THERMOMAGNETIC EFFECTS OF NONDEGENERATE KANE SEMICONDUCTORS UNDER THE CONDITIONS OF MUTUAL ELECTRON-PHONON DRAG IN A STRONG ELECTRIC FIELD

M.M. BABAYEV, T.M. GASSYM
Institute of Physics of Azerbaijan National Academy of Sciences
370143, H. Javid av., 33, Baku

The thermoelectric power and Nernst - Ettingshausen effects of nondegenerate Kane semiconductors with due regard of the electron and phonon heating and their mutual drag are investigated. It is shown that the nonparabolicity of electron spectrum significantly influences on values of thermoelectric power and Nernst - Ettingshausen coefficients, leads to the change of their dependence upon the electron temperature T_e , as well as upon the heated electric field E. Under the conditions of strong mutual electron-phonon drag for the semiconductors with parabolic spectrum of electrons the phonon part of Nernst - Ettingshausen coefficient Q_p=0, but in the nonparabolic case $Q_p \neq 0$ and Q_p is larger than the electron part of Nernst - Ettingshausen coefficient Q_e , i.e. Nernst - Ettingshauzen field mainly consists of the phonon part.

The interest to the studies of thermoelectric power and thermomagnetic effects in different systems under the conditions of carrier heating at the strong external electric field has recently been intensified [1-3]. Lei [1], Xing, Liu, Dong and Wang [2] discussed the thermoelectric power under the conditions of carrier heating at the external high electric field neglecting the contribution of the phonon drag, which is very important at low temperatures of the lattice [4]. The role of the phonon drag in thermoelectric power of hot carriers was studied by Wu, Horing and Cui [3], by taking into account only the drag of electrons by phonons (thermal drag), but the mutual drag of electrons and phonons was neglected. The thermoelectric power and thermomagnetic effects of hot carriers with regard of both the electron drag by phonons and their mutual drag were studied in [5]. In all papers [1-3,5] the electron dispersion law was assumed to be parabolic. In the publication [6] the thermoelectric power and thermomagnetic effects of hot electrons in strongly degenerated semiconductors for two-band Kane spectrum of electrons was discussed.

In this paper the thermoelectric power and transverse Nernst - Ettingshausen effect of nondegenerate Kane semiconductors placed in high electric $(\vec{E})$ and nonquantized magnetic $(\vec{H})$ fields are investigated with regard of both the drag of heated electrons by phonons and their mutual drag. The electron temperature gradient ∇T_e can be produced by the gradient of $(\vec{E})$ or by the lattice temperature gradient ∇T. The phonons were assumed to be heated or non-heated. Two-band Kane spectrum of electrons is assumed [4] as follows:

$$p(\varepsilon) = (2m_n\varepsilon)^{\frac{1}{2}}\left(1 + \frac{\varepsilon}{\varepsilon_g}\right)^{\frac{1}{2}}, \qquad (1)$$

where m_n is the electron effective mass at the bottom of the conduction band, ε_g is the band gap, p and ε are the electron momentum and energy, respectively.

The basic equations of the problem are the coupled Boltzmann transport equations for electrons and phonons. The case of quasi-elastic electron scattering by acoustic phonons is considered. For the considered case the distribution functions of electrons $f(\vec{p}, \vec{r})$ and phonons $N(\vec{q}, \vec{r})$ may be presented in the form:

$$f(\vec{p}, \vec{r}) = f_0(\varepsilon, \vec{r}) + \vec{f}_1(\varepsilon, \vec{r})\frac{\vec{p}}{p}, \quad |\vec{f}_1| \ll f_0, \qquad (2)$$

$$N(\vec{q}, \vec{r}) = N_0(q, \vec{r}) + \vec{N}_1(q, \vec{r})\frac{\vec{q}}{q}, \quad |\vec{N}_1| \ll N_0. \qquad (3)$$

Here f_0 and $\vec{f}_1$, N_0 and $\vec{N}_1$ are the isotropic and anisotropic parts of the electron and phonon distribution functions, respectively.

If the inter-electronic collision frequency ν_{ee} is much larger than the collision frequency of the electrons for the energy transfer to of lattice ν_ε , then $f_0(\varepsilon, \vec{r})$ is the Fermi distribution function with an electron temperature T_e. We consider the case when for long-wavelength (LW) phonons there is a "thermal reservoir" of short-wavelength (SW) phonons: $q_{max} \approx 2\bar{p} \ll \frac{T}{S_0}$, where S_0 is the sound velocity in the crystal, q_{max} is the maximum quasi-momentum of LW phonons. In this case $N_0(q, \vec{r})$ has the form [7]

$$N_0(q, \vec{r}) \approx \frac{T_p(\vec{r})}{S_0 q}, \qquad (4)$$

where T_p is the effective temperature of the LW phonons.

Starting from the Boltzmann transport equations we obtain the following equations for $\vec{f}_1$ and $\vec{N}_1$ in the steady state :

$$\frac{p}{m(\varepsilon)}\nabla f_0 - e\vec{E}_c\frac{p}{m(\varepsilon)}\frac{\partial f_0}{\partial\varepsilon} - \Omega(\varepsilon)[\vec{h}\vec{f}_1] + \nu(\varepsilon)\vec{f}_1 + \frac{2\pi m(\varepsilon)}{(2\pi\hbar)^3 p^2}\frac{\partial f_0}{\partial\varepsilon}\int_0^{2p}\vec{N}_1(q)W(q)\hbar\omega_q q^2 dq = 0, \quad (5)$$

$$S_0\nabla N_0 + \beta(q)\vec{N}_1 - \frac{4\pi m(\varepsilon)}{(2\pi\hbar)^3}W(q)N_0(q)\int_{q/2}^{\infty}\vec{f}_1 dp = 0. \quad (6)$$

Here e is the absolute value of the electron's charge, $\vec{E}_c = \vec{E} + \vec{E}_T$, $\vec{E}_T$ is the thermoelectric field, $m(\varepsilon)$ is the electron's effective mass, $\Omega = eH/m(\varepsilon)c$ is the electron cyclotron frequency, $\vec{h} = \vec{H}/H$, $\hbar\omega_q = s_0 q$ is the phonon energy, $W(q) = W_0 q^t$ is the square matrix element of the electron-phonon interaction (t=1 for deformation, and t=-1 for piezoelectric interaction), $\beta(q)$ and $\nu(\varepsilon)$ are the total phonon and electron momentum scattering rates, respectively.

For the Kane semiconductors with the electron spectrum (1) the expressions of $m(\varepsilon)$ and $\nu(\varepsilon)$ have the form [4]:

$$m(\varepsilon) = m_n\left(1 + \frac{2\varepsilon}{\varepsilon_g}\right) \quad (7)$$

$$\nu(\varepsilon) = \nu_0(T)\left(\frac{T_p}{T}\right)^l\left(1+\frac{2\varepsilon}{\varepsilon_g}\right)\left(1+\frac{\varepsilon}{\varepsilon_g}\right)^{-r}\left(\frac{\varepsilon}{T}\right)^{-r} \quad (8)$$

where r=3/2, l=0 for the scattering of elektrons by impurity ions and r=-t/2, l=1 for the scattering of elektreons by acoustic phonons. When LW phonons are scattered by SW phonons or by crustal boundaries, $\beta(q)$ doesn't depend on the spectrum of elektrons and has the form [7]:

$$\beta_p(q) = \frac{T^4}{4\pi\rho\hbar^4 s_0^4}q,\ \beta_b(q) = \frac{S_0}{L} \quad (9)$$

where the indices p and b denote the scattering by SW phonons and crystal boundaries, ρ and L are the density and the minimum size of a specimen, respectively. When LW phonons are scattered by electrons, $\beta(q)$ depends on the spectrum of electrons and for the spectrum (1) we obtain:

$$\beta_e(q) = \left(\frac{m_n s_0^2}{8\pi T_e}\right)^{1/2}\frac{NW_0}{T_e}\left(1+\frac{2T_e}{\varepsilon_g}\right)^2\left(1+\frac{3T_e}{2\varepsilon_g}\right)^{-3/2}q^t, \quad (10)$$

where N is the concentration of electrons.Solving the coupled equations (5) - (6) by the same way as in [5] and using the conditions $j_x = j_z = 0\left(\vec{E}\|\vec{H}\|oy,\ \nabla T_{e,p}\|oz\right)$ we obtain the following expressions for the thermoelectric field E_{Tz} and the transverse Nernst - Ettingshausen (NE) field E_{Tx}:

$$E_{Tz} + \frac{1}{e}\nabla_z\zeta(T_e) = \alpha_e\nabla_z T_e + \alpha_p\nabla_z T_p;\ \alpha_{e,p} = -\frac{\sigma_{11}\beta_{11}^{(e,p)} + \sigma_{12}\beta_{12}^{(e,p)}}{\sigma_{11}^2 + \sigma_{12}^2}, \quad (11)$$

$$E_{Tx} = -H(Q_e\nabla_z T_e + Q_p\nabla_z T_p);\ Q_{e,p} = \frac{1}{H}\frac{\sigma_{11}\beta_{12}^{(e,p)} - \sigma_{12}\beta_{11}^{(e,p)}}{\sigma_{11}^2 + \sigma_{12}^2}, \quad (12)$$

where $\alpha_{e,p}$ are the electron (e) and phonon (p) parts of the thermoelectric power and $Q_{e,p}$ are the respective parts of NE coefficient,

$$\sigma_{1i} = \int_0^{\infty}\alpha(x)\left(\frac{\Omega(x)}{\nu(x)}\right)^{i-1}[1 + b_i(x)]dx,\ x = \frac{\varepsilon}{T_e}, \quad (13)$$

$$\beta_{1i}^{(e)} = \frac{1}{e}\int_0^{\infty}\alpha(x)\left(\frac{\Omega(x)}{\nu(x)}\right)^{i-1}\left\{x - \frac{\zeta(T_e)}{T_e} + \left[1 - \frac{\zeta(T_e)}{T_e}\right]b_i(x)\right\}dx, \quad (14)$$

$$\beta_{1i}^{(p)} = \frac{1}{e}\int_0^{\infty}\alpha(x)\left(\frac{\Omega(x)}{\nu(x)}\right)^{i-1}[\lambda(x) + \lambda(1)b_i(x)]dx\ ,\ \vartheta_e = \frac{T_e}{T}\ ,\ \vartheta_p = \frac{T_p}{T}. \quad (15)$$

Here $\zeta(T_e)$ is the chemical potential of hot electrons,

$$\alpha(x) = \frac{e^2}{3\pi^2\hbar^3}\frac{p^3(x)\nu(x)}{m(x)[\Omega^2(x) + \nu^2(x)]} \times exp\left[\frac{\zeta(T_e)}{T_e} - x\right], \quad (16)$$

$$b_1(x) = \frac{\gamma(x)\nu(x)}{\Omega^2(1) + \nu^2(1)(1-\gamma_0)^2}\frac{m(x)}{m(1)}\left[\nu(1)(1-\gamma_0) - \frac{\Omega(x)\Omega(1)}{\nu(x)}\right], \quad (17)$$

$$b_2(x) = \frac{\gamma(x)\nu(x)}{\Omega^2(1) + \nu^2(1)(1-\gamma_0)^2}\frac{m(x)}{m(1)}\left[\nu(1)(1-\gamma_0) + \nu(x)\frac{m(x)}{m(1)}\right], \quad (18)$$

$$\gamma(x) = \frac{3+t}{(2p)^{3+t}}\frac{\nu_p(x)}{\nu(x)}\int_0^{2p}\frac{\beta_e(q)}{\beta(q)}q^{2+t}dq, \quad (19)$$

$$\lambda(x) = \frac{3+t}{(2p)^{3+t}}\frac{m(x)s_0^2}{T_p}\nu_p(x)\int_0^{2p}\frac{1}{\beta(q)}q^{2+t}dq, \quad (20)$$

$\nu_p(x)$ is the electron scattering frequency by phonons. The coefficient $\lambda(x)$ characterizes the efficiency of the thermal drag, whereas $\gamma(x)$ describes the same for the mutual drag.

Because of the complexity of general analysis of expressions (11) - (15), later we examine the dependence of electron momentum upon its energy in the form

$$p(\varepsilon) = (2m_n\varepsilon_g)^{1/2}\left(\frac{\varepsilon}{\varepsilon_g}\right)^s, \quad (21)$$

which for the spectrum (1) corresponds to the parabolic ($T_e<<\varepsilon_g$, $s=1/2$) and strongly nonparabolic (Te>>ε_g, $s=1$)) cases, $m(\varepsilon)$, $\nu(\varepsilon)$ and $\beta(q)$ respectively. In these cases, and may be presented in the form:

$$m(\varepsilon) = 2sm_n\left(\frac{\varepsilon}{\varepsilon_g}\right)^s, \quad (22)$$

$$\nu(\varepsilon) = 2s\nu_0(T)\vartheta_p^1\left(\frac{\varepsilon}{\varepsilon_g}\right)^{(2s-1)(1-r)}\left(\frac{\varepsilon}{T}\right)^{-r} \quad (23)$$

$$\beta(q) = \beta(T)\vartheta_e^{n(s-2)}\left(\frac{T}{\varepsilon_g}\right)^{n\left(s-\frac{1}{2}\right)}\left(\frac{s_0q}{T}\right)^k, \quad (24)$$

where $n=1$, $k=t$ for scattering of LW phonons by electrons, $n=0$, $k=0$ for the scattering by crystal boundaries and when $n=0$, $k=1$ LW phonons are scattered by SW phonons. For the spectrum (21) the chemical potential of hot nondegenerate electrons with concentration N takes the form:

$$\zeta(T_e) = T_e\ ln\frac{3\pi^2\hbar^3N}{\Gamma(1+3s)(2m_nT)^{3/2}}\left(\frac{T}{\varepsilon_g}\right)^{-3\left(s-\frac{1}{2}\right)}\vartheta_e^{-3s}. \quad (25)$$

Let us study and in weak and strong magnetic fields. In weak magnetic fields in a first approximation on we obtain

$$\alpha_e = -\frac{1}{e}\left(1+C_1\frac{\gamma_0}{1-\gamma_0}\right)^{-1}\left\{3-s+2sr-\frac{\zeta(T_e)}{T_e}+\left[1-\frac{\zeta(T_e)}{T_e}\right]C_1\frac{\gamma_0}{1-\gamma_0}\right\}, \quad (26)$$

$$\alpha_p = -\frac{1}{e}\frac{C_2+(C_1-C_2)\gamma_0}{1+(C_1-1)\gamma_0}\lambda(1), \quad (27)$$

$$Q_e = \frac{1}{ec}C_6\left(1+C_1\frac{\gamma_0}{1-\gamma_0}\right)^{-2}\left\{(4-4s+2sr)C_3+\left[(4-5s+4sr)C_1C_3-(2-s+2sr)C_4\right]\frac{\gamma_0}{1-\gamma_0}-\right.$$
$$\left.-(2-s+2sr)C_1\frac{\gamma_0}{(1-\gamma_0)^2}\right\}\mu_s(T_e), \quad (28)$$

$$Q_p = \frac{1}{ec}C_6\left(1+C_1\frac{\gamma_0}{1-\gamma_0}\right)^{-2}\left\{C_5-C_2C_3+(C_4+C_1C_5-C_1C_3-C_2C_4)\frac{\gamma_0}{1-\gamma_0}+\right.$$
$$\left.+C_1(1-C_2)\frac{\gamma_0}{(1-\gamma_0)^2}\right\}\lambda(1)\mu_s(T_e), \quad (29)$$

where is the mobility of hot electrons with spectrum (21) in the nondegenerate case:

$$\mu_s(T_e) = \frac{\Gamma(3 - s + 2sr)}{4s^2\Gamma(1 + 3s)} \frac{e}{m_n \nu_0(T)} \left(\frac{T}{\varepsilon_g}\right)^{(1-2s)(2-r)} \vartheta_e^{2-4s+2sr} \vartheta_p^{-1}. \tag{30}$$

From (26)-(29) it appears that in weak magnetic fields the mutual drag essentially influences on electron and phonon parts of thermoelectric power and NE coefficients.

In strong magnetic fields from (11) and (12) we obtain

$$\alpha_e = -\frac{1}{e}\left[1 + 3s - \frac{\zeta(T_e)}{T_e}\right], \tag{31}$$

$$\alpha_p = -\frac{1}{e} C_7 \lambda(1), \tag{32}$$

$$Q_e = \frac{c}{eH^2} \frac{1}{C_6^2} \left[(2 - 4s + 2sr)C_8 - 3s\gamma_0 C_9\right] \frac{1}{\mu_s(T_e)} \tag{33}$$

$$Q_p = \frac{c}{eH^2} \frac{1}{C_6^3} \left[C_7 C_8 - C_6 C_{10} + C_9(C_6 - C_7)\gamma_0\right] \frac{1}{\mu_s(T_e)} \lambda(1). \tag{34}$$

As it seen from (31) - (34), in strong magnetic fields thermoelectric power explicitly does not depend on mutual drag coefficient γ_0, but Q_e and Q_p linearly depend on γ_0.

Here

$$C_1 = \frac{\Gamma(1 + 3s + 2sr + 2st - sk)}{\Gamma(3 - s + 2sr)},$$

$$C_2 = \frac{\Gamma(1 + 3s + 2sr + st - sk)}{\Gamma(3 - s + 2sr)},$$

$$C_3 = \frac{\Gamma(5 - 5s + 4sr)}{\Gamma(3 - s + 2sr)},$$

$$C_4 = \frac{\Gamma(3 - s + 4sr + 2st - sk)}{\Gamma(3 - s + 2sr)},$$

$$C_5 = \frac{\Gamma(3 - s + 4sr + st - sk)}{\Gamma(3 - s + 2sr)},$$

$$C_6 = \frac{\Gamma(1 + 3s)}{\Gamma(3 - s + 2sr)},$$

$$C_7 = \frac{\Gamma(7s - 1 + st - sk)}{\Gamma(3 - s + 2sr)},$$

$$C_8 = \frac{\Gamma(7s - 1 - 2sr)}{\Gamma(3 - s + 2sr)},$$

$$C_9 = \frac{\Gamma(7s - 1 + 2st - sk)}{\Gamma(3 - s + 2sr)},$$

$$C_{10} = \frac{\Gamma(11s - 3 - 2sr + st - sk)}{\Gamma(3 - s + 2sr)}. \tag{35}$$

$$\gamma_0 = \frac{(3 + t)2^{\frac{3(t-k)}{2}}}{3 + 2t - k} \left(\frac{m_n s_0^2}{T}\right)^{\frac{t-k}{2}} \left(\frac{T\vartheta_e}{\varepsilon_g}\right)^{\left(s-\frac{1}{2}\right)(2r+2t-k-n+1)} \vartheta_e^{r+t+\frac{3n-3-k}{2}} \vartheta_p^{1-l} \frac{\beta_e(T)}{\beta(T)} \frac{\nu_{f0}(T)}{\nu_0(T)}, \tag{36}$$

$$\lambda(1) = \frac{(3 + t)2^{2-\frac{3k}{2}}}{3 + t - k} \left(\frac{m_n s_0^2}{T}\right)^{1-\frac{k}{2}} \left(\frac{T\vartheta_e}{\varepsilon_g}\right)^{\left(s-\frac{1}{2}\right)(4+t-k-n)} \vartheta_e^{\frac{3n+t-k}{2}} \frac{\nu_{f0}(T)}{\beta(T)}, \tag{37}$$

The expressions (26) - (34) are valid for any values of the mutual drag coefficient ($0 \le \gamma_0 < 1$). The thermoelectric power and thermomagnetic effects of hot carriers in absence of mutual drag ($\gamma_0 = 0$) were studied in papers [8,9]. Thus we consider here just the strong mutual drag regime. This regime takes place when the electrons and phonons are scattered mainly by each other, i.e. $k=t$, $n=1$, $r=-t/2$, $l=1$, $\vartheta_p = \vartheta_e$, $\gamma_0 = \frac{\beta_e(T)}{\beta(T)} \frac{\nu_{f0}(T)}{\nu_0(T)} \to 1$. Under these conditions the expressions (26) - (29) and (31) - (34) can be transformed to the following forms.

In weak magnetic fields electron part of thermoelectric power both in parabolic and non- parabolic cases has the

identical form and depends on degree of nonparabolisity only through the chemical potential of elektrons:

$$\alpha_e = -\frac{1}{e}\left[1 - \frac{\zeta(T_e)}{T_e}\right], \qquad (38)$$

but phonon part of thermoelectric power strongly depends on degree of nonparabolicity:

$$\alpha_p = -\frac{1}{e}\cdot\frac{4\sqrt{2}(2s)^2}{3\pi^{\frac{3}{2}}}\left(\frac{T}{\varepsilon_g}\right)^{3\left(s-\frac{1}{2}\right)}\frac{(m_nT)^{\frac{3}{2}}}{\hbar^3N}\vartheta_e^{3s}. \qquad (39)$$

As it follows from (25), (38) and (39) α_e weakly (logarithmic manner) depends upon T_e, whereas α_P strongly increases with increasing of electron temperature: $\alpha_P \sim T_e^{3/2}$ for the parabolic, and $\alpha_P \sim T_e^3$ for the strong nonparabolic cases.

The electron and phonon parts of NE coefficient in weak magnetic fields:

$$Q_e = -(2 - s - st)\frac{\mu_s(T)}{ec}\vartheta_e^{1-4s-st}, \qquad (40)$$

$$Q_p = \frac{4\sqrt{2}(2s)^2}{3\pi^{\frac{3}{2}}}\left[1 - \frac{\Gamma(1+3s-st)}{\Gamma(3-s-st)}\right]\frac{\mu_s(T)}{ec}\left(\frac{T}{\varepsilon_g}\right)^{3\left(s-\frac{1}{2}\right)}\frac{(m_nT)^{\frac{3}{2}}}{\hbar^3N}\vartheta_e^{1-s-st}, \qquad (41)$$

where $\mu_s(T)$ is the mobility of cold $(T_e=T)$ electrons.

Since $1-4s-st<0$ for the both electron - phonon scattering mechanisms $(t\pm1)$ and for each spectrum of electrons with $s\geq1/2$, from (40) we obtain that Q_e decreases with increasing of T_e. From (41) it is seen that in the parabolic case $(s=1/2)$ $Q_p=0$. In the strong nonparabolic case $(s=1)$ $Q_p\neq0$ and $Q_p \sim \vartheta_e^{-t}$, i.e. Q_p increases with increasing of T_e at piezoelectric electron-phonon interaction, and Q_p decreases with increasing of T_e at deformation interaction.

In the strong magnetic fields:

$$\alpha_e = -\frac{1}{e}\left[1 + 3s - \frac{\zeta(T_e)}{T_e}\right], \qquad (42)$$

$$\alpha_p = -\frac{1}{e}\frac{4\sqrt{2}(2s)^2}{3\pi^{\frac{3}{2}}}\frac{\Gamma(7s-1)}{\Gamma(3-s-st)}\left(\frac{T}{\varepsilon_g}\right)^{3\left(s-\frac{1}{2}\right)}\frac{(m_nT)^{\frac{3}{2}}}{\hbar^3N}\vartheta_e^{3s}. \qquad (43)$$

From (38) and (42) it follows that electron part of thermoelectric power increases in magnetic field:

$$\Delta\alpha_e \equiv |\alpha_e(H)| - |\alpha_e(0)| = \frac{1}{e}3s, \qquad (44)$$

and the increase in the non-parabolic case is bigger than in the parabolic case. The dependence of α_P upon T_e in strong magnetic field is the same as in weak magnetic field.

In the strong magnetic fields for Q_e and Q_p we obtain:

$$Q_e = -(7s - 2 + st)\frac{\Gamma(7s-1+st)}{\Gamma^2(1+3s)}\frac{c}{eH^2}\frac{1}{\mu_s(T)}\vartheta_e^{4s+st-1}, \qquad (45)$$

$$Q_p = \frac{4\sqrt{2}(2s)^2}{3\pi^{\frac{3}{2}}}\frac{\Gamma(3-s-st)}{\Gamma^2(1+3s)}\left[\Gamma(7s-1+st) - \Gamma(11s-3+st)\right]\frac{c}{eH^2}\frac{1}{\mu_s(T)}\times$$
$$\times\left(\frac{T}{\varepsilon_g}\right)^{3\left(s-\frac{1}{2}\right)}\frac{(m_nT)^{\frac{3}{2}}}{\hbar^3N}\vartheta_e^{7s+st-1}. \qquad (46)$$

As follows from expression (45), in contrast to the weak magnetic fields, in the strong magnetic fields Q_e increases with increase of T_e (for the all real cases $(4s+st-1>0)$). Expression (46) shows that for the parabolic case $Q_p=0$ whereas for the strong nonparabolic spectrum of electrons $(s=1)$ Q_p strongly increases with increase of T_e: $Q_p \sim \vartheta_e^{6+t}$ i.e. $Q_p \sim \vartheta_e^7$ at deformation interaction and $Q_p \sim \vartheta_e^5$ at piezoelectric interaction of electrons with phonons.

As it follows from (25) for the nondegenerate electrons

$$\left(\frac{T}{\varepsilon_g}\right)^{3\left(s-\frac{1}{2}\right)}\frac{(m_nT)^{\frac{3}{2}}}{\hbar^3N} \approx \exp\left[-\frac{\zeta(T)}{T}\right] >> 1, \qquad (47)$$

and from the comparison (38) with (39) and (42) with (43) it is seen that under the conditions of strong mutual drag $|\alpha_p| >> |\alpha_e|$, both in weak and in strong magnetic fields, i.e. the thermoelectric power mainly consists of the phonon part.

Since in the case of a parabolic spectrum $Q_p=0$, the NE field consists only of the electron part. But in the case of the strong nonparabolic spectrum from (40), (41), (45) and (46) it follows that $|Q_p| >> |Q_e|$, i.e. NE field mainly consists of the phonon part.

Under the conditions of the strong mutual drag ($\vartheta_e=\vartheta_p, \gamma\to 1$) the electron temperature is determined from the energy balance equation

$$\sigma_{11}(\vartheta_e)E^2 = W_{pp}(\vartheta_e), \qquad (48)$$

where $W_{pp}(\vartheta_e)$ is the power transferred by the LW phonons to the thermal reservoir of the SW phonons. The calculation of the expression $\vartheta_e(E)$ from (48) at ($\vartheta_p = \vartheta_e >> 1$ in following limiting cases gives:

Case 1) $\dfrac{\beta_p + \beta_b}{\beta_e} << \dfrac{\nu_i}{\nu_p} : \vartheta_e \sim E^{\frac{2}{5s-1}}, \qquad (49)$

Case 2) $\beta_p >> \beta_b, \dfrac{\beta_p}{\beta_e} >> \dfrac{\nu_i}{\nu_p} : \vartheta_e \sim E^{\frac{1}{4s+1}}, \qquad (50)$

Case 3) $\beta_p << \beta_b, \dfrac{\beta_p}{\beta_e} >> \dfrac{\nu_i}{\nu_p} : \vartheta_e \sim E^{\frac{2}{7s+2}}. \qquad (51)$

As it seen from (49) - (51) the nonparabolicity of electron spectrum strongly changes the E -dependence of electron temperature. Using these expressions one can easily obtain the dependence of thermoelectric power and NE coefficient upon the heated electric field in the considered cases. From (25), (38) and (42) it follows that α_e weakly (logarithmic manner) depends upon E for the all cases (49) - (51). The dependence of α_p, Q_e and Q_p upon E in these cases are shown in the table.

Table

The dependence of α_p, Q_e and Q_p upon E under the conditions of strong mutual drag

	Case 1	Case 2	Case 3
α_p	$\sim E^{\frac{6s}{5s-1}}$	$\sim E^{\frac{3s}{4s+1}}$	$\sim E^{\frac{6s}{7s+2}}$
$Q_e(\bar{\Omega} << \bar{\nu})$	$\sim E^{\frac{2(1-4s-st)}{5s-1}}$	$\sim E^{\frac{1-4s-st}{4s+1}}$	$\sim E^{\frac{2(1-4s-st)}{7s+2}}$
$Q_e(\bar{\Omega} >> \bar{\nu})$	$\sim E^{\frac{2(4s+st-1)}{5s-1}}$	$\sim E^{\frac{4s+st-1}{4s+1}}$	$\sim E^{\frac{2(4s+st-1)}{7s+2}}$
$Q_p(\bar{\Omega} << \bar{\nu})$	$\sim E^{\frac{2(1-s-st)}{5s-1}}$	$\sim E^{\frac{1-s-st}{4s+1}}$	$\sim E^{\frac{2(1-s-st)}{7s+2}}$
$Q_p(\bar{\Omega} >> \bar{\nu})$	$\sim E^{\frac{2(7s+st-1)}{5s-1}}$	$\sim E^{\frac{7s+st-1}{4s+1}}$	$\sim E^{\frac{2(7s+st-1)}{7s+2}}$

When one uses this table, he must take into account that in parabolic case $Q_p=0$, and the total NE coefficient $Q=Q_e+Q_p=Q_e$, but in strong nonparabolic case $|Q_p| >> |Q_e|$, and $Q \approx Q_p$. For instance, if d-interaction and inequality (49) are satisfied in the semiconductors, pased in the strong magnetic fields $Q \sim E^{7/2}$ for the parabolic, and for the strong nonparabolic spectra.

Under the conditions of strong mutual drag $|\alpha_p| >> |\alpha_e|$, and the total thermoelectric power $\alpha=\alpha_e+\alpha_p \approx \alpha_p$, both in parabolic and nonparabolic cases.

For instance, if inequality (49) is satisfied then $\alpha \sim E^2$, in the parabolic, and $\alpha \sim E^{3/2}$ in the strong nonparabolic cases. From the Table it is seen that for the all cases nonparabolicity of spectrum essentially changes the dependence of α and Q upon E.

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M.M. Babayev, T.M. Qasım

QARŞILIQLI ELEKTRON-FONON SÖVQÜ ŞƏRAİTİNDƏ GÜCLÜ ELEKTRİK SAHƏSİNDƏ YERLƏŞDİRİLMİŞ CIRLAŞMAMIŞ KEYN YARIMKEÇİRİCİLƏRİNDƏ TERMOMAQNİT EFFEKTLƏR

Elektron və fononların qızması və qarşılıqlı sövqü şəraitində cırlaşmamış Keyn yarımkeçiricilərində termoelektrik hərəkət qüvvəsi və Nernst–Ettingshausen effektləri tədqiq edilmişdir. Qöstərilmişdir ki, elektron spektrinin qeyri-parabolikliyi termoelektrik hərəkət qüvvəsinin və Nernst–Ettingshausen əmsalının qiymətlərinə güclü təsir edir və onların elektron temperaturundan, eləcə də qızdırıcı elektrik sahəsinin intensivliyindən asılılıqlarını dəyişdirir. Güclü elektron-fonon qarşılıqlı sövqü şəraitində, elektronlarının spektri parabolik olan yarımkeçiricilərdə Nernst–Ettingshausen əmsalının fonon hissəsi $Q_p=0$ olur, amma qeyri parabolik halda

$Q_p \neq 0$ və Q_p Nernst–Ettingshausen əmsalının elektron hissəsindən (Q_e) xeyli böyük olur, yəni Nernst–Ettingshausen sahəsi, əsasən, fonon hissədən təşkil olunur.

М.М. Бабаев, Т.М. Гасым

ТЕРМОМАГНИТНЫЕ ЭФФЕКТЫ В НЕВЫРОЖДЕННЫХ КЕЙНОВСКИХ ПОЛУПРОВОДНИКАХ, НАХОДЯЩИХСЯ В СИЛЬНОМ ЭЛЕКТРИЧЕСКОМ ПОЛЕ В УСЛОВИЯХ ВЗАИМНОГО УВЛЕЧЕНИЯ ЭЛЕКТРОНОВ И ФОНОНОВ

Исследованы термоэдс и эффекты Нернста-Эттингсгаузена в невырожденных Кейновских полупроводниках, с учетом разогрева электронов и фононов, а также их взаимного увлечения. Показано, что непараболичность спектра электронов значительно влияет на величины термоэдс и коэффициента Нернста-Эттингсгаузена, изменяет их зависимости от электронной температуры, а также от греющего электрического поля. В условиях сильного взаимного увлечения в полупроводниках с параболическим спектром электронов фононная часть коэффициента Нернста-Эттингсгаузена $Q_p=0$, а в непараболическом случае $Q_p \neq 0$ и Q_p значительно больше, чем электронная часть коэффициента Нернста-Эттингсгаузена Q_e, т.е. поле Нернста-Эттингсгаузена, в основном, состоит из фононной части.

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