Nonequilibrium fluctuations of electrons and phonons in semiconductors

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A coupled system of equations is obtained for the fluctuations of the electron and phonon distribution functions with allowance for the phonon-phonon interaction. The correlation function of a Langevin source of fluctuations that are connected with three-phonon processes is calculated subject to the same approximations as the corresponding phonon-phonon collision integral. The current-density correlation function S_ω in the sample is investigated. It is shown that an additional dispersion takes place in S_ω at the characteristic long-wave phonon relaxation frequency, when the phonons are "heated" by the nonequilibrium electrons.

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Nonequilibrium fluctuations in semiconductors have been dealt with theoretically in many papers,[1–5] in which equations were derived for the temporal evolution of the fluctuation component δf of the carrier distribution function or of its correlation functions. In a number of the developed theories,[1–3] however, the effect of the fluctuations δN of the phonon distribution function on the electronic fluctuations is neglected. As a result, these theories do not take into account local fluctuations of the sample temperature, a particularly important factor at low temperatures.[6] In addition, it is well known that at low temperatures and in strong electric fields the distribution of the long-wave acoustic phonons, from which the electrons are scattered, can deviate significantly from equilibrium.[7,8] As a result, a change takes place in the dissipative properties of the semiconductor, meaning also in its noise characteristics. A coupled system of equations for δf and δN was obtained in[4,5] but the mutual influence of the phonon and electron fluctuations was not analyzed. Furthermore, the equation for δN did not contain the phonon-phonon collision integral and the corresponding Langevin source of fluctuations. In the present paper we take the phonon-phonon interaction into account and calculate the correlators of the extraneous fluxes connected with three-phonon processes. We shall calculate the correlation function of the current-density fluctuations in the sample under conditions of electron heating. When frequencies ν_{ff} of the collisions between the long-wave and short-wave phonons are comparable with or lower than the phonon-electron collision frequencies (i.e., when the long-wave phonons are also heated), the current fluctuations cannot be calculated correctly without taking δN into account.

EQUATIONS FOR THE FLUCTUATIONS

The fluctuations of the distribution functions are, by definition, equal to

$$\delta f(\mathbf{r},\mathbf{p},t)=\sum_{\mathbf{k}} e^{-i\mathbf{kr}}(a^+_{\mathbf{p}+\hbar\mathbf{k}/2}a_{\mathbf{p}-\hbar\mathbf{k}/2}-\langle a^+_{\mathbf{p}+\hbar\mathbf{k}/2}a_{\mathbf{p}-\hbar\mathbf{k}/2}\rangle)\equiv f(\mathbf{r},\mathbf{p},t)-\langle f(\mathbf{r},\mathbf{p},t)\rangle,$$

$$\delta N(\mathbf{r},\mathbf{q},t)=\sum_{\mathbf{k}} e^{-i\mathbf{kr}}(b^+_{\mathbf{q}+\hbar\mathbf{k}/2}b_{\mathbf{q}-\hbar\mathbf{k}/2}-\langle b^+_{\mathbf{q}+\hbar\mathbf{k}/2}b_{\mathbf{q}-\hbar\mathbf{k}/2}\rangle)\equiv N(\mathbf{r},\mathbf{q},t)-\langle N(\mathbf{r},\mathbf{q},t)\rangle. \quad (1)$$

Here $a^+_\mathbf{p}$, $a_\mathbf{p}$, $b^+_\mathbf{q}$, and $b_\mathbf{q}$ are the respective creation and annihilation operators for electrons with momentum $\mathbf{p}$ and phonons with momentum $\mathbf{q}$. The kinetic equation for δf can be obtained in an approximation linear in the fluctuating quantities by the method of the equations of motion for the Heisenberg operator $f(\mathbf{r},\mathbf{p},t)$ (see[4]):

$$\left[i(\omega-\mathbf{kv})+e\mathbf{E}\frac{\partial}{\partial\mathbf{p}}+\hat{\nu}_{ee}'+\hat{\nu}_{ei}'\right]\delta f+\hat{\nu}_{ef}'\{\delta f,\delta N\}$$
$$=-(e\delta\mathbf{E}-i\mathbf{k}U_\mathbf{k})\frac{\partial f_\mathbf{p}}{\partial\mathbf{p}}+K_e; \quad (2)$$

here ω and $\mathbf{k}$ are the frequency and the wave vector of the fluctuation; $\delta\mathbf{E}$ and $\mathbf{E}$ are the fluctuating and constant electric fields; $\hat{\nu}'_{ee}$, $\hat{\nu}'_{ei}$, $\hat{\nu}'_{ef}$ are linearized collision operators (electron-electron, electron-impurity, and electron phonon, respectively); $U_\mathbf{k}=V_{-\hbar\mathbf{k}}(b^+_{\hbar\mathbf{k}}+b_{-\hbar\mathbf{k}})$; $V_\mathbf{q}$ is the matrix element of the electron-phonon interaction; K_e is the Langevin fluctuation source connected with the foregoing types of electron collisions.

Equation (2) holds in the quasiclassical case, i.e., when $\hbar\omega\ll\bar{\varepsilon}$ and $\hbar k\ll\bar{p}$ ($\bar{\varepsilon}$ and $\bar{p}$ are the average energy and momentum of the electrons). In addition, we assume for simplicity that our system is stationary and homogeneous (the electron and phonon distribution functions will be designated $f_\mathbf{p}$ and $N_\mathbf{q}$, respectively).

In (2), $U_\mathbf{k}$ is the long-wave Fourier component of the potential produced by the lattice at the electrons. This part of the electron-phonon interaction is described classically, i.e., it reduces to introduction into the kinetic equation of an additional force proportional to the lattice deformation. Such bound acousto-electric fluctuations were investigated in detail in[9–11] and will not be considered here.

The equation for δN is obtained in the same manner as for δf. It takes the form

$$\left[i\left(\omega-\mathbf{k}\frac{\partial\omega_\mathbf{q}}{\partial\mathbf{q}}\right)+\hat{\nu}_{ff}'\right]\delta N+\hat{\nu}_{fe}'\{\delta N,\delta f\}=K_{fe}+K_{ff}, \quad (3)$$

where $\hat{\nu}'_{ff}$ and $\hat{\nu}'_{fe}$ are the linearized integrals of the phonon-phonon and phonon-electron collisions; K_{ff} and K_{fe} are the Langevin sources corresponding to these collisions; $\omega_\mathbf{q}$ is the phonon energy.

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The explicit form of $\hat{\nu}'_{fe}\{\delta N, \delta f\}$ and the correlators $\langle K_{fe}(\mathbf{r}, \mathbf{q}, t) K_{fe}(\mathbf{r}', \mathbf{q}', t')\rangle_{\mathbf{k},\omega}$ were obtained in[4,5], while $\hat{\nu}'_{ff}\{\delta N\}$ and $\langle K_{ff}(\mathbf{r}, \mathbf{q}, t) K_{ff}(\mathbf{r}', \mathbf{q}', t')\rangle_{\mathbf{k},\omega}$ can be obtained in similar fashion after specifying concretely the mechanism of the phonon-phonon collisions. Assume that the main contribution to the phonon relaxation is made by three-phonon processes. In the quasiclassical approximation we then obtain $\hat{\nu}'_{ff}$ by linearizing with respect to δN the following collision integral:

$$\hat{\nu}_{ff}\{N_{\mathbf{q}}\}=\frac{4\pi}{\hbar}\sum_{\mathbf{p}\mathbf{p}'}\{2|W(\mathbf{q}\mathbf{p};\mathbf{p}')|^2\delta(\omega_{\mathbf{q}}+\omega_{\mathbf{p}}-\omega_{\mathbf{p}'})[N_{\mathbf{q}}N_{\mathbf{p}}(N_{\mathbf{p}'}+1)$$
$$-(N_{\mathbf{q}}+1)(N_{\mathbf{p}}+1)N_{\mathbf{p}'}]+|W(\mathbf{p}\mathbf{p}';\mathbf{q})|^2\delta(\omega_{\mathbf{p}}+\omega_{\mathbf{p}'}-\omega_{\mathbf{q}})$$
$$\times[N_{\mathbf{q}}(N_{\mathbf{p}}+1)(N_{\mathbf{p}'}+1)-(N_{\mathbf{q}}+1)N_{\mathbf{p}}N_{\mathbf{p}'}]\}. \qquad (4)$$

The matrix element $W(\mathbf{q}\mathbf{q}'; \mathbf{q}_1)$ differs from zero when $\mathbf{q}+\mathbf{q}'=\mathbf{G}+\mathbf{q}_1$, where $\mathbf{G}$ is the reciprocal-lattice vector.

The correlators of the extraneous fluxes are obtained in the same approximation as (4), and are equal to

$$\langle K_{ff}(\mathbf{r},\mathbf{q},t)K_{ff}(\mathbf{r}',\mathbf{q}',t')\rangle_{\mathbf{k},\omega}=\frac{2}{\hbar}\sum_{\mathbf{p}\mathbf{p}'}\{|W(\mathbf{p}\mathbf{p}';\mathbf{q})|^2\delta(\omega_{\mathbf{p}}+\omega_{\mathbf{p}'}-\omega_{\mathbf{q}})$$
$$\times[N_{\mathbf{q}}(N_{\mathbf{p}}+1)(N_{\mathbf{p}'}+1)+(N_{\mathbf{q}}+1)N_{\mathbf{p}}N_{\mathbf{p}'}](\delta_{\mathbf{q}\mathbf{q}'}-2\delta_{\mathbf{p}\mathbf{q}'})$$
$$+2|W(\mathbf{q}\mathbf{p};\mathbf{p}')|^2\delta(\omega_{\mathbf{q}}+\omega_{\mathbf{p}}-\omega_{\mathbf{p}'})[N_{\mathbf{q}}N_{\mathbf{p}}(N_{\mathbf{p}'}+1)$$
$$+(N_{\mathbf{q}}+1)(N_{\mathbf{p}}+1)N_{\mathbf{p}'}](\delta_{\mathbf{q}\mathbf{q}'}+\delta_{\mathbf{p}\mathbf{q}'}-\delta_{\mathbf{p}'\mathbf{q}'})\}. \qquad (5)$$

The quasiclassical-approach condition for the frequencies takes here a somewhat different form than before, $\hbar\omega \ll \overline{\omega}_{\mathbf{q}}$ ($\overline{\omega}_{\mathbf{q}}$ are the characteristic phonon energies).

It is impossible to solve actual problems with an exact phonon-phonon collision integral. To find the distribution function of long-wave phonons with characteristic momenta on the order of $\overline{p}$ (these are precisely the phonons from which the electrons are scattered) it is therefore frequently assumed that the main contribution to the relaxation of the long-wave phonons is made by their collisions with short-wave phonons with characteristic energies on the order of T (T is the lattice temperature). It is assumed that the short-wave phonons constitute a thermal reservoir for the long-wave phonons and are not perturbed by the latter. Naturally, a thermal reservoir is meaningful only if $T \gg s\overline{p}$ (s is the speed of sound), and we therefore assume $T \gg \omega_{\mathbf{q}}$. We retain in (4) only terms proportional to $\delta(\omega_{\mathbf{q}}+\omega_{\mathbf{p}}-\omega'_{\mathbf{p}})$, since the remaining terms do not contain collisions with short-wave phonons. We then obtain

$$\hat{\nu}_{ff}'\{\delta N_{\mathbf{q}}\}=\frac{8\pi}{\hbar}\sum_{\mathbf{p}\mathbf{p}'}|W(\mathbf{q}\mathbf{p};\mathbf{p}')|^2\delta(\omega_{\mathbf{q}}+\omega_{\mathbf{p}}-\omega_{\mathbf{p}'})[\delta N_{\mathbf{q}}(N_{\mathbf{p}}-N_{\mathbf{p}'})$$
$$+N_{\mathbf{q}}(\delta N_{\mathbf{p}}-\delta N_{\mathbf{p}'})-\delta N_{\mathbf{p}'}(N_{\mathbf{p}}+1)-N_{\mathbf{p}'}\delta N_{\mathbf{p}}]. \qquad (6)$$

Equation (6) includes the fluctuations of the short-wave phonons. To find them it would be necessary, generally speaking, to solve equations such as (3). The situation is simplified, however, if the characteristic relaxation frequency ν_{ff}^k of the short-wave phonons is high enough: $\nu_{ff}^k \gg \nu_{ff}(\mathbf{q})$, ω, ks. Then

$$\delta N_{\mathbf{p}}=(\partial N_{\mathbf{p}}^0/\partial T)\delta T, \qquad (7)$$

where $N_{\mathbf{p}}^0$ is the Planck function, and the lattice-temperature fluctuations are determined by the heat-conduction equation. Substituting this expression in (6), we readily obtain

$$\hat{\nu}_{ff}'\{\delta N_{\mathbf{q}}\}=\nu_{ff}(\mathbf{q})\left(\delta N_{\mathbf{q}}-\frac{\partial N_{\mathbf{q}}^0}{\partial T}\delta T\right)+\frac{\partial \nu_{ff}(\mathbf{q})}{\partial T}(N_{\mathbf{q}}-N_{\mathbf{q}}^0)\delta T, \qquad (8)$$

where

$$\nu_{ff}(\mathbf{q})=\frac{8\pi}{\hbar}\sum_{\mathbf{p}\mathbf{p}'}|W(\mathbf{q}\mathbf{p};\mathbf{p}')|^2\delta(\omega_{\mathbf{q}}+\omega_{\mathbf{p}}-\omega_{\mathbf{p}'})(N_{\mathbf{p}}-N_{\mathbf{p}'}).$$

Taking into account in the correlator of the extraneous fluxes only collisions with short-wave phonons, we arrive at the expression

$$\langle K_{ff}(\mathbf{r},\mathbf{q},t)K_{ff}(\mathbf{r}',\mathbf{q}',t')\rangle_{\mathbf{k},\omega}=\pi^{-1}\delta_{\mathbf{q}\mathbf{q}'}N_{\mathbf{q}}N_{\mathbf{q}}^0\nu_{ff}(\mathbf{q}). \qquad (9)$$

Thus, when the assumptions made above are valid, the correlation function $\langle K_{ff}K_{ff}\rangle_{\mathbf{k},\omega}$ is determined, just as the phonon-phonon collision integral, by the parameter $\nu_{ff}(\mathbf{q})$. So far we have spoken of only one sort of phonons. All the formulas given above can be generalized to include the case of interaction of phonons of different branches. For this purpose it is necessary to define the phonon momentum as representing two quantities, the momentum proper and the number of the branch.

The foregoing transition from the complicated formulas (4) and (5) to (8) and (9) makes it easy to take into account the influence of the phonon fluctuations on the electron fluctuations.

CONNECTIVE NOISE UNDER CONDITIONS OF HEATING OF LONG-WAVE PHONONS

When current flows in a sample, a distinctive noise due to fluctuations of the average carrier energy can be observed in the direction of the electric field E. This noise is caused by the fact that the fluctuations of the average energy of the carriers cause fluctuations of their mobility μ (if the latter depends on the average energy) and in final analysis fluctuations take place in the flowing current (or in the voltage). Convective noise has been investigated in detail in a number of studies[12,15] but the question of how it can be influenced by phonon fluctuations has nowhere been considered. To solve this problem, we make a few simplifying assumptions:

1) Since phonon heating is most probable at low temperatures, it can be assumed that the electron momentum is scattered by the impurities (with frequency ν_{ei}) while the energy is scattered by acoustic phonons.

2) Electron-electron collisions are so frequent, that the symmetrical part of the electron distribution function $f_s(\varepsilon)$ is Maxwellian with an effective temperature T_e.

3) The asymmetric part of the phonon distribution function is much smaller than the symmetric part, and this takes place either when $v_D \ll s$ (v_D is the electron drift velocity) or when the elastic collisions of the phonons with the impurities are frequent enough.[8]

4) The calculation will be made for spatially homogeneous fluctuations (i.e., for the case $k=0$) and of not

too high frequencies ($\omega \ll \nu_{ee}$, ν_{ee} is the characteristic frequency of the electron-electron collisions). Then the fluctuation $\delta f_s(\varepsilon)$ is equal to (in analogy with (7))

$$\delta f_s(\varepsilon) = (\partial f_s/\partial T_e)\,\delta T_e. \tag{10}$$

The temperature fluctuation δT_e is determined from the balance equation, which is obtained after multiplying the left- and right-hand sides of (2) by ε_p and summing over $\mathbf{p}$:

$$\frac{3}{2} i\omega n\delta T_e - \sum_{\mathbf{q}} \omega_q \left[\nu_{fe}\left(\delta N_s - \frac{\delta T_e}{\omega_{\mathbf{q}}}\right) + \delta T_e\left(N_s - \frac{T_e}{\omega_{\mathbf{q}}}\right)\frac{\partial}{\partial T_e}\nu_{fe}\right] = \mathbf{j}\delta\mathbf{E} + \mathbf{E}\delta\mathbf{j} + K_{ef}. \tag{11}$$

Here ν_{fe} is the frequency of the phonon-electron collisions, K_{ef} is the extraneous energy flux, and $\delta\mathbf{j}$ is the current fluctuation. Their values are:

$$\nu_{fe} = n\frac{s\sqrt{2\pi m}}{\hbar T_e^{3/2}}|V_{\mathbf{q}}|^2 \exp\left[-\frac{q^2}{8mT_e}\right] \tag{12a}$$

(n is the carrier density and m is their effective mass),

$$K_{ef} = \sum_{\mathbf{p}} \varepsilon_p K_e \approx -\sum_{\mathbf{q}} \omega_{\mathbf{q}} K_{fe} \tag{12b}$$

and finally

$$\delta\mathbf{j} = en\left[\mu\delta\mathbf{E} + \frac{\partial\mu}{\partial T_e}\mathbf{E}\delta T_e\right] + \mathbf{j}_{ei}^{\text{coll}}, \quad \mathbf{j}_{ei}^{\text{coll}} = e\sum_{\mathbf{p}} \frac{\partial\varepsilon_{\mathbf{p}}}{\partial\mathbf{p}}\nu_{ei}^{-1}K_e. \tag{12c}$$

The second term in the square brackets of (12c) takes into account the influence of the temperature fluctuation δT_e on the current fluctuation $\delta\mathbf{j}$.

Equation (11) includes the fluctuations of the symmetric part δN_s of the phonon distribution function, which satisfies the equation

$$(i\omega + \nu_{fe} + \nu_{ff})\delta N_s - \left[\frac{\partial}{\partial T_e}\left(\nu_{fe}\frac{T_e}{\omega_{\mathbf{q}}}\right) - N_s\frac{\partial}{\partial T_e}\nu_{fe}\right]\delta T_e = K_{fe}^s + K_{ff}^s. \tag{13}$$

Equation (13) follows directly from (3) when the assumptions listed above are satisfied.

By determining δT_e and δN_s from (11) and (13), we readily obtain the following expression for the fluctuations of the current in the direction of the field $\mathbf{E}$:

$$\delta j_E = en\mu'\delta E_E + \frac{1}{2\mu}\left\{\frac{\mu'-\mu}{E}\sum_{\mathbf{q}} \omega_{\mathbf{q}} \frac{\nu_{fe}K_{ff} - (i\omega + \nu_{ff})K_{fe}}{i\omega + \nu_{ff} + \nu_{fe}} + (\mu' + \mu)(j_{ei}^{\text{coll}})_E\right\} = en\mu'\delta E_E + \delta j_E^{\text{coll}}, \tag{14}$$

where $en\mu'$ is a function of the linear response of the system to an external perturbation:

$$\mu' = \mu\frac{A_\omega + \mathbf{j}'\mathbf{E}}{A_\omega - \mathbf{j}'\mathbf{E}}, \quad A_\omega = \frac{3}{2}i\omega n + \sum_{\mathbf{q}} \frac{(i\omega + \nu_{ff})(\nu_{ff} + \nu_{fe})}{(i\omega + \nu_{ff} + \nu_{fe})\nu_{ff}} \frac{\partial}{\partial T_e}[(T_e - T)\nu];$$

$$\nu = \frac{\nu_{ff}\nu_{fe}}{\nu_{ff} + \nu_{fe}}, \quad \mathbf{j}' = \frac{\partial\mathbf{j}}{\partial T_e}.$$

The system is stable at not all values of the field $\mathbf{E}$. Obviously, the mobility μ' must be finite at all frequencies. Hence the necessary condition for a stable state is the inequality

$$\sum_{\mathbf{q}} \frac{\partial}{\partial T_e}[(T_e - T)\nu] > \frac{\partial}{\partial T_e}\mathbf{j}\mathbf{E}. \tag{15}$$

If the right- and left-hand sides of (15) become equal, then superheat instability sets in. The approach to the boundary of this instability with increasing $\mathbf{E}$ manifests itself in an increase of the low-frequency noise. When the external circuit is shorted to the ac component of the current, then $\delta j_E = \delta j_E^{\text{coll}}$. The quantity δj_E^{coll} is the total source of current or voltage fluctuations in the sample, and in contrast to δE_E does not depend on the external circuit.

Let us calculate the correlation function of the fluctuations of the extraneous current S_ω:

$$S_\omega = \langle \delta j_E^{\text{coll}}(t)\,\delta j_E^{\text{coll}}(t')\rangle_\omega = \frac{T_e}{\pi}\left\{en\,\mathrm{Re}\,\mu' + \frac{(\mathbf{j}')^2}{|A_\omega - \mathbf{j}'\mathbf{E}|^2} \times \sum_{\mathbf{q}} \nu_{fe}\left[T_e - \nu(T\nu_{ff} + T_e\nu_{fe})\frac{T_e\nu_{fe} + (2T_e - T)\nu_{ff}}{T_e\nu_{ff}[\omega^2 + (\nu_{ff} + \nu_{fe})^2]}\right]\right\}. \tag{16}$$

In the derivation of (16) we used expression (9) as well as the correlators $\langle K_{fe}(\mathbf{q},t)K_{fe}(\mathbf{q}',t')\rangle_\omega$ calculated in[4]. It is easily seen from (16) that when $\nu_{ff} \gg \nu_{fe}$ the spectral function S_ω consists of a low-frequency and a high-frequency plateau with a transition region at frequencies on the order of the frequency of the carrier energy relaxation on the phonons:

$$\omega \sim \nu_{ef}, \quad \nu_{ef} = \frac{2}{3n}\sum_{\mathbf{q}} \nu_{fe}.$$

The condition $\nu_{ff} \gg \nu_{fe}$ means that there is no phonon heating, for in this case the energy outflow from the long-wave phonons to the thermostat is much faster than the energy inflow from the heated electrons. If $\nu_{ff} \gg \nu_{fe}$ formula (16) coincides fully with the formula obtained by Kogan and Shul'man[13] for a short-circuited sample. We note that they used Langevin method employed in the present paper.

On the other hand if $\nu_{ff} \lesssim \nu_{fe}$, then S_ω contains two characteristic frequencies near which noticeable dispersion takes place:

$$\omega_1 \sim \frac{2}{3n}\sum_{\mathbf{q}} \nu, \quad \omega_2 \sim \nu.$$

For nondegenerate carriers ω_1 is of the order of $\omega_2/f_s(\bar{\varepsilon})$, i.e., $\omega_1 \gg \omega_2$. The quantity ω_1, just as in the case mentioned above, characterizes the rate of the outflow of the electron energy to the thermostat, while the frequency ν represents the relaxation rate of the long-wave phonons. The additional dispersion at the frequency ω_2 is due to fluctuations of the phonon distribution function δN_s. The interpretation follows from the fact that the additional dispersion vanishes if we put $\delta N_s = 0$ in (11).

It is interesting to note that in the case of the strong inequality $\nu_{ff} \ll \nu_{fe}$ the dispersion at frequencies on the

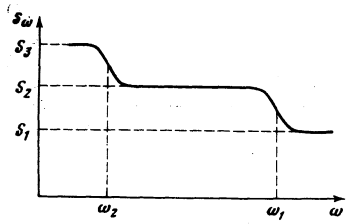

FIG. 1. Qualitative dependence of the current correlation function on the frequency in the case of heating of electrons and long-wave phonons.

order of ω_1 vanishes. The long-wave phonons and electrons behave here as a single system with a common effective temperature T_e. T_e can fluctuate only on account of phonon-phonon processes. Therefore the frequency ν_{ff} is the only characteristic frequency.

Thus the following situations are possible in a heating electric field: a) $\nu_{ff} \gg \nu_{fe}$—dispersion takes place in the noise spectrum at frequencies on the order of ν_{ef}; b) $\nu_{ff} \ll \nu_{fe}$—dispersion at frequencies on the order of ν_{ff}; c) $\nu_{ff} \sim \nu_{fe}$—dispersion at frequencies on the order of ν and $\nu/f_s(\overline{\varepsilon})$ (see Fig. 1). In all these cases the relative differences between the low-frequency and high-frequency plateaux are of the order of the relative heating (of the order of $(T_e - T)/T_e$). In case (a) the difference $S_2 - S_1$ is of the same sign as the derivative $\partial\mu/\partial T_e$. In cases (b) and (c) there is no such simple rule, but in the case of weak heating ($(T_e - T)/T_e \ll 1$) the signs of $S_2 - S_1$ and $S_3 - S_2$ coincide with the sign of the quantity

$$1+2\frac{\mu}{T}\left(\frac{\partial\mu}{\partial T_e}\right)^{-1}.$$

When the carriers are scattered by ionized impurities and $\partial\mu/\partial T_e > 0$, then the plot of S_ω is the same as in the figure.

We note in conclusion that phonon fluctuations can influence strongly the spectral function S_ω, so that an experimental investigation of the noise is of considerable interest in the study of the kinetic properties of long-wave phonons as they are heated.

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