P.I. Baranskii

ANISOTROPY OF ELECTRON PHONON DRAG THERMOEMF IN *n-Ge*

P.I. Baranskii[1], G.P. Gaidar[2]
([1]V.E. Lashkaryov Institute of Semiconductor Physics, NAS Ukraine, 45, Nauky Ave., Kyiv, 03028, Ukraine; [2]Institute for Nuclear Research, NAS Ukraine, 47, Nauky Ave., Kyiv, 03680, Ukraine)

G.P. Gaidar

• *In this paper, the concentration dependence of the phonon component of electron phonon drag thermoEMF in n-Ge at T = 83 K is studied. In the range of* $9.8\cdot10^{11} \le n_e \le 1.7\cdot10^{15}$ *cm*$^{-3}$ *the concentration dependences of the anisotropy parameter of mobility* $K=K_m/K_\tau=\mu_\perp/\mu_\parallel=f(n_e)$ *and the anisotropy parameter of electron phonon drag thermoEMF* $M=\alpha_\parallel^{ph}/\alpha_\perp^{ph}=f(n_e)$ *are studied, and the relation existing between M, K and phonon components of thermoEMF of samples in the non-deformed and elastically deformed states is established. On n-Ge crystals, in the range of* $1.51\cdot10^{15} \le n_e \le 4.86\cdot10^{17}$ *cm*$^{-3}$*, the concentration dependence of differential thermoEMF* α is obtained (at room temperature)*, and the temperature dependence of* α *in the range from* $[190 \le T \le 370]$ *K is investigated.*

Introduction

Investigations show that studying semiconductors under extreme conditions (in strong quantizing magnetic and electrical fields, at very low temperatures, under high pressures) gives a chance to obtain important information on their properties and characteristics.

Of particular interest are investigations under conditions of a strong uniaxial deformation, since such experiments provide a relatively simple way of changing the most important characteristics of semiconductor crystals in a wide range. For instance, by means of uniaxial compression, many-valley *n-Si* and *n-Ge* can be transferred into one- and two-valley state, which will provide a real opportunity for measuring such characteristics as deformation potentials, anisotropy parameters, etc.

However, it should be noted that in the investigation of semiconductors under strong deformation conditions, wide acceptance has been gained by galvanomagnetic measurements, whereas experimental works dedicated to studying thermoelectric and thermomagnetic effects under such conditions appear rather rarely. Such investigations, especially at low temperatures in the field of electron phonon drag effect, can provide information not only on the energy spectrum structure of carriers and their scattering type, but also on the mechanism of phonon-phonon interaction and, besides, will enable determination of a series of important characteristics and parameters of crystals (effective masses of charge carriers, impurity concentration, the anisotropy parameter of drag thermoEMF, relaxation times of phonon-phonon interaction, etc).

Some information from theory of anisotropic scattering

Physical phenomena caused by motion of charge carriers in semiconductors where the internal and external electrical, magnetic or thermal fields are in effect, are called kinetic phenomena and are described by the Boltzmann equation. In the steady-state case this equation is of the form

$$\left(\frac{\partial n_{\bar{k}}}{\partial t}\right)_{ex.f.} + \left(\frac{\partial n_{\bar{k}}}{\partial t}\right)_{c.} = 0\,,$$

where $n_{\vec{k}}$ is electron distribution function. The first, field term of equation, takes into account a change in electron distribution function under the influence of external fields. The second term allows for a change in distribution function as a result of collision of electrons with electrons, phonons, ionized impurities, etc. For the nondegenerate Maxwell statistics this term can be represented as

$$\left(\frac{\partial n_{\vec{k}}}{\partial t}\right)_{c.} = \sum_{\vec{k}'}\left[W_{\vec{k}\vec{k}'}\, n_{\vec{k}'} - W_{\vec{k}'\vec{k}}\, n_{\vec{k}} \right],$$

where $W_{\vec{k}\vec{k}'}$ is probability of transition at electron scattering in $\vec{k}$ -space per unit time.

Electron scattering as a result of collisions can be both isotropic and anisotropic. Scattering is said to be isotropic, when probability of transition $W_{\vec{k}\vec{k}'}$ depends only on scattering angle (that is, on the angle between vectors $\vec{k}$ and $\vec{k}'$). But if the probability of transition depends not only on scattering angle, but also on the direction of vectors $\vec{k}$ and $\vec{k}'$, such scattering is called anisotropic.

Anisotropic scattering occurs, for instance, in the case of anisotropic energy spectrum of electrons. Thus, at scattering of electrons with the anisotropic energy spectrum (in *n-Ge*), scattering on the impurity centres is strongly anisotropic, though the force field caused by scattering centres has almost spherical symmetry.

Another reason for anisotropic scattering can be the field anisotropy of impurity centre which is observed in uniaxial crystals where the anisotropy of dielectric constant occurs.

At phonon scattering, the reason for scattering anisotropy is the anisotropy of phonon spectrum.

The presence of scattering anisotropy caused by the anisotropy of effective masses and relaxation times is one of the main conditions for the existence in many-valley semiconductors of effects that are missing in isotropic semiconductors. Thus, for example, the Grabner effect [1] is of purely anisotropic nature and its magnitude is defined by the anisotropy parameter *K*.

Thermoelectric effects appear in semiconductors that are in a thermal field, and in the presence of a magnetic field $\vec{H}$ there appear thermomagnetic effects. With temperature gradient ∇T, electron redistribution according to energies takes place in the sample, as a result of which between the sample ends an electric field is created which defines diffusion thermoelectric and thermomagnetic effects.

At low temperatures, the thermoelectric and thermomagnetic effects are of a more complicated type. In this case phonon distribution function differs from the equilibrium one. The presence of temperature gradient leads to the anisotropy of phonon gas distribution which brings about the anisotropy of electron scattering on acoustic lattice vibrations. It is more common that phonons get a pulse towards the cold end, rather than towards the opposite one. Long-wave phonons from the total flux defined by the presence of ∇T interact with charge carriers and transfer a pulse to them preferably in the direction of phonon motion. There is an increase in electrical field (and current, if the circle is closed). Transport phenomena caused by a deviation of phonon distribution from the equilibrium, came to be known as drag effects. At low temperatures, the field of drag effect can be comparable to diffusion thermoelectric field, and in some cases even exceed the latter. The existence of drag effect was first indicated by L.E. Gurevich [2].

The magnitude of drag effect is directly proportional to phonon relaxation time and depends on the relaxation time of electron-phonon interaction. Due to fulfillment of the laws of conservation, carriers interact with long-wave acoustic oscillations. Therefore, electron drag must be more intensive at low temperatures, since in that case long-wave oscillations of atoms are more excited. Moreover,

the anharmonic forces of atomic interaction at long-wave oscillations are less apparent and phonon distribution comes back to equilibrium more slowly. With a rise in temperature, the interference of lattice vibrations grows due to anharmonicity of bonding forces, and a deviation of phonon distribution from equilibrium is reduced, which leads to a reduction of drag effect.

Under sufficiently low temperatures the mean free path of phonons l_{ph} can be comparable to sample dimensions (for *n-Ge* $l_{ph} \sim 0.1$ cm at $n_e \approx 10^{16}$ cm^{-3} and $T \sim 20$ K [3]) which will lead to intensive phonon scattering on its boundaries and a reduction of drag effect. As it follows from [4], in weakly doped semiconductors in the range of very low temperatures (~ 20 K) the process of phonon scattering on the sample boundaries plays a decisive role, whereas in the case of heavily doped semiconductors phonon scattering on crystal boundaries can be neglected.

According to the authors of [5], the role of boundary conditions in the investigation of thermomagnetic effects can be defining (and not only in the calculation of size effects). These conclusions are based on the fact that the presence of sample surface causes temperature inequality of the electron and phonon subsystems, which must lead to gradient nonlinearity and origination of eddy currents, which, in turn, leads to the emergence of odd in $\vec{H}$ additions to a thermomagnetic field.

Drag effect must essentially depend on impurity concentration. On the one hand, with increase in concentration, the number of charge carriers grows, which must lead to increase in drag effect, and on the other hand, phonons will be less intensively scattered on charge carriers and ionized impurities, which must result in electron phonon drag reduction.

Thermoelectric and thermomagnetic effects caused by electron phonon drag appear to be strongly anisotropic. Thus, for instance, thermoEMF anisotropy caused by drag of electrons belonging to the same energy minimum is determined by the anisotropy parameter of the drag thermoEMF $M = \alpha_{\parallel}^{ph} / \alpha_{\perp}^{ph} \neq 1$ (where $\alpha_{\parallel}^{ph}$, $\alpha_{\perp}^{ph}$ are components of the drag thermoEMF tensor), whereas the diffusion component of thermoEMF is isotropic.

The presence of scattering anisotropy ($K \neq 1$) and the anisotropy of drag thermoEMF ($M \neq 1$) accounts for the existence of thermomagnetic effects, the theoretical and experimental investigation of which provides for valuable information on the mechanisms of electron-phonon drag and other important peculiarities of kinetic effects in the region of electron phonon drag.

The following fact is noteworthy. The galvanomagnetic effects are described by electrical resistivity tensor ρ_{ik} establishing a relation between two vectors in a crystal, namely electric field intensity vector and current density vector $E_i = \rho_{ik} j_k$. For components of electrical resistivity tensor the Onsager relation $\rho_{ik}\left(\vec{H}\right) = \rho_{ki}\left(-\vec{H}\right)$ is true. For the components of thermoelectric tensor such a relation is not fulfilled, that is $\alpha_{ik}\left(\vec{H}\right) \neq \alpha_{ki}\left(-\vec{H}\right)$, though the Onsager relation $\alpha_{ik}\left(\vec{H}\right) = \Pi_{ki}\left(\vec{H}\right)/T$ (where Π_{ki} are components of the Peltier tensor) is valid. The presence of magnetic field inversion effect for components of tensor $\hat{\alpha}$ leads to additional peculiarities of thermomagnetic effects in the anisotropic media, as detailed in [1].

Tensothermomagnetic effects

Investigation of thermoelectric and thermomagnetic effects in anisotropic semiconductors under deformation conditions is covered in a restricted number of works, especially experimental, which is related to the complexity of pertinent experimental research.

Work [6] is concerned with the influence of deformation on the thermoelectric properties of many-valley semiconductors. With regard to the effect of redistribution of carriers between the valleys and ignoring the intervalley scattering which according to [7] is small at low temperatures, since there

are no phonons with moments necessary for satisfaction of the law of conservation of moment in the intervalley scattering, the author of [6] by combining the electrical conductivity and thermoEMF tensors obtained an expression valid for any deformation which gives only relative shifts of the energy minima of valleys.

Work [8] studies theoretically and experimentally changes in the Seebeck coefficient at not very large uniaxial deformation in *n-Ge* in the region of drag effect related to changes in electrical resistivity. It is shown that changes in $\Delta\alpha/\alpha$ and $\Delta\rho/\rho$ enable calculation of the anisotropy of phonon component of the Peltier tensor for electrons of the same valley.

Influence of elastic deformations on thermoEMF and thermomagnetic effects in *n-Ge* in the region of drag effect is studied in theoretical works [9, 10] based on the generalized theory of anisotropic scattering with the assumption that intervalley scattering is absent, and deformation affects only the degree of occupancy of different energy minima by carriers. Relaxation times of electron-phonon and phonon-phonon scattering, as well as phonon spectrum in *n-Ge* are taken the same as in a non-deformed crystal. Calculations are made for purely phonon scattering, however, the theory is also valid for impurity scattering. The authors of [9, 10] derived formulae for the calculation of diffusion and phonon components of thermoEMF in the presence of deformation.

In works [9, 11], based on the generalized theory of anisotropic scattering, the thermoEMF tensor is calculated under elastic deformation in arbitrary nonquantizing magnetic field, and it is shown that in the boundary cases of weak and strong fields the phonon component of thermoEMF tensor can be characterized by the anisotropy parameter $M = \alpha_{\parallel}^{ph} / \alpha_{\perp}^{ph}$. However, in arbitrary magnetic fields it is impossible.

A number of works [12 – 14] are dedicated to study of piezo-thermoEMF in *Ge* and *Si* in mixed conduction region. Under deformation of *Ge* in [111] direction at room temperature a redistribution of current carriers occurs between the valleys [7], which leads to a change in thermoEMF and its essential anisotropy.

ThermoEMF under deformation of *n-Ge* crystals in [111] direction

As already mentioned, there is a limited number of works dedicated to study of piezo-thermoEMF in *n-Ge* [8 – 11, 15], as well as experimental works dedicated to study of thermoEMF under uniaxial deformation that transfers semiconductor (for instance, *n-Ge*) from 4-valley into one-valley state.

In work [16], experimental studies of piezo-thermoEMF and magneto-piezo-thermoEMF are performed and the results are compared to calculations made on the basis of anisotropic scattering theory generalized for the case of electron phonon drag.

According to [17], in the case of pure atomic semiconductors, when impurity concentration is small, one can ignore the electron phonon drag and consider that electron and phonon distribution functions are independent. Electrical fields caused by diffusion and electron drag are added in this case [18] and thermoEMF α can be represented as a sum of diffusion (electron) and phonon components:

$$\alpha = \alpha^{e} + \alpha^{ph}. \qquad (1)$$

It should be noted that quantitative estimates made for *Ge* and *Si* in works [4] and [19] show that mutual electron phonon drag can be ignored up to concentrations $n_e \sim 10^{18}$ cm^{-3}.

The thermoEMF tensor $\hat{\alpha}$ under deformation, when ellipsoid axis coincides with deformation direction (X // [111], X is mechanical load on the sample), is of the form

$$\hat{\alpha} = \begin{vmatrix} \alpha_{11} & 0 & 0 \\ 0 & \alpha_{11} & 0 \\ 0 & 0 & \alpha_{33} \end{vmatrix}. \tag{2}$$

Accordingly, here

$$\alpha_{11} = \alpha_{11}^{e} + \alpha_{11}^{ph}, \tag{3}$$

$$\alpha_{33} = \alpha_{33}^{e} + \alpha_{33}^{ph}, \tag{4}$$

where

$$\alpha_{11}^{e} = \frac{k}{e}\left(2 - \xi^{*}\right) + \frac{k}{e}\,\frac{K \ln\frac{N_0}{N_1} + \frac{5K+4}{3}\gamma \ln\frac{N_0}{N_2}}{K + \gamma\frac{5K+4}{3}}, \tag{5}$$

$$\alpha_{11}^{ph} = \alpha_{\perp}^{ph}\,\frac{K + \gamma\frac{5K+\mathrm{M}}{3}}{K + \gamma\frac{5K+4}{3}}, \tag{6}$$

$$\alpha_{33}^{e} = \frac{k}{e}\left(2 - \xi^{*}\right) + \frac{k}{e}\,\frac{\ln\frac{N_0}{N_1} + \gamma\frac{8K+1}{3}\ln\frac{N_0}{N_2}}{1 + \gamma\frac{8K+1}{3}}, \tag{7}$$

$$\alpha_{33}^{ph} = \alpha_{\perp}^{ph}\,\frac{\mathrm{M} + \gamma\frac{8K+\mathrm{M}}{3}}{1 + \gamma\frac{8K+1}{3}}. \tag{8}$$

For an arbitrary mechanical load X (kgf/cm^2, $X < 0$) in the presented expressions

$$\gamma = \frac{N_2}{N_1} = \exp\left(\frac{4}{9}\,\frac{\Xi_u}{kT}\,\mathrm{S}_{44}\,X\right) = \exp\left(0.122\,\frac{X}{T}\right), \tag{9}$$

where N_1 is electron concentration in ellipsoid located on deformation axis; N_2 is electron concentration in each of the three minima that remained ($X < 0$ corresponds to crystal compression, $X > 0$ – to crystal tension);

$$\frac{N_0}{N_1} = \frac{1}{4}\left(1 + 3\exp\left(0.122\,\frac{X}{T}\right)\right);$$

$$\frac{N_0}{N_2} = \frac{1}{4}\left(3 + \exp\left(-0.122\,\frac{X}{T}\right)\right);$$

N_0 is electron concentration in each ellipsoid with no deformation; Ξ_u is shift deformation potential constant; S_{44} is compliance coefficient (for *n-Ge* $S_{44} = 1.46 \cdot 10^{-11}$ Pa^{-1}); $K = \frac{K_m}{K_\tau} = \frac{\mu_\perp}{\mu_\parallel} = \frac{m_\parallel}{m_\perp}\frac{<\tau_\perp>}{<\tau_\parallel>}$ is the anisotropy parameter of mobility in isoenergetic ellipsoid taken individually; $K_m = m_\parallel / m_\perp$ is the anisotropy parameter of effective mass; $m_\parallel$ and $m_\perp$ are cyclotronic effective masses for isoenergetic ellipsoid taken individually along the major axis and perpendicular to it, respectively;

$K_\tau = <\tau_\parallel> / <\tau_\perp>$ is the anisotropy parameter of scattering; $\tau_\parallel$ and $\tau_\perp$ are components of relaxation time tensor in the absence of a magnetic field within the linear approximation; $\mu_\parallel$, $\mu_\perp$ are mobilities of charge carriers along and across the longer axis of isoenergetic ellipsoid, respectively; $k / e = 86$ μV/K; $\xi^* = \xi / kT$ is reduced chemical potential; ξ is chemical potential; $\alpha_\perp^{ph}$ is component of the drag thermoEMF of electrons of one ("*n*"-th) energy minimum with no deformation.

Experimental definition of a relation between *M* and *K*

For the case of arbitrary load (X // ΔT // [111]) the measured value $\alpha = \alpha_{33}$ which, according to (4), is composed of diffusion and phonon components. Having simultaneously solved equations (4) and (7) and having omitted indexes ($_{33}$), we get:

$$\alpha - \alpha^e = \alpha_\perp^{ph} \frac{\mathrm{M} + \gamma \dfrac{8K + \mathrm{M}}{3}}{1 + \gamma \dfrac{8K + 1}{3}}. \tag{10}$$

At $X = 0$ (with no deformation) $\gamma = 1$ and $\alpha = \alpha_0$. At $X \to \infty$ (which corresponds to migration of electrons from four minima to one) $\gamma = 0$ and $\alpha = \alpha_\infty$. Accordingly, for these cases equation (10) can be written as a set of equations [17]:

$$\left.\begin{aligned} \alpha_0^{ph} &= \alpha_0 - \alpha^e = \alpha_\perp^{ph} \frac{2K + \mathrm{M}}{2\mathrm{K} + 1} \\ \alpha_\infty^{ph} &= \alpha_\infty - \alpha^e = \alpha_\perp^{ph} \cdot \mathrm{M} \equiv \alpha_\parallel^{ph} \end{aligned}\right\}, \tag{11}$$

where $\alpha_\parallel^{ph}$, $\alpha_\perp^{ph}$ are phonon components of the drag thermoEMF along and across the longer axis of isoenergetic ellipsoid, respectively; α_0 and α_∞ are thermoEMF values in the non-deformed and deformed samples, respectively; $M = \alpha_\parallel^{ph} / \alpha_\perp^{ph}$ is the anisotropy parameter of the electron phonon drag thermoEMF which is defined by respective components of thermoEMF tensor for electrons belonging to the same energy minimum.

Solving a system of equations (11) with the use of calculated data α^e and experimental values α_0 and α_∞ enables determination of parameters M and $\alpha_\perp^{ph}$. It can be shown [20] that the anisotropy parameter of the drag thermoEMF M is expressed through the anisotropy parameter of mobility K and phonon components of thermoEMF measured in the non-deformed (α_0^{ph}) and elastically deformed crystal (α_∞^{ph}) as follows

$$M = \frac{2K}{(2K+1)\dfrac{\alpha_0 - \alpha^e}{\alpha_\infty - \alpha^e}} = \frac{2K}{(2K+1)\dfrac{\alpha_0^{ph}}{\alpha_\infty^{ph}} - 1}, \tag{12}$$

where $\alpha^e = \dfrac{k}{e}\left[2 + \ln \dfrac{2\left(2\pi m^* kT\right)^{3/2}}{n_0 h^3}\right]$ is electron (diffusion) component of thermoEMF (the Pisarenko formula) [21]; n_0 is charge carrier concentration; e is electron charge; k is the Boltzmann constant; T is temperature; h is the Planck constant; $m^* = N^{2/3} \sqrt[3]{m_\parallel m_\perp^2}$ is the effective mass of density of states; N is the number of isoenergetic ellipsoids.

The values which determine the numerator and denominator of formula (12) in *n-Ge* and *n-Si* are known [22 – 25] to be concentration-dependent. The purpose of this work was to establish information as to the type of dependence of M on charge carrier concentration $n_e \equiv N_i$ (if such dependence exists, of

course) by conducting corresponding experiments and analysis of the results obtained.

Table 1 gives the results of processing the experimental and estimated data for determination of the anisotropy parameter of the drag thermoEMF *M*.

Table 1

The values were measured on n-Ge samples at temperature T = 83 K on condition of X // ∇T // [111] and X ≤ 6000 kgf/cm².

№	n_e, cm^{-3}	α_0^{ph}, μV/K	α_∞^{ph}, μV/K	$\frac{\alpha_0^{ph}}{\alpha_\infty^{ph}}$	α^e, μV/K	$K=\frac{K_m}{K_\tau}$	$M=\frac{\alpha_\parallel^{ph}}{\alpha_\perp^{ph}}$
1	$9.8\cdot10^{11}$	1005	9205	0.109	1395	16.2	12.27
2	$1.6\cdot10^{13}$	921	7921	0.116	1159	16.0	11.3
3	$1.6\cdot10^{13}$	821	7348	0.112	1152	16.0	11.9
4	$6.9\cdot10^{13}$	842	7282	0.115	978	15.4	11.57
5	$1.7\cdot10^{15}$	723	5668	0.127	757	11.4	11.3

The results of processing the data obtained with the use of formula (12) and the data defining the right-hand side of this expression allowed showing for the concentration range $9.8 \cdot 10^{11} \le n_e \equiv N_i \le 1.7 \cdot 10^{15}$ cm^{-3} that at $T \approx 83$ K the anisotropy parameter of the drag thermoEMF $M = \alpha_\parallel^{ph} / \alpha_\perp^{ph}$ measured by piezo-thermoEMF(that is, in the absence of a magnetic field) is virtually concentration-independent, as is seen from Table 1. Though all the components of the right-hand side of formula (12) (namely: K, α_0^{ph}, α_∞^{ph} and even α^e that does not appear in (12) directly, but was used in the system of equations (11) when finding phonon components α_0^{ph} and α_∞^{ph}) are essentially dependent on $n_e \equiv N_i$. Thus, the anisotropy of mobility $K = K_m / K_\tau = \mu_\perp / \mu_\parallel$ with increasing concentration from $9.8\cdot10^{11}$ to $1.7\cdot10^{15}$ cm^{-3} is constantly decreasing (approximately by a factor of 1.42). And parameter of the electron phonon drag M within the accuracy of measurements performed is virtually unchanged and equal to $M = \alpha_\parallel^{ph} / \alpha_\perp^{ph} \cong 11.7 \pm 0.3$ at the temperature of measurement $T = 83$ K. Thus, unlike the anisotropy parameter of mobility K which is formed by combination of electron scattering mechanisms on crystal lattice vibrations and impurity centres, the phonon component of thermoEMF (to be more precise, its anisotropy, that is, the ratio $M = \alpha_\parallel^{ph} / \alpha_\perp^{ph}$) is essentially independent of concentration $n_e \equiv N_i$ (at least, in the investigated limits $9.8\cdot10^{11} \div 1.7\cdot10^{15}$ cm^{-3}) and is completely defined by oscillations of the huge concentration of atoms in crystal lattice sites (~ 10^{22} cm^{-3}).

This remark, certainly, to a large extent concerns other effects related to directed motion of not only electrons (or holes), but also impurity atoms in the presence of thermal field nonuniformities (or directed temperature gradients ∇T) in crystal lattice. Manifestation of effects in question can be most noticeable on placing nonuniformly doped semiconductor devices (with *p-n*-junctions) in a spatially inhomogeneous thermal field.

Of course, avoiding nonuniformly doped semiconductor crystals is impossible in principle, because *p-n*-junctions serve the basis for creation of semiconductor devices. However, it is not only desirable, but necessary to be concerned with the uniformity of thermal fields where such devices are to work for a long time, especially in important units of up-to-date automated systems that are designed for a long-term operation (and, what is more, under sever conditions).

This work was performed with the following assumptions.

1) relation (4) is not violated over the entire investigated concentration range.
2) interminimum scattering in the case of *n-Ge*, unlike *n-Si*, can be ignored. It follows from the fact that within the theory of anisotropic scattering one can describe quantitatively (rather than qualitatively) without account of interminimum scattering such important characteristics and properties of *n-Ge* as:

a) concentration dependence of the anisotropy parameter [26] over a much larger range n_e than the range used in this work;
b) piezo-resistance of *n-Ge* with uniaxial elastic deformation in [111] direction under mixed scattering conditions [27];
в) concentration [28], angular [29] and other dependences of magnetoresistance and the Hall effect not only in weak magnetic fields, but also at $\mu H/c \approx 1$ values.

It should be emphasized that such successful description of different effects by the theory that does not take into account interminimum scattering in *n-Ge* is not related at all to reduced response of investigated effects to this kind of scattering, but is a consequence of inessential interminimum scattering in similar crystals. This is also supported by a comparative study on *n-Si* crystals [30].

Study on the concentration and temperature dependences of differential thermoEMF α in *n-Ge* single crystals

In our work we have studied experimentally the concentration dependence of differential thermoEMF in *n-Ge* crystals in the range of $1.51\cdot10^{15} \le n_e \le 4.86\cdot10^{17}$ cm^{-3} at room temperature. The results (given in Fig. 1) show that with a rise in concentration almost by three orders, differential thermoEMF is reduced less than a factor of 2. It means that differential thermoEMF in *n-Ge* crystals is little sensitive to concentration. Thus, choosing any concentration from said range, one can get differential thermoEMF within ~ 940 ÷ 530 μV/K.

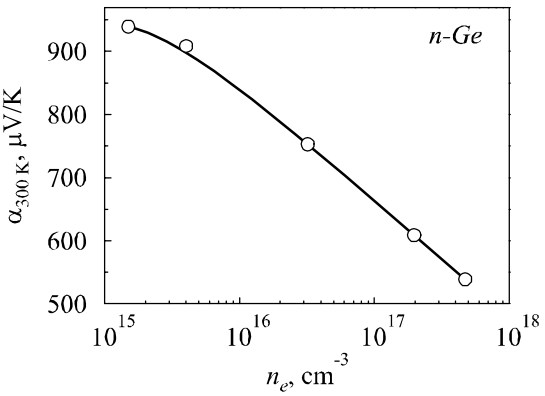

Fig. 1. Dependence of differential thermoEMF α in n-Ge samples on charge carrier concentration n_e at temperature $T \approx 300$ K.

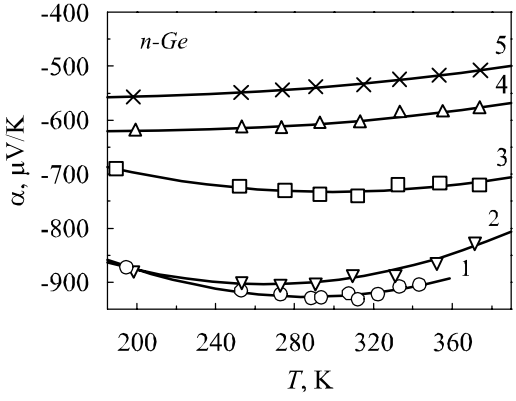

Fig. 2. Temperature dependence of differential thermoEMF α in n-Ge samples at different n_e values: 1 – $1.51\cdot10^{15}$; 2 – $6.2\cdot10^{15}$; 3 – $3.18\cdot10^{16}$; 4 – $2.09\cdot10^{17}$; 5 – $4.86\cdot10^{17}$ cm^{-3}.

On the same samples we have studied changes in the values of differential thermoEMF α versus temperature in the range of [190 ≤ T ≤ 370] K. These changes, as is evident from Fig. 2, proved to be insignificant and even in the samples with a minimum impurity concentration ($n_e = 1.51\cdot10^{15}$ and $6.2\cdot10^{15}$ cm^{-3}) they did not go beyond the limits of 12 ÷ 15%.

Conclusions

1. A system of two equations was used which allowed according to the results of measuring the phonon component of thermoEMF obtained in the experiments with *n-Ge* crystals under ordinary conditions (α_0) and under directed pressure (leading the phonon component to saturation α_∞) to obtain the experimental values of the anisotropy of mobility ($K = \mu_\perp/\mu_\parallel$), as well as the anisotropy parameter of electron phonon drag thermoEMF ($M = \alpha_\parallel^{ph}/\ \alpha_\perp^{ph}$).
2. On *n-Ge* samples in the range of $9.8\cdot10^{11} \le n_e \le 1.7\cdot10^{15}$ cm^{-3} the concentration dependence of the anisotropy parameter of mobility $K = K(n_e \equiv N_i)$ was obtained, and the value of the anisotropy parameter of electron phonon drag thermoEMF $M = \alpha_\parallel^{ph}/\ \alpha_\perp^{ph} = 11.7 \pm 0.3$ was found.
3. In the same concentration range n_e the concentration dependences of the phonon component of thermoEMF were found both under ordinary conditions (α_0^{ph}) and in the elastically deformed *n-Ge* (α_∞^{ph}) samples.
4. The concentration dependence of differential thermoEMF α was obtained on *n-Ge* crystals in the range of $1.51\cdot10^{15} \le n_e \le 4.86\cdot10^{17}$ cm^{-3} at room temperature, and changes in the values of differential thermoEMF α versus temperature were studied in the range of [$190 \le T \le 370$] K.

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