# Electronic properties of multi–phase systems with varying configuration of inclusions

Vladimir V. Shchennikov*[a], Sergey V. Ovsyannikov[a], Grigoriy V. Vorontsov[a], Vsevolod V. Shchennikov Jr[b,c]

[a]Institute of Metal Physics, Russian Academy of Sciences, Urals Division, GSP-170, 18 S.Kovalevskaya Str., Yekaterinburg 620219, Russia, e-mail: vladimir.v@imp.uran.ru

[b]Division of Computer Sciences, Department of Mathematics and Mechanics, Urals State University, 51 Lenin Av., Yekaterinburg 620083, Russia

[c]Institute of Mathematics and Mechanics, Urals Division of Russian Academy of Sciences, GSP-384, 16 S.Kovalevskaya Str., Yekaterinburg 620219, Russia,

## ABSTRACT

Multi-component systems (heterophases, layered, porous, misfit, composite) present the interest for different spheres of science and engineering. The paper covers both theoretical and experimental investigations of such systems with varying concentration and configuration of inclusions. En equations describing the dependence of electronic properties (thermomagnetic and galvanomagnetic as well as electrical and thermoelectric ones) of such systems on concentration and configuration of inclusions are presented. The equations derived may be used for analysis of electronic properties of advanced heterostructures. The above model describing the dependence of electronic properties of multi-component heterophase systems on concentration and configurations of inclusions allows to point out the ways for improving of electronic properties (thermoelectric effectiveness, thermoelectric and thermomagnetic figure of merit, etc.) and for extending of functional possibilities of such systems. So, the approach offered may be used for optimization of properties and for design of microdevices with improved characteristics.

The work was partly supported by the Russian Foundation for Basic Research (RFBR), Gr. No. 01 - 02 – 17203.

**Keywords**: heterostructures, multi-component heterosystems, variable geometrical configuration, diamond probes, thermoelectric power, semiconductor micro-devices, quality control, high pressures, Nernst-Ettingshausen effects.

## 1. INTRODUCTION

The modern ultrahigh pressure technique with diamond anvils allows to test the samples with the sizes about electronic micro-devices ones ~ 10–100mkm [1]. The non-electrical type of investigations (various optics, X-ray, etc) was developed more actively, than electrical ones – electrical resistance [2], thermoelectric power $S$ [3,4] and magnetoresistance (MR) measurements at ultrahigh pressure [5]. The MR-technique at high pressures developed by using of sintered diamond anvils with pressed outputs to a sample [5] was able to test the value of mobility of charge carriers and the variation of scattering mechanism at high pressure phases of HgX (X-Te, Se, S, O) [5]. The similar two-terminal MR-technique have been offered for determination of concentration and mobility of electrons in semiconductor micro-devices (HgCdTe infrared detectors of 100∗50∗8 mkm sizes) [6]. In papers [7-9] the technique of thermomagnetic (TM) measurements have been developed at ultrahigh pressures up to 30 GPa allowing to estimate the mobility of charge carriers and directly to determine the scattering parameter of ones [10]. It seems, that TM measurements are more effective in compare with galvanomagnetic (GM) analogous (Hall effect and MR) [7-11], while the TM testing of micro-samples was absent even at ambient pressure [9].

In the vicinity of phase transitions under pressure applied the materials are the mixture of phases. Varying the value of pressure one may change the concentration and configuration of phase inclusions. So, heterophase structures may serve as a model of real layered fabricated devices, the most properties of which being dependent on the concentration and configuration of phases inclusions [12-14]. The interest to the investigations of these phenomena is connected with proposed application in engineering. Thus, semiconductor-metal phase transitions induced by nanosecond heating and cooling of small regions of the memory cell may be used for nonvolatile memory develop [15]. The approach to a real heterophases structures was developed by the orientated inclusions model with the variable phase configuration , and the calculations of the thermoelectric and galvanomagnetic properties were performed [12,16,17]. But TM properties of heterophase systems weren't considered up to now. The automated setup for simultaneous measurements of electrical, thermal and volumetric properties of thin microsamples at high pressures up to 30 GPa was developed in [13,14,16], and a big amount of semiconductors undergoing the pressure-induced phase transitions were tested by using of one [18-31]. The crystal structure investigations by X-ray, synchrotron and neutron radiation allowed to attribute origin of unusual properties at high pressure to inclusions of phases [32]

The purpose of the present paper was to obtain the mathematical equations for TM and GM effects, including longitudinal and transverse Nernst-Ettingshausen ones, Maggi-Righi-Leduc, and Magnetoresistance for multi-component heterosystems. The equations for thermoelectric effectiveness and figure of merit will be also derived. Such equations will allow to analyze the electronic properties of multi-component systems under the variation of concentration and geometrical configuration of components. Using the equations one can establish the optimal internal parameters (concentration and configuration of components) corresponding to optimal electronic properties, including thermoelectric effectiveness and figure of merit. Thus, the equations may be used for design of multi-component heterosystems for different applications.

## 2. THE MODEL OF CALCULATIONS

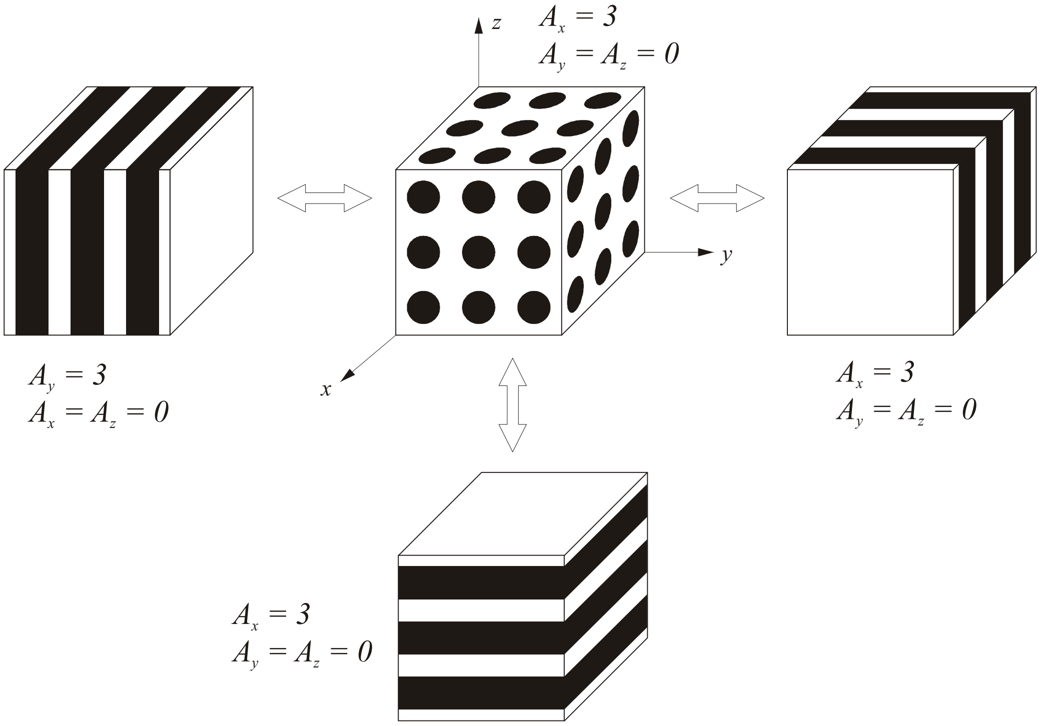


Fig.1. Peculiar cases of materials with various configuration of component's inclusions (planes). The parameters *A* for different cases are given at the figures.

The calculations were performed by using of simple but pictorial model of heterophase system (Fig. 1) [12-14]. Usually characteristics of material determined from experiments are the effective one's (averaged over total volume of substance measured ). These effective properties contain "geometrical" parameters of every phase: concentration, shape, and position of inclusions [33-35]. Effective properties (thermal, magnetic, mechanical [33]) usually are calculated by two main approaches: in the first local properties of system are supposed to be well-known functions of coordinates, in the second one they are considered statistically as random fields. The expressions for effective specific resistance ( $\rho$ ) of multi-component heterosystem were got from the solving a problem of isotropic dielectric ellipsoid in electric field [36]. In book [33] expressions were received for upper and lower bound of effective conductivity of system in cellular model of statistic approach. In cellular model total volume is covered by system of non-overlapping cells in form of ellipsoids. Under the chaos packing of ellipsoids the dependence of bounds on form of inclusions are determined by parameters $G_i$ ( $^1/_9$ =< $G_i$ =< $^1/_3$), which are equal $^1/_9$, $^1/_6$, $^1/_3$ for spherical, needle and disk inclusions respectively. To take into account the manner of ellipsoids packing in this approach two additional parameters ought to be inputted, and in some cases the close values for upper and lower bounds of $\rho$ may be received [33]. But this approach is very difficult because of enormous awkward calculations, so it's using quite seldom. In recent papers [12-14] the approach was developed for multi-component composite materials. Unlike the most previous models [37-39] where the shape of inclusions is fixed, the configuration parameter of phase inclusions in a mentioned one is variable between the extreme limiting cases of parallel and consequent (electrical, thermal) connection. The second novel feature is the considering and comparing of several properties of material simultaneously for the same configuration. The validity of the "geometry" parameters choice obtained for any one feature may be proved or rejected by such combined testing. Effective electrical resisrivity $\rho$ or conductivity $\sigma = 1/\rho$ (and thermal conductivity $\lambda$) in this approach are viewed as a normalized sum of phase contributions in two equivalent considerations of "consequent" and "parallel" electrical (thermal) connection of phases [12-14].

$$\rho = \sum c_i \cdot \rho_i \cdot f_i \cdot (\sum c_i \cdot f_i)^{-1} \qquad \textbf{(4)}$$

$$\sigma = \sum c_i \cdot \sigma_i \cdot f_i(\sigma) \cdot (\sum c_i \cdot f_i(\sigma))^{-1} \qquad \textbf{(5)}$$

where sum of phase concentrations $c_i$ is equal to 1 and configuration parameters along electrical (thermal) current are:

$$f_i = 3\rho / [A\rho + (3-A)\rho_i], \qquad f_i(\sigma) = 3\sigma_i / [A\sigma_i + (3-A)\sigma]. \qquad \textbf{(6)}$$

For constant $A$ equal to 0, 3 and 1 Eqs. 4, 5- coincide respectively with the cases of parallel and consequent electrical connections, and the spherical shape of component inclusions (Fig. 1) [37,38]. Intermediate values of 0 <$A$ < 3 correspond to interpolated configuration of inclusions in the certain direction (like elongated or contracted ellipsoids) (Fig.1).

For two-phase composite Eq. 4 goes to:

$$A \cdot \rho^2 + \rho \cdot [\rho_2 \cdot (3c_1 - A) + \rho_1 (3c_2 - A)] - \rho_1 \cdot \rho_2 \cdot (3 - A) = 0 \qquad \textbf{(7),}$$

and the dependencies of $\rho$ and $\lambda^{-1}$ on $c_i$ are similar to ones of the certain models of ellipsoidal inclusions [35-40]. The dependencies for $\rho(c)$, $\lambda(c)$ obtained for typical cases are shown at Figs. 2,3. By using of the analogy between the electrical, elastic etc. phenomena [41] the similar equations may be obtained for elastic properties. The appropriate equation for $S$ of heterophase materials is:

$$S = (\sum_i S_i \cdot c_i \cdot f_i \cdot (\rho) \cdot \lambda_i^{-1} \cdot f_i(\lambda)) / (\sum_i c_i \cdot f_i \cdot (\rho) \cdot \sum_i c_i \cdot \lambda_i^{-1} \cdot f_i(\lambda)). \qquad \textbf{(8)}$$

In [12,14] the altering equation for $S$ instead of Eq. 5 was obtained by interpolation procedure from limiting cases A=0, 3 and spherical shape of inclusions $A$=1 [42-44].

$$S = (\sum_i S_i \cdot c_i \cdot f_i \cdot (\rho) \cdot \lambda_i^{-1} \cdot f_i(\lambda)) / (\sum_i c_i \cdot f_i \cdot (\rho) \cdot \lambda_i^{-1} \cdot f_i(\lambda)) \qquad \textbf{(9).}$$

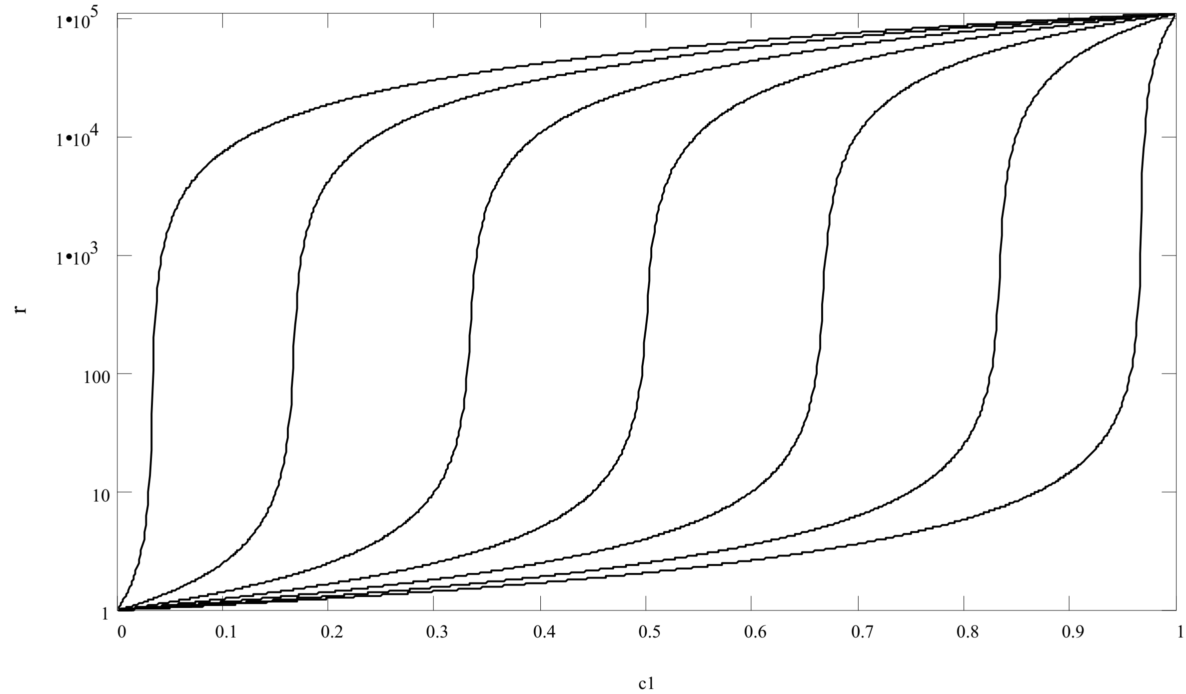


Fig. 2. Calculated dependencies of resistivity $r=\rho(c_1)$ of two-component heterosystem ($\rho_1=10^5$, $\rho_2=1$ a.u.) on concentration of $c_1$ component I. The component I has been taken as low conducting. The parameters $A$ are equal to: ***1*** – 0.1; ***2*** – 0.5; ***3*** – 1.0 (spheres); ***4*** – 1.5; ***5*** – 2.0; ***6*** – 2.5; ***7*** – 2.9.

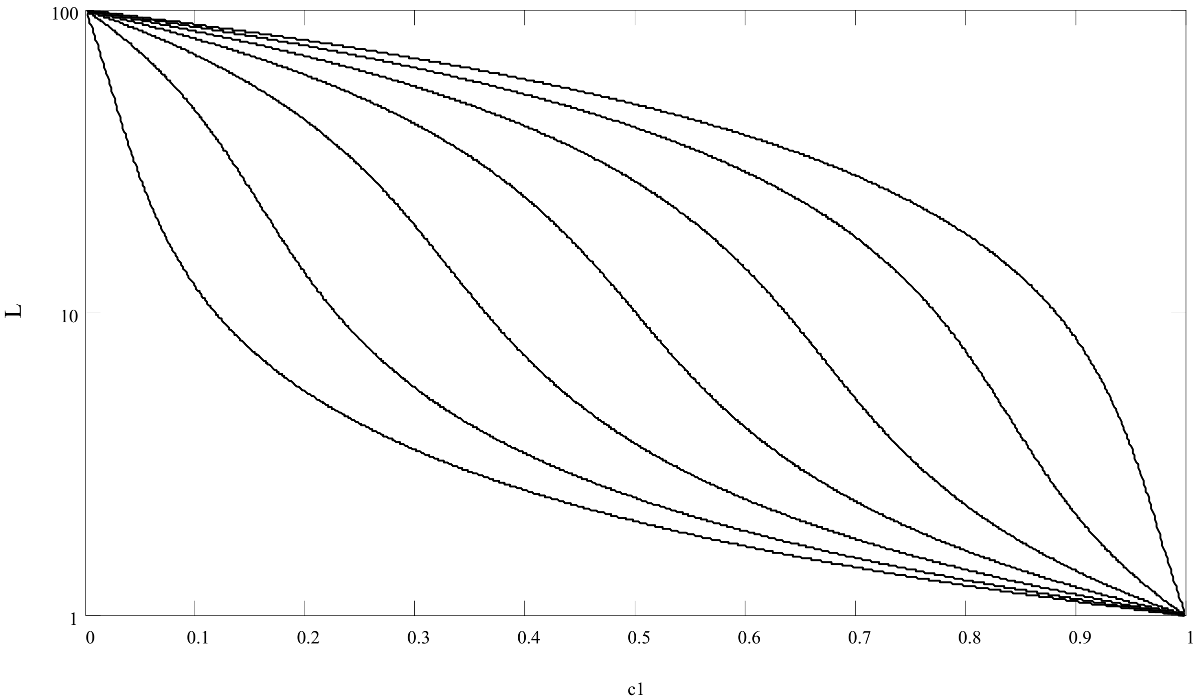


Fig. 3. Calculated dependencies of thermal conductivity $L=\lambda(c_1)$ of two-component heterosystem ( $\lambda_1=1$, $\lambda_2=100$ a.u. ) on concentration $c_1$ of component I. The parameters $A$ are equal to: ***1*** – 0.1; ***2*** – 0.5; ***3*** – 1.0 (spheres); ***4*** – 1.5; ***5*** – 2.0; ***6*** – 2.5; ***7*** – 2.9;

The divergence of Eq.8 and Eq.9 may be revealed only in case $\lambda_1 << \lambda_2$ near the threshold of "insulator" - "metal" transition (Fig. 4), and in particular for $\lambda_1 \to 0$ (porous material). It's interesting to choose ultimately correct version for equation for *S*, but now there are a few experimental data. Corresponding equations for magnetoresistance (MR) and Hall effect (*R*) were considered in [31]. By using the approach above the similar equations were obtained for thermomagnetic Nernst-Ettingshausen effects (in next Section). Based on the above equations, the dependencies of figure of merit as well as thermoelectric effectiveness as functions of variable geometrical configuration and concentration of inclusions (components) were obtained in the present work.

## 3. RESULTS AND DISSCUSSION

All entities in Eq. (8) at $B \neq 0$ – $\rho$ , $\rho_1$ and $\rho_2$, $\lambda_i$, $\lambda_1$ and $\lambda_2$ and $S_1$ and $S_2$ are functions of magnetic field *B*. In thermal conductivities $\lambda_1$ and $\lambda_2$ only electronic part $\lambda_{ie}$ are dependent on *B*, while the lattice contributions $\lambda_{ip}$ are constants:

$$\lambda_i(B) = \lambda_{ie}(B) + \lambda_{ip} \qquad (11).$$

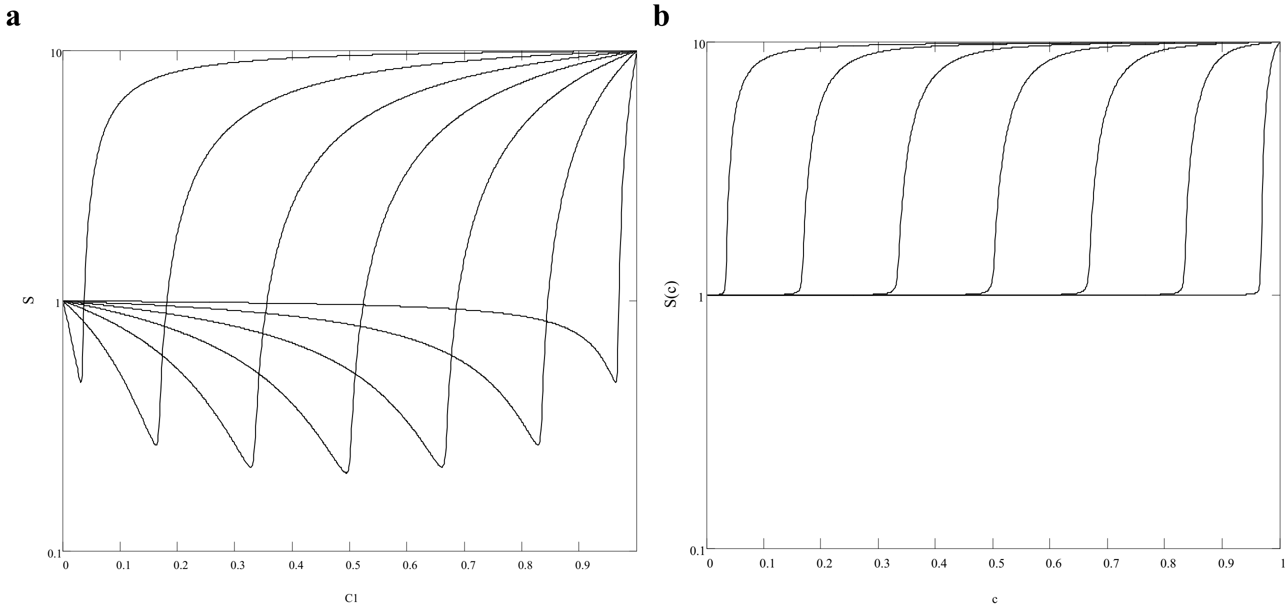


Fig. 4. Calculated dependencies of thermoelectric power $S(c_1)$ of two-component heterosystem ($\lambda_1$=1 $\lambda_2$=100 $\rho_1$=$10^5$ $\rho_2$=1 $S_1$=10 $S_2$=1 a.u.) on concentration $c_1$ of component I. The component I has been taken as low conducting. The parameters *A* are equal to: (***a***): ***1*** – 0.1; ***2*** – 0.5; ***3*** – 1.0; ***4*** – 1.5; ***5*** – 2.0; ***6*** – 2.5; ***7*** – 2.9; (*b*): ***1*** – 0.1; ***2*** – 0.5; ***3*** – 1.0; ***4*** – 1.5; ***5*** – 2.0; ***6*** – 2.5; ***7*** – 2.9;

By exploring the above approach the coefficient of transverse Nernst-Ettinsghausen effect Q for heterophase system was obtained:

$$Q = \frac{\sum_i c_i \cdot Q_i \cdot f_i^T(\lambda) \cdot \lambda_i^{-1} \cdot f_i(\rho)}{\left(\sum_i c_i \cdot \lambda_i^{-1} \cdot f_i^T(\lambda)\right) \cdot \left(\sum_i c_i \cdot f_i^H\right)} \qquad (12),$$

where $f_i^T$ and $f_i^H$ are configuration parameters along the thermal gradient ΔT and along the Hall direction $V_H$ (Fig.2).

In work [12] the approximate Equation for $S$ was obtained (corresponding to Eq. 9) :

$$S = S_2 + (S_1 - S_2)\frac{(\rho\lambda - \rho_2\lambda_2)}{(\rho_1\lambda_1 - \rho_2\lambda_2)} \tag{13}$$

Eq.(13) tends to

$$S(B) = \frac{S_1(B)\big(\rho(B)\lambda(B) - \rho_2(B)\lambda_2(B)\big) - S_2(B)\big(\rho(B)\lambda(B) - \rho_1(B)\lambda_1(B)\big)}{\rho_1(B)\lambda_1(B) - \rho_2(B)\lambda_2(B)} \tag{14}$$

For intrinsic non-degenerate electron gas at low magnetic fields $\mu B$ <1 the dependence of electron part of conductivity is described as folows:

$$\lambda_{ie}(B) = n_i\mu_i\left(r + \frac{5}{2}\right)\frac{k^2T}{e}\left\{1 - a_r(\mu_i^{\ 2}B)\right\} \tag{15}$$

Where $n_i$ the electronics (holes) concentration and $a_r$ the multiplier depending on $r$. For acoustic phonons ($r$ = - 1/2 $a_r$ = 1.6, for charged centers scattering ($r$=3/2), $a_r$ = 2.8 [34]. The thermal conductivity of lattice is usually much more than electronic one, so the variation of $\lambda$ on $B$ may be neglected [10]. By submitting the phase entities as well as "effective entities" $\rho$, $\lambda$ determined by Eq. (4-7) it's possible to calculate the transverse and longitudinal N-E effects for heterophase systems (Eq. 12-14)

It's interesting to compare the behavior of transverse galvanomagnetic Hall effect and the thermomagnetic Nernst-Ettinsghausen effects at the simplest limiting cases. The first interesting case is the stock of layers perpendicular to the thermal gradient the magnetic field is in place of layers (Fig. 1a). The expression for Hall effect and transverse Nernst-Ettinsghausen one are:

$$\begin{gathered} R = \sum R_i C_i \rho_i^{-1}\left(\sum C_i\rho_i^{-1}\right)^{-1} \\ Q = \left(\sum C_i Q_i \lambda_i^{-1}\rho_i^{-1}\right)\cdot\left(\sum C_i\rho_i^{-1}\right)^{-1}\cdot\left(\sum C_i\lambda_i^{-1}\right)^{-1} \end{gathered} \tag{16.a}$$

The second and third limiting cases are the layers along the thermal flow, the magnetic field being perpendicular to layers planes or along (Fig. 1b,c).

$$\begin{gathered} R = \left(\sum C_i R_i \rho_i^{-1}\right)\cdot\left(\sum C_i\rho_i^{-1}\right)^{-1} \\ Q = \sum C_i Q_i \end{gathered} \tag{16.b}$$

and

$$\begin{gathered} R = \left(\sum C_i R_i \rho_i^{-2}\right)\cdot\left(\sum C_i\rho_i^{-1}\right)^{-2} \\ Q = \left(\sum C_i Q_i \rho_i^{-1}\right)\cdot\left(\sum C_i\rho_i^{-1}\right)^{-1} \end{gathered} \tag{16.c}$$

At intermediate case of spherical inclusions ($A^\gamma$=1) the equation for $R$ and $Q$ are the follows:

$$\begin{gathered} R = \left(\sum C_i R_i\left(\frac{1}{\rho + 2\rho_i}\right)^2\right)\cdot\left(\sum C_i\frac{1}{\rho + 2\rho_i}\right)^{-2} \\ Q = \left(\sum C_i Q_i\left(\frac{\rho}{\rho + 2\rho_i}\right)\frac{1}{\lambda_i + 2\lambda}\right)\cdot\left(\sum C_i\frac{1}{\lambda_i + 2\lambda}\right)^{-1}\left(\sum C_i\frac{\rho}{\rho + 2\rho_i}\right)^{-1} \end{gathered} \tag{17}$$

From the Eq.16 the behavior of thermomagnetic and galvanomagnetic effects, namely Hall and N-E under mixing seems rather different. The most difference was seen from Eq. (16.b). By using the equations obtained it's possible to compare the behavior of $R$ and $S$ for the certain substance (HgX, PbX, Te, Se, Si) near the phase transition points, as well as for a certain layered semiconductor micro-devices [45-51]. At Fig. 5 the dependence of $Q$ on composition is shown for various thermal conductivities of components for a certain case ($A$=1). The behavior of $Q(c)$ looks like one of thermoelectric power $S$(see Fig. 4a).

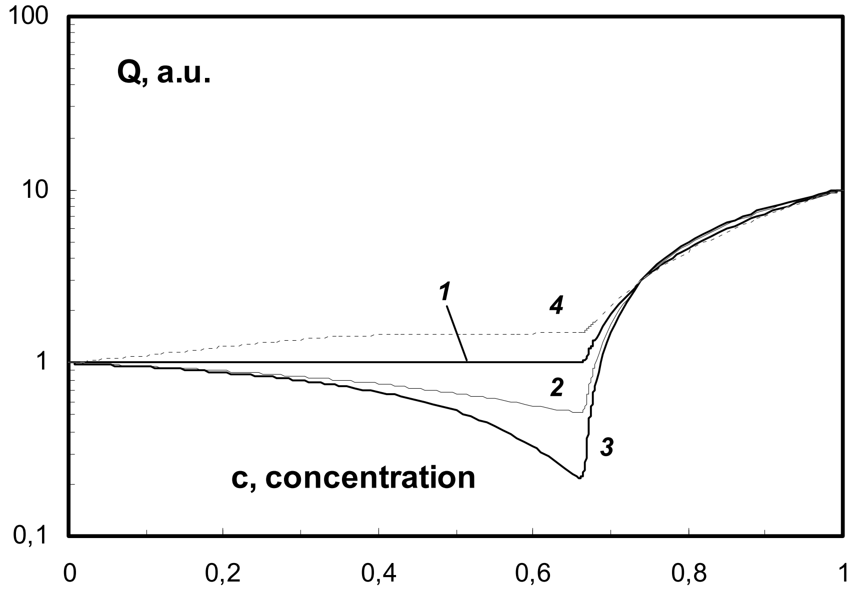


Fig. 5. Dependencies of transverse Nernst–Ettingshausen effect $Q(c)$ of two-component heterosystem ($\rho_1=10^5$, $\rho_2=1$, $S_1=10$, $S_2=1$, $Q_1=10$, $Q_2=1$ a. u.) on concentration of component I. The parameter $A$=1 (spheres). ***1*** – $\lambda_1=1$, $\lambda_2=1$ a. u.; ***2*** – $\lambda_1=1$, $\lambda_2=10$ a. u.; ***3*** – $\lambda_1=1$, $\lambda_2=100$ a. u.; ***4*** – $\lambda_1=1$, $\lambda_2=0.01$ a. u.

Thermoelectric effectiveness ($\alpha$) and thermoelectric figure of merit ($z$) are important thermoelectric parameters of materials depending on resistivity $\rho$, thermal conductivity $\lambda$, and thermoelectric power $S$:

$$\alpha = \frac{S^2}{\rho} \qquad\qquad z = \frac{S^2}{\rho \cdot \lambda} \tag{18}$$

As all entities $\rho$, $\lambda$, $S$ depend on concentration and geometrical configuration of each component of heterosystem, so the thermoelectric effectiveness ($\alpha$) and thermoelectric figure of merit ($Z$) are also functions of components' parameters. We will try to analyze the peculiarities of $\alpha$ and $z$ in example of two-component heterosystem.

The examples given at Figs. 6,7 have shown that thermoelectric effectiveness may have an extremum a certain value of $c$, so the thermoelectric effectiveness of composite can significantly exceed $\alpha$ of each component. In a certain region of concentrations the composite can possess the high values of thermoelectric effectiveness and thermoelectric figure of merit. That is loosing a little in thermoelectric figure of merit on can win greatly in thermoelectric effectiveness. Optimal values of concentration in this case correspond to $A/3$. As we see at Figs. 6, 7 the highest thermoelectric effectiveness will be in case of layered system.

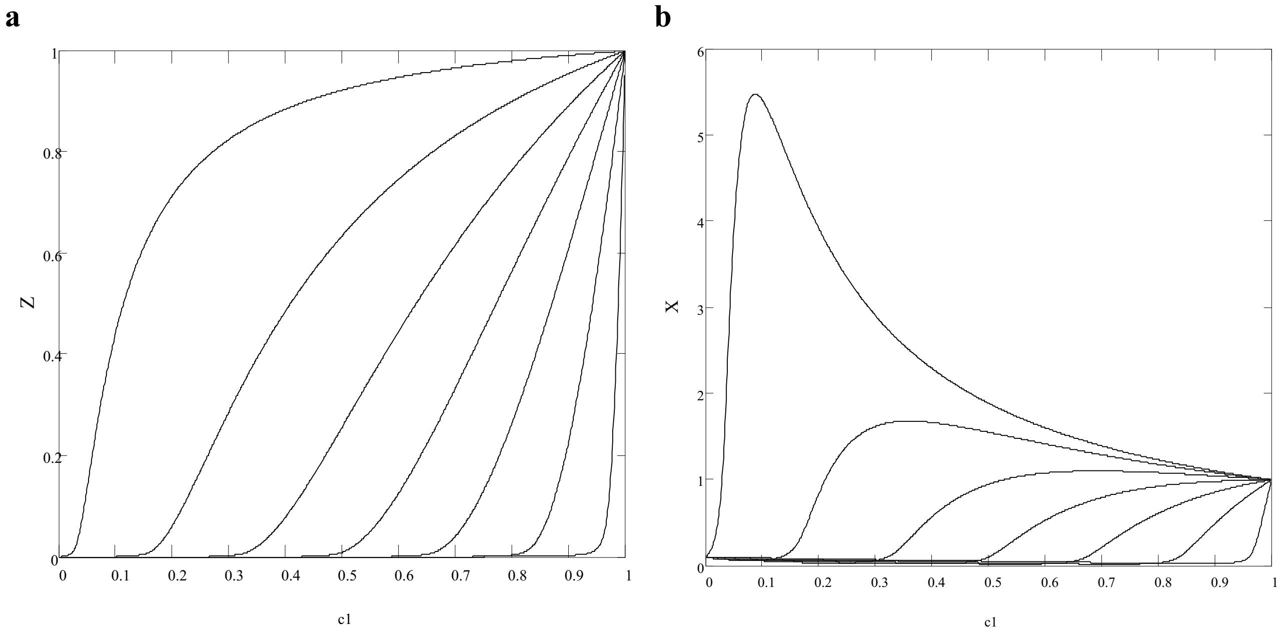


Fig. 6. Dependencies of normalized thermoelectric figure of merit (***a***) and thermoelectric effectiveness (***b***) of two-component heterosystem calculated from Eq. 8 ($\lambda_1$=1, $\lambda_2$=100, $\rho_1$=$10^4$, $\rho_2$=1, $S_1$=100, $S_2$=1 a.u.) on concentration $c_1$ of component I. The component I has been taken as low conducting. The parameters $A$ are equal to: (***a***): ***1*** – 0.1; **2** – 0.5; ***3*** – 1.0 (spheres); ***4*** – 1.5; **5** – 2.0; ***6*** – 2.5; **7** – 2.9; (***b***): ***1*** – 0.1; ***2*** – 0.5; ***3*** – 1.0 (spheres); ***4*** – 1.5; ***5*** – 2.0; ***6*** – 2.5; ***7*** – 2.9;

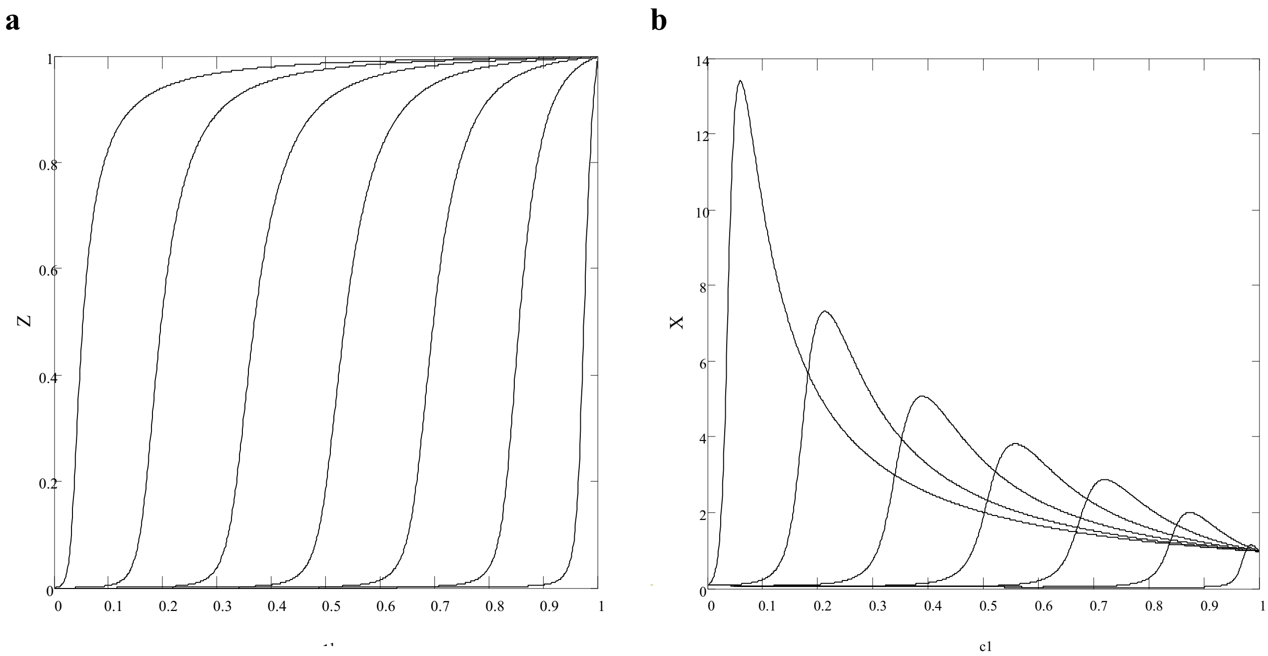


Fig. 7 Dependencies of normalized thermoelectric figure of merit (***a***) and thermoelectric effectiveness (b) $\alpha/\alpha_1$ of two-component heterosystem calculated from Eq. 9. ($\lambda_1$=1, $\lambda_2$=100, $\rho_1$=$10^4$, $\rho_2$=1, $S_1$=100, $S_2$=1 a.u.) on concentration of component I. Parameter $A$: (***a***): ***1*** – 0.1; ***2*** – 0.5; ***3*** – 1.0; ***4*** – 1.5; ***5*** – 2.0; ***6*** – 2.5; ***7*** – 2.9; (***b***): ***1*** – 0.1; ***2*** – 0.5; ***3*** – 1.0; ***4*** – 1.5; ***5*** – 2.0; ***6*** – 2.5; ***7*** – 2.9;

## 4. CONCLUSION

Mathematical approach developed for estimation of effective thermomagnetic properties as well as other electronic ones of composite materials with different orientations of inclusions has shown that complex behavior on concentration and geometrical configuration of components (Figs. 2-7). The equations derived may be used for analysis of heterostructures and micro-devices [6, 11]. Presence of components with peculiar shape in microdevices and microstructures can lead to both positive and negative effects. For example one can improve the heatsink from Integrated Circuits (IC), or improve the thermoelectric effectiveness and thermoelectric and thermomagnetic figures of merit of thermo-transducers. Negative effects may reveal themselves, for example, in appearance of parasitic thermoelectric or thermomagnetic signals in working microdevices. The model developed in the present work is able to account all effects arising due to configuration of components in real microdevices.

## ACKNOWLEDGEMENTS

This work was supported by the Russian Foundation for Basic Research (RFBR), Gr. No. 01-02-17203 and by US Civil Research and Development Foundation, Gr. TGP-599.

## REFERENCES

1. K. Shimizu, K. Suhara, M. Ikumo etc. Lett. Nature, **393**, 767, 1998.
2. S.T. Weir, J. Akella, C.A. Ruddle, Y.K. Vohra, S.A. Catledge. Epitaxial Diamond Encapsulation of Metal Microprobes for High Pressure Experiments. Applied Physics Letters, vol. 77, pp. 3400-3402, 2000.
3. N. Sakai, K. Takemura, K. Tsuji, J. Phys. Soc. Japan, 51, 1811, 1982.
4. I.M. Tsidil'kovskii, V.V. Shchennikov, N.G. Gluzman. Fizika i Technika Poluprovodnikov, vol. 17, pp. 958, 1983.
5. V.V .Shchennikov, Fizika Tverdogo Tela, vol. 35, pp. 401, 1993.
6. J.R. Lowney, W.R. Thurber, D.G. Seiler. Transverse magnetoresistance: A novel two-terminal method for measuring the carrier density and mobility of a semiconductor layer. Applied Physics Letters, vol. 64, No. 22, pp. 3015-3017, 1994.
7. V.V. Shchennikov, S.V. Ovsyannikov. Thermoelectric and galvanomagnetic properties of chalcogens (Te, Se) at high pressure up to 30 GPa. JETP Letters, vol. 74, No. 10, pp. 486-490, 2001.
8. V.V. Shchennikov, S.V. Ovsyannikov. Thermoelectric and galvanomagnetic investigations of VI Group semiconductors Se and Te at high pressure up to 30 GPa. Solid State Communications, vol. 121, No 6-7, pp. 323-327, 2002.
9. S.V. Ovsyannikov, V.V. Shchennikov. Thermo- and galvanomagnetic technique for semiconductors testing at high pressure up 30 GPa. Physica E: Low-dimensional Systems and Nanostructures, vol. 17, pp.546-548, 2003.
10. I.M. Tsidil'kovskii. Thermomagnetic phenomena in semiconductors, State Publ. of Phys.- Math. Lit, Moscow, 1960.
11. S.V. Ovsyannikov, V.V. Shchennikov. Thermo- and galvanomagnetic investigations of semiconductors at high pressure up to 30 GPa. Proceedings of Design, Process Integration and Characterization for Microelectronics, March, 3-8, 2002, Santa Clara, CA, USA, SPIE, vol. 4692, pp. 235-242, 2002.
12. V.V. Shchennikov. ThermoEMF and conductivity of materials in the vicinity of semiconductor – metal phase transition. Fizika Metallov i Metallovedenie 67, N 1, pp. 93-96, 1989.
13. V.V. Shchennikov, A.Yu. Derevskov, V.A Smirnov. Phase transitions registration at high pressure up to 30 GPa., in High Pressure chemical engineering, edited by Ph.Rudolf von Rohr and Ch.Trepp (Elsevier, Amsterdam- - Tokyo), pp. 604-607, 1996.
14. V.V. Shchennikov, A.Yu. Derevskov, V.A. Smirnov. High pressure investigations of conducting materials. Proceedings of SPIE, v. 3213, p. 261 – 268, 1997.
15. G. Wicker, MICRO/MEMS'99 Technical Program, Royal Pines Resort, Queensland, Australia, 27-29 October 1999, p.3.
16. V.V. Shchennikov, A.Yu. Derevskov, V.A. Smirnov. Sintered diamond plungers application for high pressure investigations of conducting materials. in J.L. Davidson et al (Editors) Proceedings of the Fifth International Symposium on Diamond Materials, The Electrochemical Society, Inc., Pennington, NJ, v. 97-32, p. 597, 1997.

17. V.V. Shchennikov. Magnetoresistance of heterophase materials in region of semiconductor – metal transition. Rev. high press. science and tech., vol. 6, p. 686, 1997.
18. V.V. Shchennikov. Magnetoresistance of Iodine at high pressure. Fizika Tverdogo Tela (St.-Peterburg) 38, N 9, pp. 2680-2685, 1996.
19. V.V. Shchennikov, N.P. Gavaleshko, V.M. Frasynyak. Semiconductor – metal transitions in HgMgTe and HgSeS at ultrahigh pressures. Fizika Tverdogo Tela, vol. 35, N 2, pp. 389-394, 1993.
20. V.V. Shchennikov, V.I. Osotov. Magnetoresistance of Selenium at high pressure up to 30 GPa. Fizika Tverdogo Tela, vol. 37, N 2, pp. 448-456, 1995.
21. V.V. Shchennikov. Magnetoresistance and ThermoEMF of Tellurium at high pressure up to 30 GPa. Fizika Tverdogo Tela, vol. 42, N 4, pp. 626-631, 2000.
22. V.V. Shchennikov. Semiconductor – metal transition of some materials at high pressure up to 30 GPa. Phys. stat. sol.(b), 223, N 1-2, pp. 561-565, 2001.
23. V.V. Shchennikov. Magnetoresistance of mercury chalcogenides at ultrahigh pressures. Fizika Tverdogo Tela, vol. 35, N 3, pp. 783-788, 1993.
24. V.V. Shchennikov. Magnetoresistance of methastable high pressure phases. Fizika Tverdogo Tela (St.-Peterburg) 37, N4, pp.1015-1021, 1995.
25. I.M. Tsidil'kovskii, V.V. Shchennikov, N.G. Gluzman. TermoEMF of mercury chalcogenides at ultrahigh pressure. Sov. Phys. Semiconductors, 17, N 5, pp. 604-607, 1983.
26. V.V. Shchennikov, N.G. Gluzman. ThermoEMF of hexagonal mercury selenide. Fizika i technika poluprobodnikov, vol. 15, N 4, pp. 715-717, 1982.
27. V.V. Shchennikov, A.E. Kar'kin, N.P. Gavaleshko, V.M. Frasynyak. Magnetoresistance of HgSeS crystals at hydrostatic pressure up to 1GPa. Fizika Tverdogo Tela, vol. 39, N 10, pp. 1717-1722, 1997.
28. V.V. Shchennikov, A.E. Kar'kin, N.P. Gavaleshko, V.M. Frasynyak. Influence of pressure and anion substitution at electrical properties of HgTeS crystals. Fizika Tverdogo Tela, vol. 42, No. 2, pp. 210-217, 2000.
29. V.V. Shchennikov, N.P. Gavaleshko, V.M. Frasynyak, V.I. Osotov. Phase transition induced by hydrostatic pressure in HgSeS crystals. Fizika Tverdogo Tela, vol. 37, No. 8, pp. 2399-2408, 1995.
30. V.V. Shchennikov, N.P. Gavaleshko, V.M. Frasynyak. Phase transitions in HgTeS crystals at high pressure. Fizika Tverdogo Tela, vol. 37, No. 11, pp. 3532-3535, 1995.
31. V.V. Shchennikov, Magnetoresistance of heterophase materials at high pressure. Anthony J. Toprac, Kim Dang (Editors), Process, Equipment, and Materials Control in Integrated Circuit Manufacturing IV, Proceedings of SPIE, v. 3507, p. 254, 1998.
32. G.A. Samara and H.G. Drickamer. Effect of Pressure on the Resistance of PbS and PbTe. J. Chem. Phys., vol. 37, No. 5, pp. 1159-1160, 1962.
33. B.M. Askerov. Kinetic effects in semiconductors, St.Petersburg: Nauka, 1970.
34. K. Seeger. Semiconductor Physics. Springer-Verlag, Wien-N.Y., 1973.
35. M.D. Beran. The application of statistics theory for definition thermal, electric and magnetic properties of non-uniform materials. In book: J. Sandetski. Mechanics of composite materials, Academic Press, New York and London, pp. 242-286, 1974.
36. G.N. Dul'nev, V.V. Novikov. Transfer processes in inhomogeneous media. Energoatomizdat, Leningrad, p 248, 1991.
37. V.B. Makhov, B.Z. Pevzner. Influence the type of structure at the properties of heterogeneous materials. Izv. AN USSR, Neorganicheskie materialy, vol. 21, No. 9, 1985.
38. L.D. Landau, E.M. Lifshits. Electrodynamics of solid mediums. Moscow: Fizmatgiz. p. 532, 1959.
39. V.I. Odelevskii. Computation of total conductivity of heterophase systems. Zhurnal Technicheskoi Fiziki, vol. 21, No. 6, pp. 667-677, 1951.
40. V.P. Kazantsev. Ellipsoidal anisotropic non-uniformity in conducting anisotropic medium. Zhurnal tekhnicheskoi fiziki, 51, No. 9, pp. 1964-1966, 1981.
41. V. Halpern. The thermopower of binary mixtures. J. Phys. C: Solid State Phys., vol. 16 ,L217, 1983.
42. V.A. Pantyukhin. Effective conductivity of anisotropic mediums with the ellipsoidal inclusions. Zhurnal tekhnicheskoi fiziki, 56, No. 9, pp. 1867-1868, 1986.
43. V.V. Shchennikov, G.L. Shtrapenin. The effective conductivity of heterophase system: influence of geometrical parameters. Rasplavy, vol. 2, No. 6, pp. 103-106, 1990.
44. S.V. Airapetyants. Thermoelectric force and the additional thermocoductivity of statistical mixture. Zhurnal Technicheskoi Fiziki, vol. 27, No. 3, pp. 4478-483, 1957.

45. S.V. Ovsyannikov, V.V. Shchennikov, S.V. Popova, A.Yu. Derevskov. Semiconductor –metal transitions in lead chalcogenides at high pressure. Physica Status Solidi (b), vol. 235, No.2, pp. 521-525, 2003.
46. V.V. Shchennikov, S.V. Ovsyannikov. Thermo- and galvanomagnetic measurements of semiconductors at ultrahigh pressure. Physica Status Solidi (b), vol. 235, No. 2, pp. 288-292, 2003.
47. V.V. Shchennikov, S.V. Ovsyannikov. Thermo- and galvanomagnetic properties of lead chalcogenides at high pressures up to 20 GPa. JETP Letters, vol. 77, No. 1-2, pp. 88-93, 2003.
48. V.V. Shchennikov, S.V. Ovsyannikov. Thermoelectric power, magnetoresistance of lead chalcogenides in the region of phase transitions under pressure. Solid State Communications, vol. 126, No. 7, pp. 373-378, 2003.
49. V.V. Shchennikov, S.V. Ovsyannikov, N.Yu. Frolova. High – pressure study of ternary mercury chalcogenides: phase transitions, mechanical and electrical properties. Journal of Physics D: Applied Physics, vol. 36, No. 16, pp. 2021-2026, 2003.
50. S.V. Ovsyannikov, V.V. Shchennikov. Thermomagnetic and thermoelectric properties of semiconductors (PbTe, PbSe) at ultrahigh pressure. Physica B: Physics of Condensed Matter, in press, 2004.
51. V.V. Shchennikov, S.V. Gudina, A.Misiuk, S.N. Shamin, S.V. Ovsyannikov. Thermoelectric properties of Czochralski-grown Silicon at high pressure up to 16 GPa. European Physical Journal: Applied Physics, in press, 2004.

* e-mail: vladimir.v@imp.uran.ru, Tel: +7 3432 783545