

RELAXATION PHENOMENA IN ELECTRON PLASMA OF SEMICONDUCTORS

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The hydrodynamics of the electron subsystems of semiconductors is studied in the approximations of the ideal and real liquid, taking into account processes of relaxation of temperatures and macroscopic velocities of electrons and phonons without assuming the local equilibrium of the system. A set of integral equations for the electron distribution function of the first order in gradients is obtained, which determines the sources in the hydrodynamic equations of the ideal liquid approximation and the dissipative flows of energy and momentum of electrons. The steady states of the system in the ideal liquid approximation are investigated. The exact formulas for the electron mobility of the semiconductor and its conductivity are derived and kinetic coefficients that determine current in a spatially inhomogeneous state are calculated. In the presence of an electric field, the phenomenon of difference of temperatures of the electron and phonon subsystems is predicted. The obtained expressions are specified for the case of temperatures much higher than the Debye temperature.

Keywords: semiconductor, hydrodynamic states, ideal and real liquid approximations, temperature and velocity relaxation, steady states, mobility, conductivity, the Debye temperature.

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1. Introduction

This work continues the investigation of hydrodynamic states in the presence of relaxation processes of temperatures and velocities equalization in the system. This problem deserves attention, which is noted, for example, in the review [1]. In [2], we developed the general theory of hydrodynamic states of a polar semiconductor in the Bloch model, in which it is assumed that nonequilibrium electron subsystem interacts with the equilibrium phonon subsystem (its temperature T_0). The study is based on Bogolyubov's linear kinetic equation [3] for the electron distribution function, which takes into account the interaction of electrons with optical phonons in the Fröhlich model in the presence of a small homogeneous external electric field and considers the electron system as a rarefied one.

The theory of hydrodynamic states is always based on the kinetics of spatially homogeneous states of the system. The kinetics of relaxation processes in such states is complicated by the fact that in their theory there is no small parameter [4] and the corresponding distribution function of the system $f_p^{(0)}$ (it is the main approximation when describing hydrodynamic states) is unknown. Usually in theory it is assumed [4] that a local equilibrium is quickly established in the electron subsystem. This means that the distribution function $f_p^{(0)}$ is given by the formula $f_p^{(0)} = w_{p-mu}(T)$, where T and u_l are the temperature and macroscopic velocity of the electron subsystem. However, only the Maxwell distribution without velocity and with phonon temperature $w_p(T_0) \equiv w_p$ is a solution of the kinetic equation. In fact, under this assumption, one investigates states in the vicinity of the local equilibrium that do not arise in natural evolution.

In our previous paper [5] in the study of the electron-ion plasma in the generalized Lorentz model an exact expression was found for the distribution function in terms of the eigenfunctions of the collision integral operator. In paper [2] this consideration was extended to the case of the electron-phonon plasma of semiconductors, which posed the problem of constructing the hydrodynamics of this system that is considered here.

The paper is constructed as it follows. Section 2 describes our approach to constructing the theory of hydrodynamic states of semiconductors and presents the results of deriving the equations of hydrodynamics of the ideal liquid approximation taking into account relaxation processes. Section 3 discusses hydrodynamics in the real liquid approximation. Section 4 considers the steady states of the system in the ideal liquid approximation and discusses some of the observed phenomena.

2. Hydrodynamic states in an ideal liquid approximation

This investigation is based on the reduced description of the hydrodynamic states of semiconductors by densities of energy $\varepsilon(x,t)$, momentum $\pi_l(x,t)$ and electron mass $\sigma(x,t) \equiv mn(x,t)$ (in short notation by parameters $\xi_\mu(x,t)$) [2]. These quantities satisfy time equations, which differ from the corresponding conservation laws in differential form by the presence of sources associated with the interaction of electrons with phonons and an external homogeneous electric field. The study is based on the idea of Bogolyubov's functional hypothesis, which introduces the electron distribution function $f_p(x, \xi(t))$ as a functional of parameters $\xi_\mu(x,t)$ after the passage of free path time. The integro-differential equation for the functional $f_p(x, \xi)$ (kinetic equation at the reduced description) is derived in the usual way and is supplemented by the definition of the parameters $\xi_\mu(x)$ (by additional conditions). At the same time, the structure of the time equation for the parameters $\xi_\mu(x,t)$ is recognized in terms of $f_p(x, \xi)$

$$\frac{\partial \xi_\mu(x,t)}{\partial t} = L_\mu(x, f_p(\xi(t))) . \quad (1)$$

The kinetic equation at the reduced description for the functional $f_p(x, \xi)$ is solved (as usual in the development of hydrodynamics) in the theory of perturbations in small gradients of parameters $\xi_\mu(x)$ (small parameter g). The electric field is considered to be of the first order of smallness in g . Contributions of the s -th order in gradients to the quantities $f_p(x, \xi)$ and $L_\mu(x, f_p(\xi))$ are denoted as $f_p^{(s)}$ and $L_\mu^{(s)} \equiv (\partial \xi_\mu / \partial t)^{(s)}$.

As noted, the contribution of the main approximation $f_p^{(0)}$ to the distribution function is determined by the eigenvectors of the collision integral operator [2]

$$f_p^{(0)} = w_p(1 + g_p^{(0)}), \quad g_p^{(0)} \equiv \frac{2}{3n} A_p(\varepsilon - \varepsilon_0) + \frac{1}{mn} B_p p_n \pi_n . \quad (2)$$

The required scalar A_p and vector $p_l B_p$ eigenfunctions and the corresponding eigenvalues are determined by formulas

$$\begin{aligned} \mathbf{K}A_p &= \lambda_T A_p, & \mathbf{K}B_p p_l &= \lambda_u B_p p_l & (\langle A_p \rangle &= 0) \\ \langle A_p \varepsilon_p \rangle &= 3n/2, & \langle B_p \varepsilon_p \rangle &= 3n/2 \end{aligned} \quad (3)$$

($\langle a_p \rangle$) is the average value of a quantity a_p with the Maxwell distribution w_p ; the last line in (3) normalizes the eigenfunctions). The distribution function $f_p^{(0)}$ determines the energy $q_l^{(0)}$ and momentum fluxes $t_{nl}^{(0)}$ in the main in gradients approximation

$$q_l^{(0)} = \frac{2}{3\sigma} \langle \varepsilon_p^2 B_p \rangle \pi_l, \quad t_{nl}^{(0)} = \frac{2}{3} \varepsilon \delta_{nl} \quad (4)$$

and equations of hydrodynamics of the main and first in gradients approximation [2]

$$\begin{aligned} \left(\frac{\partial \varepsilon}{\partial t} \right)^{(0)} &= -\lambda_T (\varepsilon - \varepsilon_0), & \left(\frac{\partial \pi_l}{\partial t} \right)^{(0)} &= -\lambda_u \pi_l; \\ \left(\frac{\partial \varepsilon}{\partial t} \right)^{(1)} &= -\frac{2}{3} \langle \varepsilon_p^2 B_p \rangle \frac{\partial}{\partial x_l} \frac{\pi_l}{\sigma} + \frac{1}{m} \pi_l F_l - \{ \varepsilon_p, g_p^{(1)} \}, \\ \left(\frac{\partial \pi_l}{\partial t} \right)^{(1)} &= -\frac{2}{3} \frac{\partial \varepsilon}{\partial x_l} + \frac{1}{m} \sigma F_l - \{ p_l, g_p^{(1)} \}, & \frac{\partial \sigma}{\partial t} &= -\frac{\partial \pi_l}{\partial x_l} \end{aligned} \quad (5)$$

($F_n \equiv -eE_n$; e is modulus of charge of an electron). Here the contribution of the first order in gradients $f_p^{(1)}$ to the distribution function $f_p(x, \xi)$ is determined by the formula $f_p^{(1)} = w_p g_p^{(1)}$. In addition, (5) uses the quantities of the type $\{a_p, b_p\} \equiv \langle a_p \mathbf{K} b_p \rangle$ which introduces a symmetrical and positively defined bilinear form $\{a_p, b_p\}$. Contributions to first-order hydrodynamic equations that contain the function $g_p^{(1)}$ are related to the electron-phonon interaction and, along with the contributions of the electric field, are sources in the laws of conservation of energy and momentum of electrons.

3. Real liquid approximation

In our paper [2] the kinetic equation at reduced description was obtained, which is an equation for the distribution function $f_p(x, \xi)$. In the first in gradients approximation, it gives an equation for the first-order contribution $f_p^{(1)}$

$$\begin{aligned} \frac{\partial f_p^{(0)}}{\partial n} \frac{\partial n}{\partial t} + \frac{\partial f_p^{(0)}}{\partial \pi_s} \left(\frac{\partial \pi_s}{\partial t} \right)^{(1)} + \frac{\partial f_p^{(0)}}{\partial \varepsilon} \left(\frac{\partial \varepsilon}{\partial t} \right)^{(1)} + \frac{\partial f_p^{(1)}}{\partial \pi_s} \left(\frac{\partial \pi_s}{\partial t} \right)^{(0)} + \frac{\partial f_p^{(1)}}{\partial \varepsilon} \left(\frac{\partial \varepsilon}{\partial t} \right)^{(0)} + \\ + \frac{\partial f_p^{(1)}}{\partial \partial_l \pi_s} \frac{\partial}{\partial x_l} \left(\frac{\partial \pi_s}{\partial t} \right)^{(0)} + \frac{\partial f_p^{(1)}}{\partial \partial_s \varepsilon} \frac{\partial}{\partial x_s} \left(\frac{\partial \varepsilon}{\partial t} \right)^{(0)} = -\frac{p_l}{m} \frac{\partial f_p^{(0)}}{\partial x_l} - F_l \frac{\partial f_p^{(0)}}{\partial p_l} + I_p(f_p^{(1)}) \end{aligned} \quad (6)$$

where the following identity was taken into account

$$\int d^3 x' a(x') \frac{\delta}{\delta \xi_\mu(x')} \left[b(\xi(x)) \frac{\partial \xi_{\mu'}(x)}{\partial x_n} \right] = a(x) \frac{\partial \xi_{\mu'}(x)}{\partial x_n} \frac{\partial b(\xi)}{\partial \xi_\mu} \Big|_{\xi \rightarrow \xi(x)} + b(\xi(x)) \frac{\partial a(x)}{\partial x_n} \delta_{\mu\mu'} \quad (7)$$

($I_p(f_p)$ is the collision integral). To equation (6) the conditions that define the hydrodynamic variables should be added

$$\int d^3 p f_p^{(1)} \varepsilon_p = 0, \quad \int d^3 p f_p^{(1)} p_l = 0, \quad \int d^3 p f_p^{(1)} = 0. \quad (8)$$

The solution of equation (6) together with (8) is sought for reasons of rotational invariance in the form

$$f_p^{(1)} = w_p \left(C_{lp} F_l + D_{lp} \frac{\partial n}{\partial x_l} + G_{lp} \frac{\partial \varepsilon}{\partial x_l} + F_{slp} \frac{\partial \pi_s}{\partial x_l} \right) = w_p g_p^{(1)}. \quad (9)$$

In this definition the coefficients D_{lp} , G_{lp} , and $F_{slp} \sim 1/n$ whereas C_{lp} do not depend on n , because the Maxwell distribution is proportional to the density and the collision integral depends linearly on the distribution function [2].

Substitution (9) in (6) with account for (7) gives the relation, which must be an identity. The gradients of the hydrodynamic parameters and the electric field are independent, so the coefficients at them in the left and right sides of the obtained relation must be the same. This gives a set of integral equations for functions C_{lp} , D_{lp} , G_{lp} , and F_{slp}

$$\begin{aligned} & \frac{1}{n} \delta_{sl} + \frac{4}{9n} A_p \left(\frac{1}{mn} \langle B_p \varepsilon_p^2 \rangle + \frac{1}{2} \{ \varepsilon_p, F_{mmp} \} \right) \delta_{sl} + \\ & + F_{slp} \lambda_u + \frac{\partial F_{slp}}{\partial \pi_s} \lambda_u \pi_s + \frac{\partial F_{slp}}{\partial \varepsilon} \lambda_T (\varepsilon - \varepsilon_0) - \frac{1}{mn} B_p p_s p_l = \mathbf{K} F_{slp}; \\ & \frac{2}{3mn} B_p p_l \left(1 + \frac{1}{2} \{ p_s, G_{sp} \} \right) + G_{lp} \lambda_T + \frac{\partial G_{lp}}{\partial \pi_s} \lambda_u \pi_s + \\ & + \frac{\partial G_{lp}}{\partial \varepsilon} \lambda_T (\varepsilon - \varepsilon_0) - \frac{2}{3mn} p_l A_p = \mathbf{K} G_{lp}; \quad (10) \\ & \frac{2}{3mn} B_p p_l \left(1 + \frac{1}{2} \{ p_s, D_{sp} \} \right) + \frac{\partial D_{lp}}{\partial \pi_s} \lambda_u \pi_s + \frac{\partial D_{lp}}{\partial \varepsilon} \lambda_T (\varepsilon - \varepsilon_0) - \frac{1}{mn} p_l = \mathbf{K} D_{lp}; \\ & \frac{1}{n} \left(\frac{2}{3} \frac{\partial A_p}{\partial p_l} (\varepsilon - \varepsilon_0) + \frac{1}{m} \frac{\partial B_p}{\partial p_l} p_s \pi_s \right) + \frac{1}{m T_0} p_l + \frac{2}{3mn} A_p [p_l (\varepsilon - \varepsilon_0) / T_0 - \pi_l] + \\ & + \frac{1}{3mn} B_p p_l \left(\frac{1}{3} \{ p_s, C_{sp} \} - n \right) + \frac{1}{mn} B_p (\delta_{ls} - p_l p_s / m T_0) \pi_s = \mathbf{K} C_{lp} \end{aligned}$$

Equations (10) show that the functions C_{lp} , D_{lp} , G_{lp} , and F_{slp} have the following tensor structure

$$\begin{aligned} C_{lp} &= C_p' p_l + C_p'' \pi_l, & D_{lp} &= D_p p_l, & G_{lp} &= G_p p_l, \\ F_{slp} &= F_p' \delta_{ls} + F_p'' h_{lsp} & (h_{lsp} &\equiv p_l p_s - \frac{1}{3} p^2 \delta_{ls}) \end{aligned} \quad (11)$$

where scalar coefficients C_p' , C_p'' , D_p , G_p , F_p' , and F_p'' are introduced. Equations for them can be written on the basis of equations (10). Note that the calculations, which led to equations (10), do not exclude the presence of contributions associated with the momentum density π_l in the tensor structure of the functions C_{lp} , D_{lp} , G_{lp} , and F_{slp} . Relations (8) with (9) and (11) substituted in them give the following additional conditions to equations (10) written in terms of functions C_p' , C_p'' , D_p , G_p , F_p' , and F_p''

$$\begin{aligned} \langle C_p'' \rangle = 0, \quad \langle F_p' \rangle = 0; \quad \langle C_p' \varepsilon_p \rangle = 0, \quad \langle D_p \varepsilon_p \rangle = 0, \quad \langle G_p \varepsilon_p \rangle = 0; \\ \langle C_p'' \varepsilon_p \rangle = 0, \quad \langle F_p' \varepsilon_p \rangle = 0. \end{aligned} \quad (12)$$

The calculation of the functions C_p' , C_p'' , D_p , G_p , F_p' , and F_p'' will be performed in a subsequent paper by the method of their truncated expansion in the Sonine polynomials (see an example of such calculations in [6]).

Using formulas (9) and (11), we obtain expressions for sources in the equations of hydrodynamics of the ideal liquid approximation (5)

$$\begin{aligned} \{p_l, g_p^{(1)}\} &= \frac{1}{3} \{p_s, C_p' p_s\} F_l + \frac{1}{3} \{p_s, D_p p_s\} \frac{\partial n}{\partial x_l} + \frac{1}{3} \{p_s, G_p p_s\} \frac{\partial \varepsilon}{\partial x_l}, \\ \{\varepsilon_p, g_p^{(1)}\} &= \frac{1}{3} \{\varepsilon_p, F_p'\} \frac{\partial \pi_l}{\partial x_l}. \end{aligned} \quad (13)$$

Similarly to (4), it is possible to calculate the dissipative fluxes of energy and momentum of the system that gives

$$\begin{aligned} q_l^{(1)} &= \frac{2}{3} \left(\langle C_p' \varepsilon_p^2 \rangle F_l + \langle D_p \varepsilon_p^2 \rangle \frac{\partial n}{\partial x_l} + \langle G_p \varepsilon_p^2 \rangle \frac{\partial \varepsilon}{\partial x_l} \right), \\ t_{sl}^{(1)} &= \frac{4m}{15} \langle F_p'' \varepsilon_p^2 \rangle \left(\frac{\partial \pi_s}{\partial x_l} + \frac{\partial \pi_l}{\partial x_s} - \frac{2}{3} \delta_{sl} \frac{\partial \pi_m}{\partial x_m} \right) \end{aligned} \quad (14)$$

(the second formula takes into account the last two relations from (12)). In these formulas, the energy ε , momentum π_l and particle n densities are considered as independent hydrodynamic variables. Formulas (14) describe all dissipative phenomena in the system in a laboratory reference frame where the isotropy is broken by the electron momentum density π_l (or the macroscopic velocity of the electron system u_l), but all the kinetic coefficients of the system are scalar. However, with the traditional choice of hydrodynamic variables, including temperature T , velocity u_l and particle density n

$$\pi_l = m n u_l, \quad \varepsilon = \frac{3}{2} n T + \frac{1}{2} m n u^2 \quad (15)$$

anisotropy is present.

4. Discussion

The obtained results can be concretized by an approximate solution of equations (3) for eigenfunctions A_p , $B_p p_l$ and the corresponding eigenvalues λ_T , λ_u of the collision integral operator \mathbf{K} , as well as equations (10) for the functions C_p' , C_p'' , D_p , G_p , F_p' , and F_p'' . We have previously considered the problem of calculating eigenfunctions and eigenvalues by the method of truncated expansion of eigenfunctions in the Sonine orthogonal polynomials $S_n^\alpha(x)$ ($n=0,1,2,\dots$). Here α is a parameter that defines a family of polynomials. The use of these polynomials is due to the fact that the weight function in the condition of their orthonormalization is proportional to the Maxwell

distribution with an additional power factor $\varepsilon_p^{\alpha-1/2}$. In the approximation of one polynomial these functions and eigenvalues are given by formulas [7]

$$\begin{aligned} A_p &= \left(\varepsilon_p - \frac{3}{2} T_0 \right) \frac{1}{T_0^2}, & B_p &= \frac{1}{T_0}; \\ \lambda_T &= \frac{2}{3nT_0^2} \{ \varepsilon_p, \varepsilon_p \}, & \lambda_u &= \frac{1}{3mnT_0} \{ p_l, p_l \}. \end{aligned} \quad (16)$$

According to (5), (13), and (15), the equations of hydrodynamics of the system in the ideal liquid approximation have the structure

$$\begin{aligned} \frac{\partial \varepsilon}{\partial t} &= -\lambda_T (\varepsilon - \varepsilon_0) - enu_l E_l + a \frac{\partial u_l}{\partial x_l} + bu_l \frac{\partial n}{\partial x_l}, & \frac{\partial \sigma}{\partial t} &= -\frac{\partial \pi_l}{\partial x_l}. \\ \frac{\partial \pi_l}{\partial t} &= -\lambda_u \pi_l - enE_l + \left[cE_l + d \frac{\partial T}{\partial x_l} + h \frac{\partial n}{\partial x_l} + \frac{m}{3} d \frac{\partial u^2}{\partial x_l} \right]. \end{aligned} \quad (17)$$

The terms with scalar coefficients a, b, c, d , and h are related to the contributions of the distribution function $f_p^{(1)}$ (9) to the sources given in (13). This distinguishes the developed theory from the ordinary hydrodynamics, in which the contribution to the distribution function of the first order in a small parameter of the theory $f_p^{(1)}$ determines only dissipative processes. According to the definition (15) of temperature T and velocity u_l of the electron subsystem, equation (17) can be rewritten as

$$\begin{aligned} \frac{\partial u_l}{\partial t} &= - \left(\lambda_u - \frac{1}{n} \frac{\partial nu_s}{\partial x_s} \right) u_l - \frac{e}{m} E_l + \frac{1}{mn} \left[cE_l + d \frac{\partial T}{\partial x_l} + h \frac{\partial n}{\partial x_l} + \frac{m}{3} d \frac{\partial u^2}{\partial x_l} \right], \\ \frac{\partial T}{\partial t} &= -\lambda_T (T - T_0) + \frac{T}{n} \frac{\partial nu_s}{\partial x_s} + \left(2\lambda_u - \lambda_T + \frac{1}{n} \frac{\partial nu_s}{\partial x_s} \right) \frac{m}{3} u^2 + \frac{2}{3n} a \frac{\partial u_s}{\partial x_s} - \\ &\quad - \frac{2}{3n} u_l \left[cE_l + d \frac{\partial T}{\partial x_l} + (h-b) \frac{\partial n}{\partial x_l} + \frac{m}{3} d \frac{\partial u^2}{\partial x_l} \right]. \end{aligned} \quad (18)$$

Note that the obtained equations (17) and (18) in the spatially homogeneous state of the system and in the absence of the electric field are exact since expression (2) for the distribution function of the main approximation $f_p^{(0)}$ is exact. In the steady state, equations (18) give the velocity of the electron subsystem and the temperature difference of the electron and phonon subsystems

$$\begin{aligned} u_l^{\text{st}} &= -\frac{e}{m\lambda_u} E_l + \frac{1}{mn\lambda_u} \left[cE_l + d \frac{\partial T}{\partial x_l} + h \frac{\partial n}{\partial x_l} \right], \\ T^{\text{st}} - T_0 &= \left(\frac{2\lambda_u}{\lambda_T} - 1 \right) \frac{m}{3} u^{\text{st}2} + \frac{2a}{3n\lambda_T} \frac{\partial u_l^{\text{st}}}{\partial x_l} - \frac{2}{3n\lambda_T} u_l^{\text{st}} \left[cE_l + d \frac{\partial T}{\partial x_l} + (h-b) \frac{\partial n}{\partial x_l} \right]. \end{aligned} \quad (19)$$

(because $\partial nu_s / \partial x_s = \partial \sigma / \partial t$). In expressions (19) for u_l^{st} and $T^{\text{st}} - T_0$ only the main contributions in the small parameter of the theory g are left, because in deriving

equations (17) only contributions up to the first order in g inclusive are taken into account. In our work [5], the values u_l^{st} in $T^{\text{st}} - T_0$ are calculated in a spatially homogeneous state and it is proved that the coefficient c in (17) is equal to zero. The confirmation of this result in the approach of the present work requires the solution of the last integral equation from (10) with respect to the function C'_p taking into account formulas (11) and (12) since according to (5) and (13) $c = e\{p_s, C'_p p_s\}/3$. This problem as well as the solution of all integral equations (10) will be considered in a subsequent paper.

Further a number of obtained results are given, assuming that the coefficient $c = 0$. The first formula from (19) in the spatially homogeneous state gives an expression for the mobility of electrons in the system

$$u_l^{\text{st}} \equiv -vE_l, \quad v = \frac{e}{m\lambda_u} \quad (\partial\xi_\mu(x)/\partial x_l = 0). \quad (20)$$

The electric current j_l in the steady state of the semiconductor, using the expression for the macroscopic velocity u_l^{st} from (19), is given by the formulas

$$j_l \equiv -neu_l, \quad j_l^{\text{st}} = -neu_l^{\text{st}}; \quad j_l^{\text{st}} \equiv \sigma \left[E_l - \alpha \frac{\partial T}{\partial x_l} - \beta \frac{\partial n}{\partial x_l} \right], \quad (21)$$

$$\sigma = \frac{ne^2}{m\lambda_u}, \quad \sigma\alpha = \frac{ed}{m\lambda_u}, \quad \sigma\beta = \frac{eh}{m\lambda_u}$$

where σ is the conductivity of the semiconductor, α and β are some kinetic coefficients. Note that our expressions for the mobility and conductivity of electrons are exact. This can be proved similarly as it was proved in our work for the completely ionized plasma in the generalized Lorentz model [5].

The second equation (19) allows investigating the temperature distribution of electrons in the steady states of the system. For this purpose, it is necessary to substitute velocity u_l^{st} from (19) into this formula. A somewhat cumbersome result is simplified in the spatially homogeneous case:

$$T^{\text{st}} - T_0 = \frac{e^2(2\lambda_u - \lambda_T)}{3m\lambda_T\lambda_u^2} E^2 \quad (\partial\xi_\mu(x)/\partial x_l = 0). \quad (22)$$

Note that this expression is exact and can be proved similarly to what is done in our paper for the completely ionized plasma in the generalized Lorentz model [5]. The result that $T^{\text{st}} - T_0 \sim E^2$ was early discussed in paper [8] for the completely ionized plasma on the basis of the Boltzmann equation but with a number of assumptions that complicate accuracy control.

Note also, that the calculation of the relaxation coefficients λ_T and λ_u , based on the Bogolyubov kinetic equation, is more complex than one for plasma in the Lorentz model. In our approach to the semiconductor theory, calculations of λ_T and λ_u at high temperatures will be adequate. The corresponding research was carried out in our paper [7] where these expressions for λ_T and λ_u are obtained from formulas (16)

$$\lambda_u = \frac{16\omega\alpha}{3\sqrt{2\pi}} v^{-1/2} [1 + O(v)], \quad \lambda_T = \frac{8\omega\alpha}{3\sqrt{2\pi}} v^{3/2} [\ln v + O(1)] \quad (v \equiv h\omega/T_0 \ll 1). \quad (23)$$

Here ω is the characteristic frequency of optical phonons, α is a small Fröhlich constant (see explanation after formula (4) in [2]). Temperature T_0 is taken much higher than the Debye temperature T_D , because $T_D \sim \hbar\omega$. As a result, formulas (22) and (23) give

$$T^{\text{st}} - T_0 = \frac{3\pi}{2^5} \frac{e^2 E^2}{m\omega^2 \alpha^2} \frac{1}{v \ln v} \quad (v = \hbar\omega / T_0 \ll 1). \quad (24)$$

It is planned to evaluate the possibility of experimental observation of this phenomenon.

5. Conclusions

The development of the theory of hydrodynamic states of the semiconductors with account for relaxation of the temperatures and velocities of the electron and phonon subsystems is continued starting from our paper [2]. The first order contribution to the electron distribution function, which defines dissipative fluxes of energy and momentum in the system and sources in hydrodynamic equations of the ideal liquid approximation, is investigated. The set of integro-differential equations for this function is obtained. It is established that at the reduced description of the system by energy, momentum and mass densities its kinetic coefficients are scalar ones in contradiction with isotropy violation by momentum density of electron subsystem. Steady states of semiconductors are investigated in hydrodynamics of the ideal liquid approximation. Exact expressions for the mobility of electrons and conductivity of the system are obtained. An influence of spatial inhomogeneities in semiconductor states on electron current is investigated. The phenomenon of the difference between electron and phonon temperatures at steady states in the presence of electric field is predicted.

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