the copper is H ≈ 0e. The anomalous impurity scattering apparently makes possible an instability of states with temperature gradient in other metals of the first group, too (Ag, Au).

[1] L. E. Gurevich and B. L. Gel'mont, Zh. Eksp. Teor. Fiz. 47, 1806 (1964) [Sov. Phys.-JETP 20, 1217 (1965)].
[2] L. E. Gurevich and B. L. Gel'mont, ibid. 51, 183 (1966) [24, 124 (1967)].
[3] L. E. Gurevich and E. F. Shender, Fiz. Tverd. Tela 10, 625 (1968) [Sov. Phys.-Solid State 10, 491 (1968)].
[4] I. R. Long, C. G. Grenier, and I. M. Reynolds, Phys. Rev. 140A, 187 (1965).
[5] S. S. Shalyt and N. A. Red'ko, Fiz. Tverd. Tela 10, 1557 (1968) [Sov. Phys.-Solid State, 10, 1233 (1968)].
[6] W. B. Pearson, ibid. 3, 1411 (1961) [3, 1024 (1961)].

## HOT ELECTRONS IN CROSSED ELECTRIC AND QUANTIZING MAGNETIC FIELDS

A. M. Zlobin and P. S. Zyryanov
Institute of Metal Physics, Siberian Division, USSR Academy of Sciences
Submitted 8 August 1968
ZhETF Pis. Red. 8, No. 9, 484 - 488 (5 November 1968)

Even in a fairly weak field, carrier heating may cause the effective temperature[1)] T* in a semiconductor to exceed greatly the temperature of the thermostat [1], which equals the lattice temperature[2)] T. The energy received by the electrons from the electric field is first transferred to the long-wave phonons (LP) (for only they interact with the electrons), from which it is subsequently transferred to the short-wave thermal phonons (TP). If the frequency of the collisions between the LF and the electrons, $\tau_{pe}^{-1}$, is much smaller than the frequency $\tau_{pp}^{-1}$ of collision between the LP and the TP, then the LP have practically the same temperature T* as the electrons, and the energy relaxation process is limited by the frequency $\tau_{pp}^{-1}$ (the phonon "bottleneck" effect). When $\tau_{pe}^{-1} \ll \tau_{pp}^{-1}$, the LP have the same temperature as the TP (the thermostat) and the rate of energy relaxation is limited by the value of $\tau_{pe}^{-1}$. We wish to call attention in this paper to an experimental possibility of varying, in a wide range, the ratio of $\tau_{pe}^{-1}$ and $\tau_{pp}^{-1}$ with the aid of a quantizing magnetic field. We shall consider the heating of electrons in orthogonal fields, and electric field $E_x$ and a quantizing magnetic field $\vec{H}$. The temperature of the "hot electrons" T* is usually calculated from the energy-balance equation by equating the Joule power W to the power $P_{ep}$ obtained by the phonons from the electrons. If the samples are bounded and $\Omega\tau \gg 1$ ($\Omega = |e|H/mc$ - carrier cyclotron frequency and $\tau$ - their momentum relaxation time), it becomes necessary to take into account the contribution of the Hall field to W, since it exceeds the external applied field by a factor $(\Omega\tau)$.[3)] We shall assume that the work performed by the electric field (including the Hall field) when the electron is displaced a distance $\sim \ell = \sqrt{ch/|e|H}$ ($\ell$ - magnetic length, or in our case the quantum Larmor radius) during the course of scattering is small compared with the

[1)] This concept can be used only when the frequency of the inter-electron collisions is the highest among the characteristic frequencies of the problem.

[2)] The sample is assumed to be small enough to neglect the change in the total phonon energy resulting from the heating of the electrons.

[3)] The Hall field was not taken into account in [2, 3], and therefore the results obtained there hold for bounded samples only when the electron and hole densities are equal, and possibly also in special devices such as the Corbino disc.

characteristic energy of the electron. It is then possible to calculate W with the aid of the electric conductivity tensor $\sigma_{ik}(T, T^*)$, obtained in the approximation of the linear transport theory but with allowance for the difference between the electron and phonon temperatures. The calculations lead to the formula $W = W_x^2 \sigma_{xy}^2(T, T^*)\sigma_{xx}^{-1}(T, T^*)$. To calculate $P_{ep}$ we use the usual kinetic equation that takes collisions of the LP with the TP and the electrons into account. It follows from this equation that the phonon distribution function $N_q$ is of the form[1)]

$$N_q = [N_q(T^*)\tau_{pe}^{-1}(q, T^*) + N_q(T)\tau_{pp}^{-1}(q,T)][\tau_{pe}^{-1}(q,T^*) + \tau_{pp}^{-1}(q,T)]^{-1}, \tag{1}$$

where $N_q(T)$ is the Planck function; in the quantum limit

$$\tau_{pp}^{-1}(q,T^*) = \frac{\sqrt{2\pi}\; m^2 s A^{ak} n\, q^2}{h(mT^*)^{3/2}|q_z|} \exp\left[-\frac{\ell^2 q_\perp^2}{2} - \frac{\hbar^2 q_z^2}{8mT^*}\right] \tag{2}$$

($A^{ak} = C^2\hbar/2\rho s V$, C - deformation-potential constant, $\rho$ - crystal density, V - volume of sample, n - electron density, and s - speed of sound). According to [4]

$$\tau_{pp}^{-1}(q, T) \simeq \frac{1}{4\pi\rho}\left(\frac{T}{\hbar s}\right)^4 \hbar q \; . \tag{3}$$

We shall consider below not too strong magnetic fields, such that $\ell^{-1} \ll T/\hbar s \equiv q_T$. Very strong fields $\ell^{-1} \gtrsim q_T$ call for a special investigation.

2. The case $\tau_{pe}(q, T^*) \gg \tau_{pp}(q, T)$ is realized when

$$\alpha\left(\frac{T}{\theta}\right)^4 \gg \frac{n}{N}\frac{a}{\ell}\left(\frac{C}{T^*}\right)^2, \tag{4}$$

($\alpha$ - numerical factor on the order of 10, $\theta$ - Debye temperature, N - density of the number of lattice atoms, and a - lattice constant). Under these conditions all the phonons have the same temperature as the thermostat, and $P_{ep} \sim n\tau_{ep}^{-1}(T^*, H)[1 - (T/T^*)]$ and decreases with increased heating, since the electron momentum drift relaxation frequency is $\tau_{ep}^{-1} \sim (T^*)^{-3/2}$. On the other hand, $W \sim n\tau_{ep}(T^*)$ and increases with increasing T*. The energy balance leads to the conclusion that there exists a critical value of the electric field, $E_{cr}$, above which strong heating of the electrons takes place and leads to lifting of the quantization of the orbital motion and causes the system to go over into the stable classical region ($T^* > \hbar\Omega > \hbar/\tau$), since $(\tau_{ep}^{-1})_{class} \sim T^{*1/2}$. The table lists the values of $E_{cr}$ as functions of H and T for different energy and momentum relaxation mechanisms. It is easy to verify that all the limitations imposed on the value of E apply also in the case of $E_{cr}$.

3. The case $\tau_{pe}(q, T^*) \ll \tau_{pp}(q, T)$ takes place at sufficiently low temperatures when an inequality inverse to (4) holds (the phonon "bottleneck" effect). In this case the electron energy dissipation is determined by the power transferred from the LP to the TP, which is equal to

---

1) $N_q$ is assumed isotropic, inasmuch as under the conditions considered here the phonon drift velocity is small compared with s.

| Momentum relaxation mechanisms | $\tau^{-1}(T, T^*, H)$ | $E_{cr}$ for different electron energy relaxation mechanisms | | | $\sqrt{n}E_{cr}$ in case of phonon bottleneck |
|---|---|---|---|---|---|
| | | Acoustic phonons | Piezoelectric phonons | Optical phonons | |
| Acoustic phonons | $\sim H^2 T^1 T^{*-3/2}$ | $\sim H^2 T^{-1/2}$ | $\sim H^{3/2} T^{-1/2}$ | $\sim H^2 T^{-3/4}$ | $\sim H^{7/4} T^{5/2}$ |
| Neutral phonons | $\sim H^2 T^0 T^{*-3/2}$ | $\sim H^2 T^{-1}$ | $\sim H^{3/2} T^{-i}$ | $\sim H^2 T^{-5/4}$ | $\sim H^{7/4} T^2$ |
| Ionized impurities | $\sim H^0 T^0 T^{*-3/2}$ | $\sim H^1 T^{-1}$ | $\sim H^{1/2} T^{-1}$ | $\sim H^1 T^{-5/4}$ | $\sim H^{3/4} T^2$ |
| Piezo-acoustic phonons | $\sim H^1 T^1 T^{*-3/2}$ | $\sim H^{3/2} T^{-1/2}$ | $\sim H^1 T^{-1/2}$ | $\sim H^{3/2} T^{-3/4}$ | $\sim H^{5/4} T^{5/2}$ |
| Optical phonons ($T \ll \theta$) | $\sim H^1 T^{*-1}$ exp | $\sim H^{3/2} T^{-3/4}$exp | $\sim H^1 T^{-3/4}$exp | $H^{3/2} T^{-1}$exp | $H^{5/4} T^{9/4}$ exp |

exp denotes here $\exp(-h\omega_0/t$.

$$P_{pp}(T, T^*) = \Sigma_q \hbar\omega_q [N_q(T) - N_q(T^*)] \tau_{pp}^{-1}(q, T) \ .$$

We note that the maximum energy of the phonons that are emitted by the electrons in the quantizing magnetic field does not depend on T* and $\ell^{-1} < q_T$, and therefore the TP system can be regarded as a thermostat. In the absence of quantization of the orbital motion this is not the case [5]. The dependences of $E_{cr}$ on H and T for different momentum relaxation mechanisms are shown in the last column in the table for the considered case of the phonon "bottleneck." We call attention to the fact that if inequality (4) is satisfied $E_{cr}$ does not depend on the electron density and decreases with increasing T for all the relaxation mechanisms under consideration. To the contrary, under the conditions of the phonon "bottleneck," $E_{cr}$ always increases with T and decreases with increasing electron density. The effect of the phonon "bottleneck" takes place, for example, in n-Ge at T = 15°K, H = $10^5$ Oe, and n $\geq 10^{13}$ cm$^{-3}$.

We note in conclusion that in fields $E < E_{cr}$ there exists a region of negative differential resistance of the type noted in [2], and then when $\vec{E} = \vec{E}_{cr}$ the magnetoresistance drops rapidly (lifting of the electron orbital-motion quantization by the heating); in the classical region the magnetoresistance depends strongly on E and on the dominating scattering mechanisms.


[1] V. I. Davydov, Zh. Eksp. Teor. Fiz. 7, 1069 (1937).
[2] R. F. Kazarinov and V. G. Skobov, ibid. 42, 1047 (1962) [Sov. Phys.-JETP 15, 762 (1962)]
[3] V. P. Kalashnikov and R. V. Pomortsev, FMM 17, 343 (1964).
[4] S. Simons, Proc. Phys. Soc. 83, 749 (1964); P. S. Zyryanov and G. G. Taluts, Zh. Eksp. Teor. Fiz. 49, 1942 (1965) [Sov. Phys.-JETP 22, 1326 (1965)].
[5] L. E. Gurevich and T. M. Gasymov, Fiz. Tverd. Tela 9, 106 (1967) [Sov. Phys.-Solid State 9, 78 (1967)].