$ cm^2. In this case the phonon temperature profile is represented by curve 3 in Fig. 2, and the electron temperature profile is represented by curve 1 for $\kappa_{ep}/\kappa_e < -1$ and by curve 2 for $\kappa_{ep}/\kappa_e > 2ka$.

We know that the temperature drop in the electron subsystem is caused[1] by the thermal emf V_x:

$$V_x = \alpha(T_e(-a) - T_e(a)), \qquad (6)$$

where α is the thermoelectric coefficient. It was assumed previously that electron-phonon drag increases V_x only because of the increase in α (see Ref. 1, for example), since in all cases we find $|T_e(a) - T_e(-a) < T_1 - T_2$. The analysis carried out above shows that the drag-related classification of current carriers according to the energies, which leads to a sharp increase in $|T_e(a) - T_e(-a)|$, raises new possibilities for a significant increase of the thermoelectromotive force if the conditions in (3) are satisfied.

[1]F. G. Bass, V. S. Bochkov, and Yu. G. Gurevich, Elektrony i fonony v organichennykh poluprovodnikakh (Electrons and Phonons in Bounded Semiconductors), Nauka, Moscow, 1984, p. 287.
[2]A. I. Klimovskaya and O. V. Snitko, Pis'ma Zh. Eksp. Teor. Fiz. 7, 194 (1968) [JETP Lett. 7, 149 (1968)].

Translated by S. J. Amoretty