**E.I. Rogacheva,** *doc. phys. - math. Sciences, Professor*
**K.V. Novak, D.S. Orlova**
**O.N. Nashchekina,** *cand. phys. - math. Sciences, Assistant Professort*
**A.Yu. Sipatov,** *doc. phys. - math. Sciences, Professor*
**G.V. Lisachuk,** *doc. techn. Sciences, Professor*

National Technical University "Kharkiv Polytechnic Institute"
2 Kyrpychova Str., Kharkiv, 61002, Ukraine

# SIZE EFFECTS AND THERMOELECTRIC PROPERTIES OF $Bi_{0.98}Sb_{0.02}$ THIN FILMS

*The room-temperature dependences of thermoelectric properties (the Seebeck coefficient S, the electrical conductivity σ, the Hall coefficient RH, and the thermoelectric power factor P = S2·σ) on the thickness (d = 5 - 250 nm) of the $Bi_{0.98}Sb_{0.02}$ solid solution thin films grown on mica substrates by thermal evaporation in vacuum from a single source were obtained. It is shown that the monotonic component of the σ(d) dependence is well described within the framework of the Fuchs-Sondheimer theory for the classical size effect. The presence of an oscillating component in the d-dependences of σ, S, RH and S2·σ is attributed to the manifestation of the quantum size effect, and the experimentally determined period of quantum oscillations Δd = 45 ± 5 nm is in good agreement with the Δd value calculated theoretically within the framework of the model of an infinitely deep potential well. Bibl. 77, Fig. 1.*

**Key words:** $Bi_{0.98}Sb_{0.02}$ solid solution, thin film, thickness, thermoelectric properties, size effect, oscillation period.

## Introduction

$Bi_{1-x}Sb_x$ solid solutuions are well known as effective thermoelectric (TE) materials for refrigerating devices operating at temperatures below ~200 K [1, 2]. The growing interest in $Bi_{1-x}Sb_x$ solutions is due not only to the possibility of their practical use in TE power engineering but also to their unique properties associated with the characteristics of their energy spectrum and the possibility of its qualitative rearrangement with changing composition, accompanied by a number of phase transitions [3-7]. Bi exhibits semimetallic properties: the electron $L_s$ – band and $T$ – band of "heavy" holes overlap. As *Sb* is added to *Bi*, the distance between the electron $L_s$ – band and $L_\alpha$ – band of "light" holes decreases and at $x = 0.023 \div 0.04$ (different authors report different values of $x$), the energy gap between them becomes zero, i.e. a gapless state occurs. With further increase in $x$, the gap between the $L_s$ and $L\alpha$ bands increases again, simultaneously the

overlap of *T* and *Ls* bands decreases, and at $x = 0.06 \div 0.07$, a semimetal – indirect semiconductor phase transition takes place. Then at $x = 0.08 \div 0.09$, the tops of *T* and *Ls* valence bands coincide, and in the range $x \cong 0.09 \div 0.15$ the indirect semiconductor becomes a direct-gap one. In [8-12], it was shown that the concentration-dependent anomalies of the transport properties correspond to the critical compositions associated with electronic phase transitions and the percolation-type transition from dilute to concentrated solid solutions. According to [13,14], electronic phase transitions of such types take place in the $Bi_{1-x}Sb_x$ films.

Recently, interest in the properties of the $Bi_{1-x}Sb_x$ solid solutions has sharply increased after it was found that they exhibit the properties of topological insulators – the newest materials of quantum physics, in which the strong spin-orbit interaction leads to the appearance of topological metallic surface states with a linear Dirac E(k) dispersion [15-17]. The $Bi_{1-x}Sb_x$ solid solution with $x = 0.1$ was the first experimentally discovered 3D-topological insulator [16]. In recent years, after it was established that the best TE materials (including $Bi_{1-x}Sb_x$) belong to the topological insulators class, the possibility of using the unique properties of the topological surface layer to develop fundamentally new ways to increase in TE figure of merit ZT has been discussed.

The development of nanotechnologies and the possibility of enhancing *ZT* in low-dimensional structures [18] have stimulated studies of $Bi_{1-x}Sb_x$ thin-film structures. Besides, using thin films, in which the relative contribution of the metal layer to the conductivity is larger as compared to bulks, is beneficial for studying the properties of the topological layer. However, when studying thin films, it should be taken into account that in the thin-film state the manifestations of classical size effect (CSE) and quantum size effect (QSE) are possible, which can significantly change the properties of films in comparison with bulk crystals [19]. The CSE is caused by diffuse scattering of charge carriers at the film boundaries and manifests itself when the film thickness *d* is comparable to the mean free path *l* of charge carriers. The QSE results from the quantization of the charge carrier energy spectrum and is observed when the value of *d* becomes comparable to the Fermi wavelength, where *h* is Planck's constant, *m** is the effective mass, and EF is the Fermi energy. One of the manifestations of the QSE is an oscillatory behavior of the *d*-dependences of the transport properties. Due to the extremely low *m** value and anomalously high mobility of electrons in *Bi* and *Bi1-xSbx*, these materials are very convenient for studying QSE. It is in thin *Bi* films that the *d*-dependent oscillations of the galvanomagnetic properties were observed for the first time [20] and explained theoretically [21].

After that a very large number of works dealing with size effects in Bi films have appeared (see, e.g. [19,22- 51]. Based on the results of studies of the *d*-dependences of transport properties, some authors [23,27,31,38,39,43,44,49,50] determined *l* and the surface scattering coefficient *p* (the fraction of charge carriers which are specularly reflected from the surface) for *Bi* films using the Fuchs- Sondheimer theory (FST) [52,53] or other methods. It was found that at room temperature in monocrystalline *Bi* films *l* lies in the range of 600-1000 nm, whereas in polycrystalline films $l = 100$ -250 nm, and $p = 0$ - 0.8. The discrepancy in *l* and *p* values obtained

by different authors was apparently connected with the fact that these parameters depend both on the film structure, which in turn is determined by the sample preparation technology, and on the method of *l* and *p* determination.

After the size-dependent oscillations of the kinetic coefficients had observed in *Bi* films in [20], the existence of such oscillations was confirmed in a large number of works [19,22-51] in which the oscillating dependences of electrical resistance ρ, the Hall coefficient RH, Seebeck coefficient *S* and magnetoresistance Δρ/ρ on *d* were also interpreted as a manifestation of the QSE. The oscillation periods Δ*d* determined experimentally for *Bi* thin films by different authors were in the range of 25-45 nm. Some authors [54 – 60] even considered quantum corrections to conductivity, which are the result of quantum interference.

The next step was studying the transport properties of thin films of *Bi1-xSbx* solid solutions [61 – 74] in order to identify CSEs and QSEs. It turned out that, like in *Bi* films, the *d*-dependences of the kinetic properties in *Bi1-xSbx* exhibit CSE. The authors of [65] estimated *l* for epitaxial $Bi_{1-x}Sb_x$ films with *x* in the range of 0 - 0.142 from the *d*-dependences of electron mobility at 4.2 K using the FST theory. According to [65], l varies within the range of 1000 - 6000 nm. The authors of [71, 72] calculated *l* for polycrystalline $Bi_{1-x}Sb_x$ films from the room temperature σ(*d*) and *S*(*d*) dependences under the assumption of total diffuse scattering of carriers (*p* = 0) at *x* = 0.07 [71] and x = 0.12 [72], before and after annealing, and obtained *l* = 60 and 180 nm, *l* = 150 and 230 nm respectively.

The first studies [61 – 63] of the *d*-dependences of σ, *S*, and ρ of $Bi_{1-x}Sb_x$ films confirmed the presence of QSE in $Bi_{1-x}Sb_x$ thin films. The authors of [61,62] investigated the σ(d) and *S*(*d*) dependences at 90 K for polycrystalline $Bi_{1-x}Sb_x$ films ($d \leq 300$ nm) with *x* = 0.018 and 0.035 and found that as compared with *Bi* films Δ*d* increases up to Δ*d* = 70 and 90 nm, respectively. In [63], it was also shown that introduction of a small amount of *Sb* (*x* ~ 0.04) into Bi films with *d* = 420 - 570 nm prepared by thermal evaporation of *Sb* in vacuum and subsequent diffusion annealing, resulted in an increase in Δ*d* from Δ*d* ~ 26 nm for pure *Bi* to Δ*d* ~ 65 nm for *Bi1-xSbx* at 4.2 K. Further more detailed systematic studies of the *d*-dependences (*d* = 400 - 200 nm) of the σ, $R_H$ and Δρ/ρ at 4.2 K, carried out by the authors of [64-68], showed that as x increases to 0.059, Δ*d* increases to ~110 nm, however, further increase in *x* to 0.142 leads to a decrease in Δ*d* down to ~50 nm, which was attributed by the authors of [64-68] to a change in the parameters of the band spectrum of $Bi_{1-x}Sb_x$ under changing composition.

It can be seen that in various studies of the size effects in $Bi_{1-x}Sb_x$ films, films with different compositions, different thicknesses, prepared using different technologies were used and measurements were carried out at different temperatures. Meanwhile, the properties of $Bi_{1-x}Sb_x$ crystals and, to even greater extent, of films are very sensitive to various types of external influences, and therefore the various physical parameters of thin films should be compared for the same temperatures, the same intervals of the studied d's, and the same technologies of the film

preparation. In addition, in the available literature, either CSEs or QSEs were usually investigated, although both types of size effects can manifest themselves simultaneously.

In [73, 74] we reported the observation of oscillations with $\Delta d = 80 \pm 5$ nm [73] and with $\Delta d = 105 \pm 5$ nm [74] in the room-temperature $d$-dependences of σ, $R_H$, $\Delta\rho/\rho$ and $S$ for $Bi_{1-x}Sb_x$ polycrystalline thin films ($d = 5 – 400$ nm) prepared by the thermal evaporation in vacuum of the crystals with $x = 0.045$ and $x = 0.09$ and the subsequent deposition on (111) mica substrates at $T_S = 380 \div 5$ K. The earlier determined at room temperature $\Delta d$ for *Bi* films prepared under similar conditions was ~ 30 nm [46]. Simultaneously in [73,74] we investigated CSE and estimated $l$ using the FST theory as $800 \pm 40$ nm ($x = 0.045$) and as $900 \pm 50$ nm ($x = 0.09$). The value of p practically did not depend on composition and was equal to 0.8. The composition $x = 0.045$ corresponds to the semimetallic state and lies between the critical compositions corresponding to the transition to the gapless state ($x \sim 0.03$) and the transition from the semimetal to an indirect-gap semiconductor ($x \sim 0.06$). The composition $x = 0.09$ corresponds to the direct-gap semiconductor region.

Thus, the compositions of $Bi_{1-x}Sb_x$ films studied in [73, 74] and films of pure *Bi* [46] were prepared and investigated using the same preparation and measurement techniques, and all those compositions lay outside the phase transition regions, whose presence could distort the manifestation of size effects. It was of interest to study under identical conditions thin films obtained from semimetallic *Bi1-xSbx* crystals with compositions between the critical compositions corresponding to the percolation transition ($x \sim 0.01$) and the transition to the gapless state ($x \sim 0.03$). The composition $x = 0.02$ belongs to such compositions.

The purpose of this work is to prepare semimetallic films of various $d$ with composition $x = 0.02$ using the technique similar to described in [46, 73, 74] and by measuring the $d$-dependences of TE characteristics to identify the manifestations of the classical and quantum size effects, estimate the values of $l$, p and $\Delta d$ and compare them with those obtained in [46, 73, 74]

## Results and discussions

The objects of this study are thin films of $Bi_{0.98}Sb_{0.02}$ solid solution with thicknesses $d = 5 – 250$ nm obtained by thermal evaporation in vacuum of $Bi_{0.98}Sb_{0.02}$ polycrystal and subsequent deposition on mica substrates at 380 K. The methods of preparing films, measuring their thickness, characterising the micro- and crystal structure, and measuring the TE properties are similar to those described in [46,73,74].

In Fig. 1,*a,b,c,d*, the dependences of σ, $S$, $R_H$ and TE power factor $P = S^2\sigma$ on d at 300 K are shown. A nonzero conductivity was observed starting from the critical thickness $d_c = 9$ nm, which corresponds to the transition from an island film to a channeled structure. According to earlier electron microscopic studies [46], the $Bi_{1-x}Sb_x$ films grow on mica substrates in an island-like

fashion in the epitaxial orientation (001) $Bi_{1-x}Sb_x$ || (001) mica. *Bi1-xSbx* films on mica represent mosaic single crystals with high-angle twin-type boundaries.

It is seen that all thickness dependences exhibit a distinctly non-monotonic behavior. With increasing film thickness, σ, S and $R_H$ show a tendency to increase. However, along with the general trend to increase with increasing *d*, the kinetic coefficients exhibit an oscillatory behavior, too. For all *d*-dependences one can isolate a monotonic component and oscillatory one. We attribute the presence of the monotonic component to the CSE and the oscillatory component to QSE.

According to the FST of the CSE [52,53], the dependence of electrical conductivity on *d*, provided that $d << l$, is described by the following equation:

$$\frac{\sigma_d}{\sigma_\infty} = \frac{3}{4} \cdot \frac{1+p}{1-p} \cdot \frac{d}{l} \cdot \ln \frac{l}{d}, \qquad (1)$$

where *l* is the mean free path in the bulk material, *p* is the surface scattering coefficient; Δ*d* is the electrical conductivity of a film with thickness *d*; and $\sigma_\infty$ is the conductivity of a bulk crystal. The value of *p* lies between 0 (for entirely diffuse scattering) and 1 (for entirely specular reflection). In the latter case, the CSE will not be observed. The FST assumes that CSE occur when scattering is predominantly diffuse, i.e., at sufficiently low *p* values. It should be noted that the FST adopts a number of simplifiying assumptions: it considers a metal with a spherical Fermi surface and isotropic *l* independent of *d*; *p* is assumed to be constant, i.e. the same for both surfaces, independent of *d*, the angle of incidence on the surface, and electron trajectories. Assuming the value of electrical conductivity for $Bi_{0.98}Sb_{0.02}$ films with a thickness of *d* = 200-300 nm ($\sigma \approx 4000$ (Ohm cm)$^{-1}$) as $\sigma_\infty$ and varying the values of p and *l*, theoretical σ(*d*) dependences were calculated. Comparing the experimental and theoretical Δ(*d*) dependences calculated within the framework of the FST, we established that the best match of the results of theoretical calculations and experimental data was observed for $p = 0.5 \pm 0.05$ and $l = 800 \pm 40$ nm. In Fig. 1,a, the theoretical dependence Δ(*d*) calculated using equation (1) is shown as the dotted line.

In Fig. 1,b, the *S*(*d*) dependence is presented. *S* has the negative sign, like in bulk Bi and $Bi_{0.98}Sb_{0.02}$. With increasing *d*, a tendency to an increase in the magnitude of the *S* values is observed. In Fig. 1,c, the $R_H(d)$ dependence is given. It can be seen that, in contrast to the sign of *S* in films and bulk crystal, the sign of $R_H$ in films turns out to be positive. With increasing *d*, $R_H$ exhibits a tendency to increase in magnitude. The oscillations are even more pronounced than in the σ(*d*) and *S*(*d*) dependences.

The periods of oscillations observed in the dependences of σ, *S*, $R_H$ on *d* are practically the same for all kinetic coefficients, amounting to $\Delta d = 45 \pm 5$ nm.

Using the data for σ and S, the TE power factor was calculated as $P = S^2\sigma$. The behavior of the *P(d)* dependences is similar to that of the σ*(d)* and *S(d)* curves (Fig. 1,*d*). The values of TE

power factor for "thick" films ($d$~200-400 nm) were practically equal to those for bulk $Bi_{0.98}Sb_{0.02}$ crystals, from which the films were obtained.

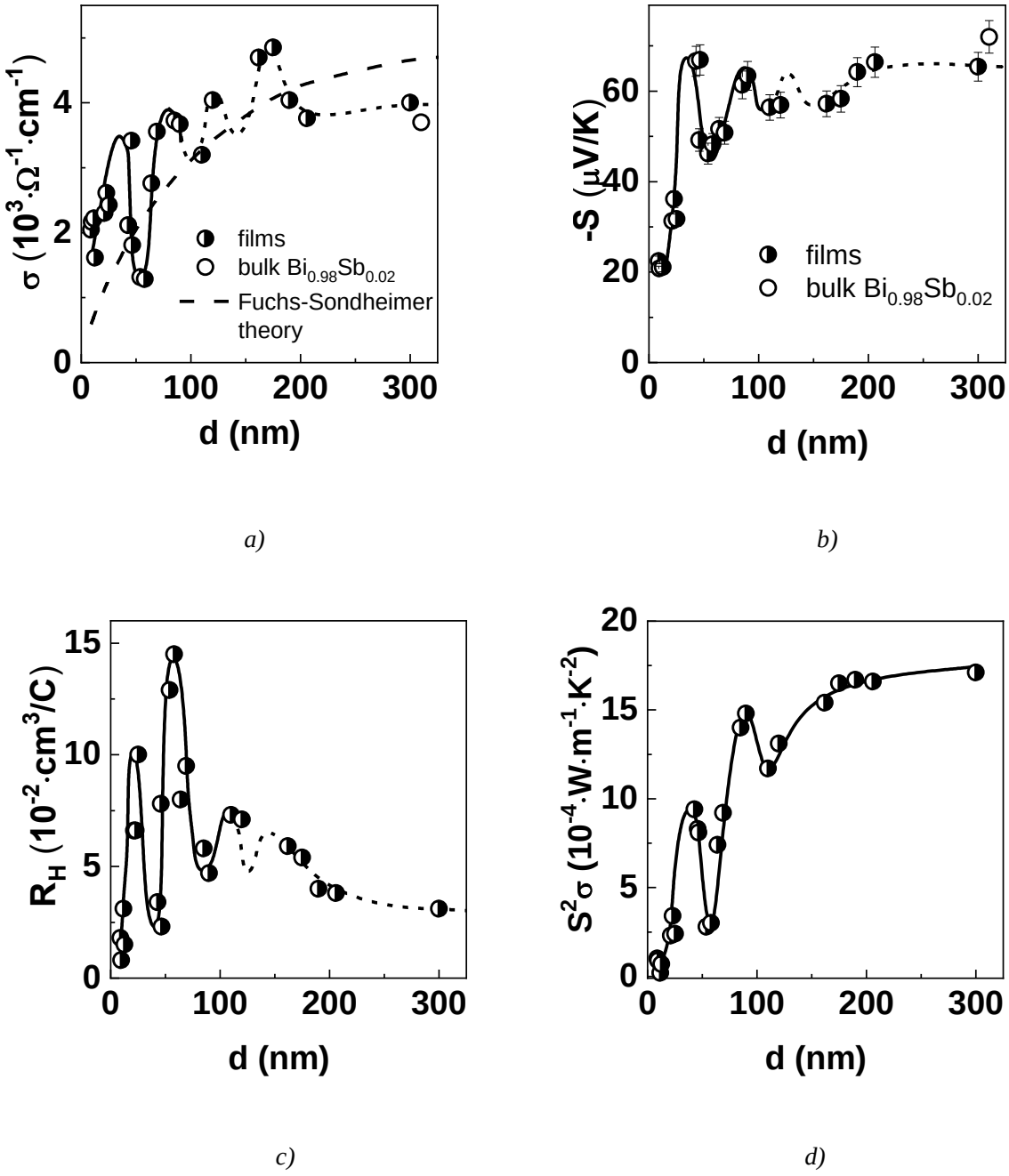


*Fig. 1. Room-temperature dependences of the electrical conductivity σ (a), the Seebeck coefficient S(b), the Hall coefficient $R_H$(c), and the thermoelectric power factor $P = S^2 \sigma$ (d) on $Bi_{0.98}Sb_{0.02}$ thin films thickness d for $Bi_{0.98}Sb_{0.02}$ thin films prepared by thermal evaporation in vacuum on mica substrates.*

In Fig. 1,a the theoretical dependence σ (*d*) calculated using the Fuchs - Sondheimer theory (FST) is shown as a dotted line.

It is natural to assume that the oscillating behavior observed in the *d*-dependences of *σ, R*H, and *S* is the result of size quantization in the $Bi_{0.98}Sb_{0.02}$ thin films. For observing QSEs in polycrystalline films, the formation of texture is required, though the film does not need to be monocrystalline. Due to the axial symmetry of the Bi band structure relative to the trigonal axis, oscillations of the electrical conductivity appear, if the trigonal axes are normal to the film surface in all crystallites.

A thin film of a semimetal is a quantum well, within which the movement of charge carriers is limited in one direction. Such a system is a convenient model object, since its properties are close to the model of a potential well with infinitely high walls. This model is simpler as compared to the finite width and height barrier model. The possibility of the observation of the oscillations in a film grown on an amorphous substrate is explained by the presence of texture in $Bi_{0.98}Sb_{0.02}$ thin films in the direction of electron confinement [19].

Restricting the motion of electrons leads to the quantization of the transverse component of quasimomentum and, accordingly, the energy spectrum. For a barrier of an infinite height, using the effective mass approximation, the energy levels can be presented as:

$$E_n = \frac{\hbar^2}{2m_z^*}\frac{\pi^2}{d^2}n^2 + \frac{\hbar^2 k_x^2}{2m_x^*} + \frac{\hbar^2 k_y^2}{2m_y^*} \qquad (2)$$

where $m_x$*, $m_y$* are the components of the effective mass for motion parallel to the film surface and $m_z$* is the effective mass for motion perpendicular to the film surface, *n* is the discrete quantum number. At fixed *n* values, the energy changes continuously as a function of $\kappa_x$ and $\kappa_y$, corresponding to each subband *n*, and the energy spectrum consists of overlapping subbands. The $Bi_{0.98}Sb_{0.02}$ solid solution is a semimetal with degenerate charge carriers; therefore, the quantization condition for this material can be expressed in terms of the Fermi wavelength and the Fermi energy $E_F$:
Using this approximation, one can estimate the oscillation period Δ*d*:

$$\Delta d = \frac{h}{\sqrt{8m_z^*\varepsilon_F}} \qquad (3)$$

Knowing the effective mass of electrons and the Fermi energy for the *Bi1-xSbx* solid solution with $x = 0.02$ from the literature data [4] for bulk crystals ($m^*x = 0.02 = 0.8\ m^*_{Bi}$, $m^*_{Bi} = 0.012 \pm 0.002\ m_o$ $E_F$ = 22.7 meV) and using equation (3), we calculated the theoretical period of quantum oscillations as Δ*d* = 52 nm. It can be seen that the theoretical value is in good agreement

with the experimentally determined $\Delta d$. It should be noted that although σ, $R_H$ and $S$ were measured independently, in all $d$–dependent studies, distinct oscillations with approximately the same periods were observed for all measured chatracteristics. Comparing the value of $\Delta d$ obtained in this work with the one we obtained earlier for *Bi1-xSbx* films prepared by a similar procedure but with different concentration $x$ [46,73,74], we found that with increasing $x$, $\Delta d$ increases, amounting to 30, 45, 80, and 105 nm for films with $x$ equal to 0, 0.02, 0.045, and 0.1, respectively.

As follows from the data obtained, $R_H$ for all $Bi_{0.98}Sb_{0.02}$films has a positive sign, while $S$ is negative. This difference can be explained by the strong anisotropy of *Bi* single crystals, which also occurs, but to a lesser extent, when *Sb* is introduced into *Bi*. According to [75], in Bi single crystals $R_H$ has a positive sign only in the direction of a trigonal axis, while in the perpendicular directions the $R_H$ sign changes to negative. In contrast to $R_H$, the Seebeck coefficient remains negative in any crystallographic direction [75]. That is why in all Bi films grown along the trigonal axis [001] a positive sign of $R_H$ and a negative sign of $S$ were observed [46]. However, let us note that we observed a change in the sign of $R_H$ with increasing $d$ in films with a high *Sb* content [73, 74] and explained this by the fact that for such samples the perpendicular orientation of the trigonal axis [001] relative to the substrate becomes less perfect. This explanation is confirmed by the results obtained in [29], where in polycrystalline Bi films the $R_H$ sign, as well as the $S$ sign, was negative, since there was no anisotropy in those films and the contribution of the bisector and bipolar components responsible for the negative sign of $R_H$ was predominant. The fact that the positive sign of $R_H$ in $Bi_{0.98}Sb_{0.02}$films was observed for all $d$'s indicates that upon the introduction of a small amount of *Sb* (2 at.%), the degree of texture of the film remains rather high.

It follows from the experimental data obtained in this work that the thickness oscillations of the transport properties of $Bi_{0.98}Sb_{0.02}$ are distinctly manifested even at room temperature, although it is expected that thermal smearing of energy levels increases with increasing temperature and can become comparable to the spacing between the quantized levels. In a number of works on *Bi* and *Bi1-xSbx* films, measurements were carried out at 4.2 K, however, the oscillations did not manifest themselves more clearly. In our works on IV-VI and V2VI3 films (see, for example, [76,77]) we reported that the amplitude of the quantum oscillations in the room temperature thickness dependences is quite large. That is why, perhaps, the weak temperature dependence of the oscillation amplitude is not determined by the specificity of $Bi_{0.98}Sb_{0.02}$ thin films but is common for films of different types and requires theoretical interpretation.

## Conclusions

1. In the room-temperature dependences of the electrical conductivity σ, the Hall coefficient $R_H$, and the Seebeck coefficient $S$ of $Bi_{0.98}Sb_{0.02}$thin films on $d$ ($d$ = 5 - 250 nm), monotonic and oscillating components can be distinguished, which indicates the manifestation of classical and quantum size effects.

2. The monotonic component of is well described within the framework of the Fuchs - Sondheimer theory with the mean free path of electrons $l \approx 800 \pm 40$ nm and the surface scattering coefficient $p \approx 0.5 \pm 0.05$.
3. The experimentally measured period of quantum oscillations ($\Delta d = 45 \pm 5$ nm) is in good agreement with that calculated theoretically within the framework of the model of an infinitly deep potential well. Comparing the value of $\Delta d$ obtained in this work with those obtained earlier for *Bi1-xSbx* films prepared by a similar procedure but with different values of *x*, we found that with increasing *x*, $\Delta d$ increases, amounting to 30, 45, 80, and 105 nm for films with *x* equal to 0, 0.02, 0.045, and 0.1, respectively.
4. In contrast to the previously investigated films with $x = 0.045$ and $x = 0.09$, in which the $R_H$sign depended on the film thickness, in $Bi_{0.98}Sb_{0.02}$films, the $R_H$ sign remained positive for all *d*'s, like in pure *Bi*. At the same time, the sign of *S* was negative. The observed effect is associated with the fact that the sign of $R_H$ is different in different directions and with the increasing degree of texture disorientation under increasing *x*.
5. The room-temperature *d*-dependence of the TE power factor *P* also exhibits an oscillatory behavior. The values of power factor for "thick" films (*d*~200-400 nm) were practically similar to those for bulk $Bi_{0.98}Sb_{0.02}$ crystals, which were used as a charge for thin film preparation.

**Acknowledgements** This work was supported by the Ukrainian Ministry of Education and Science (Project # M 0625).

## References

1. Rowe D.M. (Ed.) (1995). *CRC Handbook of Thermoelectrics*. London, New York, Washington: CRC Press, Boca Raton.
2. Anatychyk L.I. (1979). *Termoelementy i termoelektricheskiie ustroistva. Spravochnik. [Thermoelements and thermoelectric devices. Reference book]*. Kyiv: Naukova dumka [in Russian].
3. Brandt N.B., Chudinov S.M, Karavaev V.G. (1976). Study of a gapless state induced by a magnetic field in bismuth-antimony alloys. *Zh. Eksper. Teor. Fiz*. 70(6), 2296.
4. Brandt N.B.,. Chudinov S.M (1970). Oscillatory effects in semimetallic $Bi_{1-x}Sb_x$ alloys under pressure. *Zh. Eksper. Teor. Fiz*., 59(5), 1494-1507.
5. Oelgart G., Schneider G., Kraak W. (1976). The semiconductor-semimetal transition in $Bi_{1-x}Sb_x$ alloys. *Phys.Stat.Sol*, 74(b), 1976, 75-78.
6. Brandt N.B., Semenov M.V., Falkovsky L.A. (1977). Experiment and theory on the magnetic susceptibility of Bi-Sb alloys. *J. Low Temp. Phys*., 27(1,2), 75-90.

7. Lenoir B., Cassart M., Michenaud J.-P. (1996). Transport properties of Bi-rich Bi-Sb alloys. *J. Phys. Chem. Solids*, 57(1), 89-99.
8. Rogacheva E.I., Drozdova A.A., Nashchekina O.N., Dresselhaus M.S., Dresselhaus G. (2009). Transition into a gapless state and concentration anomalies in the properties of $Bi_{1-x}Sb_x$ solid solutions. *Appl. Phys. Lett*., 94 (20), 202111.
9. Rogacheva E.I., Drozdova A.A., Nashchekina O.N. (2010). Percolation effects in semimetallic Bi-Sb solid solutions. *Phys.Stat. sol*, 207(A), 344–347.
10. Rogacheva E.I., Doroshenko A.N., Drozdova A.A., Nashchekina O.N., Men'shov Yu.V. (2020). Galvanomagnetic properties of polycrystalline $Bi_{1-x}Sb_x$ solid solutions in the concentration range x = 0-0.25. *Functional Materials*, 27(3), 488-496.
11. Rogacheva E.I. and Drozdova A.A. (2006). Thermoelectric properties of polycrystalline Bismuth-Antimony Solid Solutions. *J. Thermoelectricity*, 2, 22-28.
12. Doroshenko A.N., Rogacheva E.I., Drozdova A.A., Martynova K.V., Men'shov Yu.V.(2016). Thermoelectric properties of the polycrystalline Bi1-xSbx solid solutions in the concentration interval x = 0 – 0.25. *J. Thermoelectricity*, 4, 23-36.
13. Rogacheva E.I., Nashchekina O.N., Orlova D.S., Doroshenko A.N., Dresselhaus M.S. (2017). Influence of composition on the thermoelectric properties of Bi1−xSbx thin films. *J. Electronic Mater.* 46(7), 3821-3825.
14. Rogacheva E.I., Doroshenko A.N., Sipatov A.Yu. (2020). Electronic phase transitions in thin Bi1-XSbX films. *J. Thermoelectricity*, 2, 12-24.
15. Fu L., Kane C.L., Mele E.J. (2007). *Phys. Rev. Lett*., 98, 106803.
16. Hsieh D., Qian D., Wray L., Xia Y.,. Hor Y.S, Cava R.J.,. Hasan M.Z. (2008). *Nature*, 452, 970.
17. Hasan M.Z. Kane C.L. (2010). *Rev. Mod. Phys*., 82, 3045.
18. Dresselhaus M.S. , Yu-Ming Lin, Koga T. , Cronin S.B. , Rabin O., Black M.R. , Dresselhaus G. (2001). In *Semiconductors and Semimetals, Recent Trends in Thermoelectric Materials Research* III, USA, San Diego, CA, Academic Press, 2001, 1–121.
19. Komnik Yu.F. (1979). *Fizika metalicheskikh plionok [Physics of metal films]*. Moscow: Atomizdat [In Russian].
20. Ogrin Y.F., Lutsky V.N., Yelinson M.I. (1966). Observation of quantum size effects in thin bismuth films. *Sov. Phys. JETP Lett*., 3, 71-73.
21. Sandomirskii V.B. (1967). *Quantum size effect in semimetal films*. Soviet Phys. JETP, 25(1), 101-106.
22. Duggal P., Rup R., Tripathi P. (1966). Quantum size effect in thin bismuth films. *Appl. Phys. Let*., 9(8), 293-295.
23. Komnik Yu.F., Buchsztab E.I. (1968). Observation of the quantum and classical size effects in polycrystalline thin bismuth films. *Soviet Physics JETP*, 54, 34-37.
24. Traon JJ.Y.le, Combet H.A. (1969). Electrical conductivity and Hall effect in thin layers of

bismuth between 4,2K and 300K. *J. Phys*., 30, 419-426.

25. Thornburg D.D., Wayman C.M. (1969). Quantum and classical size effects in the thermoelectric power of thin bismuth films. *Philos. Magaz.*, 20(167), 1153-1161.
26. Lal A., Duggal V.P. (1970). Thermoelectric power of thin single crystal bismuth films. *Philos. Magaz.*, 22(175), 189-191.
27. Hoffman R.A., Frankl D.R. (1971). Electrical transport properties of thin bismuth films. *Phys. Rev. B.*, 3(6), 1825-1833.
28. Komnik Yu.F., Andrievskii V.V., Buhshtab E.I. (1970). Features of the magnetoresistance of thin bismuth films. *Physics of the Solid State*, 12(11), 3266 – 3269.
29. Petrosyan V.I., Molin V.N., Dagman E.I., Tavger B.A., Skripkina P.A., Aleksandrov L.N. (1971). Features of quantum size effects in thin non-textured polycrystalline bismuth films obtained by the electric flash method. *Fizika Metallov i Metallovedenie*, 32, 725 – 730 [in Russian].
30. Garcia N., Kao Y.H., Strongin M. (1972). Galvanomagnetic studies of bismuth films in the quantum-size-effect region. *Phys. Rev. B.*, 5(6), 2029-2039.
31. Subotowicz M., Jalochowski M., Mikolajczak B, Mikolajczak P. (1973). Measurements of the physical properties of thin Bi films from 180 to 40000 AA. *Phys. Stat. Sol. A*., 17(1), 79-87.
32. Abrasimov V.M., Yegorov B.N., Krykin M.A. (1973).Size effect of kinetic coefficients in polycrystalline bismuth films. *Sov. Phys. JETP*, 37(1), 113-116.
33. Inoue M., Yagi H., Tamaki Y. (1973). Anomalies in the Hall coefficient of bismuth films. Japan. *J. Appl. Phys*., 12, 310.
34. Mikolajczak P., Piasek W., Subotowicz M. (1974). Thermoelectric power in bismuth thin films. *Phys. Stat. Sol. A*., 25(2), 619-628.
35. Borzyak P.G., Vatamanyuk V.I., Kulyupin Yu.A. (1974). Peculiarties of the thickness dependences of the bismuth films structure and resistivity. *Phys. Stat. Sol. A.*, 22, 3-6.
36. Baba S., Sugawara H., Kinbara A. (1976). Electrical resistivity of thin bismuth films. *Thin Solid Films*, 31, 329-335.
37. Bondar E. A., Vatamanyuk V.I., Chumak A.A. (1976). Thickness dependence of the current carrier concentration in bismuth films. *Thin Solid Films*, 34, 387-389.
38. Komnik Yu.F., Andrievsky V.V. (1977). Kinetic properties of electrons in bismuth thin films. *Thin Solid Films*, 42, 1-6.
39. Kochowski S., Opilski A. (1978). Concentration and mobility of charge carriers in thin polycrystalline films of bismuth. *Thin Solid Films*, 48, 345-351.
40. Saleh M., Buxo J., Dorville G., Sarrabayrouse G. (1979). Electrical and elastoresistance properties of evaporated thin films of bismuth. *Revue de Physique Applique*, 14, 405-413.
41. Asahi H., Kinbara A. (1980). Size effect in electrical properties of thin epitaxial bismuth films. *Thin Solid Films*, 66, 131-137.

42. Boxus J., Uher C., Heremans J., Issi J -P. (1981). Size dependence of the transport properties of trigonal bismuth. *Phys. Rev. B*., 23, 449–452.
43. Akhtar S.M., Khawaja E.E. (1985). A study of the resistivity and the. thermoelectric power of thin films of Sb and Bi. *Phys. Stat. Sol. A*., 87, 335-340.
44. Damodara Das V., Soundararajan N. (1987). Size and temperature effects on the Seebeck coefficient of thin bismuth films. *Phys. Rev. B*., 35(12), 5990-5996.
45. Chu H.T., Zhang W. (1992). Quantum size effect and electric conductivity in thin films of pure bismuth. *J. Phys. Chem. Solids*, 53, 1059.
46. Rogacheva E.I., Grigorov S.N., Nashchekina O.N., Lyubchenko S.G., Dresselhaus M.S. (2003). Quantum-size effects in n-type bismuth thin films. *Appl. Phys. Let*., 82(15), 2628-2630.
47. Rogacheva E.I., Lyubchenko S.G., Nashchekina O.N., Meriuts A.V., Dresselhaus M.S. (2009). Quantum size effects and transport phenomena in thin Bi layers. *Microelectronics Journal*, 40, 728-730.
48. Rogacheva E.I., Lyubchenko S.G., Drozdova A.A. (2009). Effect of magnetic field on galvanomagnetic properties of mica/Bi/EuS heterostructures. *Microelectronics Journal*, 40, 821–823.
49. Mustafaev Z., Fraiman B.S., Chudnovskiy A.F. (1971). Thermal conductivity of thin layers of bismuth. *Semiconductors*, 5(1), 242-246 [in Russian].
50. Okun I.Z., Fraiman B.S., Chudnovskiy A.F. (1972). Magnetoresistance of thin bismuth layers. *Semiconductors*, 6(4), 715-717 [in Russian].
51. Burchakova V.I., Gitsu D.V., Kozlovskiy M.I. (1972). Features of thermoelectric power of bismuth thin films. *Physics of the Solid State*, 14(3), 1972, 907-909 [in Russian].
52. Fuchs K. (1938).The conductivity of thin metallic films according to the electron theory of metals *Proc. Cambridge Philos. Soc*., 34, 100-108.
53. Sondheimer E.H. (1952). The mean free path of electrons in metals. *Adv. Phys*., 1(1), 1-42.
54. Savchenko A.K., Lutskiy V.N., Rilik A.S. (1981). About the influence of quantum corrections on the resistance of thin bismuth films. *Sov. Phys. JETP Lett*., 34(6), 367-371.
55. Buhshtab E.I., Komnik Yu.F., Butenko A.V. Andrievskiy V.V. (1982). Features of the magnetoresistance of thin bismuth films in the region of manifestation of quantum corrections. *Sov. J. Low Temp. Phys*., 8(4), 440-445.
56. Komnik Yu.F., Buhshtab E.I., Butenko A.V. Andrievskiy V.V. (1982). Localization effects in bismuth films in a weak magnetic field. Sov. *J. Low Temp. Phys*., 8(12), 1289-1292.
57. Komnik Yu.F., Bukhshtab E.I., Butenko A.V., Andrievsky V.V. (1982). Separation of the electron localization and interaction in bismuth film resistance. *Solid State Communs*., 44(6), 865-867.
58. Fumio Komori, Shun-inhi Kobayashi, Wataru Sasaki (1983). The anti-localization effect in

Bi thin films. *J. Phys. Soc. Japan*, 52(2), 368-371.

59. Woerlee P.H., Verkade G.C., Jansen G.M. (1983). An experimental investigation on weak localisation, spin-orbit and interaction effects in thin bismuth films. *J. Phys. C: Solid State Phys.*, 16, 3011-3024.
60. McLachlan D.S. (1983). Weak-localization, spin-orbit, and electron-electron interaction effects in two- and three-dimensional bismuth films. *Phys. Rev. B.*, 28(12), 6821-6832.
61. Favennec M.M.E., Le Contellec M., Le Traon J.Y. (1972). Study of quantum size effects by elastroresistance, thermoelectric power and conductivity measurements in Bi and $Bi_xSb_{1-x}$. *Thin Solid Films*, 13(1), 73-79.
62. Favennec M.P., Le Contellec M. (1973). Quantum size effects in the thermoelectric power of Bi and $Bi_xSb_{1-x}$ thin films. *Solid State Communs*., 13(2), 141-146.
63. Komnik Yu. F., Bukhshtab E. I., Nikitin Yu. V. (1975). Quantum size effect in bismuth films with antimony adding. *Sov. J. Low Temp. Phys*., 1, 243–246.
64. Bukhshtab E. I., Komnik Yu. F., Nikitin Yu. V. (1978). Electrical properties of thin bismuth-antimony films. I. Changes in the properties with varying composition. *Sov. J. Low Temp. Phys*., 4(8), 474 – 479.
65. Komnik Yu. F., Nikitin Yu. V., Bukhshtab E. I. (1978). Electrical properties of thin bismuth-antimony films. II. Changes in the properties with varying thickness. *Sov. J. Low Temp. Phys*., 4(9), 538 – 544.
66. Komnik Yu. F., Nikitin Yu. V., Bukhshtab E. I. (1878). Electrical properties of thin bismuth-antimony films. III. Quantum size effect. *Sov. J. Low Temp. Phys*., 4(10), 591 – 595.
67. Nikitin Yu. V., Bukhshtab E. I., Komnik Yu. F. Electrical properties of thin bismuth-antimony films. IV. Temperature dependence, Sov. J. Low Temp. Phys., 4(11), 1978. 679 – 684.
68. Komnik Yu. F., Bukhshtab E. I., Nikitin Yu. V. (1978). Specific features of the galvanomagnetic properties of thin films of $Bi_{1-X}Sb_X$ in the semimetal and semiconductor regions. *Thin Solid Films*., 52, 361 – 364.
69. Damodara Das V., Meena N. (1981). Electrical properties of Bi80Sb20 alloy thin films, vacuum-deposited at different substrate temperatures. *J. Mater. Science*, 16(12), 3489–3495.
70. Tang M.Y., Dresselhaus M.S., A band structure phase diagram calculation of 2D BiSb films, Materials research society symposium proceedings, 886, 2006, 129134.
71. Mallik R.C., Damodara Das V. (2005). Study of structural-, and thickness-dependent thermoelectric and electrical properties of $Bi_{93}Sb_7$ alloy thin films. *J. Appl. Phys*. 98, 0237101-0237108.
72. Mallik R.C., Damodara Das V. (2005). Size- and temperature-dependent thermoelectric and electrical properties of $Bi_{88}Sb_{12}$ alloy thin films. *Vacuum*, 77(3), 275-285.
73. Rogacheva E.I., Orlova D.S., Dresselhaus M.S., Tang S. (2011). Size effects in Bi-Sb solid solutions thin films. *MRS Online Proceedings Library*, 1314, 1-6.

74. Rogacheva E.I., Orlova D.S., Nashchekina O.N., Dresselhaus M.S., Tang S. (2012). Thickness dependence oscillations of transport properties in thin films of atopological insulator $Bi_{91}Sb_{9}$. *Appl. Phys. Lett*., 101, 023108(1-4).
75. Michenaud J-P., Issi J-P. (1972). Electron and hole transport in bismuth. *J. Phys. C:Solid State Phys*., 5, 3061-3072.
76. Rogacheva E.I., Nashchekina O.N., Tavrina T.V., Us M.A., Dresselhaus M.S., Cronin S.B., Rabin O. (2003). Quantum size effects in IV-VI quantum wells. *Physica E*, 17, 313-315.
77. Rogacheva E.I., Budnik A.V., Sipatov A.Yu., Nashchekina O.N., Dresselhaus M.S.(2015). Thickness dependent quantum oscillations of transport properties in topological insulator $Bi_2Te_3$ thin films. *Appl. Phys. Lett*. 106, 053103.

Submitted 21.09.2020

**Рогачова О.І.,** *док. фіз.-мат. наук, професор*
**Новак К.В.,Орлова Д.С.,**
**Нащекіна О.М.,** *канд. фіз.-мат. наук, доцент*
**Сіпатов О.Ю.,** *докт. фіз.-мат. наук, професор*
**Лісачук Г.В.** *докт. техн. наук, професор*

Національний технічний університет
«Харківський політехнічний інститут»,
вул. Кирпичова 2., Харків 61002, Україна

## РОЗМІРНІ ЕФЕКТИ ТА ТЕРМОЕЛЕКТРИЧНІ ВЛАСТИВОСТІ ТОНКИХ ПЛІВОК $Bi_{0.98}Sb_{0.02}$

*При кімнатній температурі отримано залежності термоелектричних властивостей (коефіцієнта Зеєбека S, електропровідності σ, коефіцієнта Холла $R_H$ і термоелектричної потужності $P = S^2 \cdot \sigma$) від товщини (d = 5 - 250 нм) тонких плівок твердих розчинів $Bi_{98}Sb_2$, вирощених на підкладках зі слюди методом термічного випаровування у вакуумі із одного джерела. Показано, що монотонна складова залежності σ(d) добре описується в рамках теорії Фукса-Зондгеймера для класичного розмірного ефекту. Виявлена осцилююча складова d-залежностей σ, S, $R_H$ та $S^2 \cdot \sigma$ пов'язується з проявом квантового розмірного ефекту, і визначений експериментально період квантових осциляцій $\Delta d = 45 \pm 5$ нм добре узгоджується зі значенням Δd, теоретично розрахованим в рамках моделі нескінченно глибокої потенційної ями. Бібл. 77, рис. 1.*

**Ключові слова:** $Bi_{0.98}Sb_{0.02}$ твердий разчин, тонка плівка, товщина, термоелектричні властивості,, розмірний ефект, період осциляцій.

**Рогачева Е.И.,** *докт. физ.-мат. наук, профессор*
**Новак К.В., Орлова Д.С.**
**Нащекина О.М.,** *канд. физ.-мат. наук, доцент*
**Сипатов А.Ю.,** *докт. физ.-мат. наук, профессор*
**Лисачук Г.В.,** *докт. техн. наук, профессор*

Национальный Технический Университет
«Харьковский Политехнический Институт»,
ул. Кирпичева, 2, Харьков, 61002, Украина

## РАЗМЕРНЫЕ ЭФФЕКТЫ И ТЕРМОЭЛЕКТРИЧЕСКИЕ СВОЙСТВА ТОНКИХ ПЛЕНОК $Bi_{0.98}Sb_{0.02}$

*При комнатной температуре получены зависимости термоэлектрических свойств (коэффициента Зеебека S, электропроводности σ, коэффициента Холла $R_H$ и термоэлектрической мощности $P=S^2\sigma$) от толщины (d = 5 - 250 nm) тонких пленок твердых растворов $Bi_{98}Sb_2$, выращенных на подложках из слюды методом термического испарения в вакууме из одного источника. Показано, что монотонная составляющая зависимости σ(d) хорошо описывается в рамках теории Фукса-Зондгеймера для классического размерного эффекта. Обнаружена осциллирующая составляющая d-зависимостей σ, S, $R_H$ и $S^2\sigma$ связывается с проявлением квантового размерного эффекта, и определенный экспериментально период квантовых осцилляций $\Delta d = 45 \pm 5$ нм хорошо согласуется со значением Δd, теоретически рассчитанным в рамках модели бесконечно глубокой потенциальной ямы. Библ. 77, рис. 1.*

**Ключевые слова:** $Bi_{0.98}Sb_{0.02}$, твердый раствор, тонкая пленка, толщина, термоэлектрические свойства, размерный эффект, период осцилляций.

## References

1. Rowe D.M. (Ed.) (1995). *CRC Handbook of Thermoelectrics*. London, New York, Washington: CRC Press, Boca Raton.
2. Anatychyk L.I. (1979). *Termoelementy i termoelektricheskiie ustroistva. Spravochnik. [Thermoelements and thermoelectric devices. Reference book]*. Kyiv: Naukova dumka [in Russian].

3. Brandt N.B., Chudinov S.M, Karavaev V.G. (1976). Study of a gapless state induced by a magnetic field in bismuth-antimony alloys. *Zh. Eksper. Teor. Fiz*. 70(6), 2296.
4. Brandt N.B.,. Chudinov S.M (1970). Oscillatory effects in semimetallic $Bi_{1-x}Sb_x$ alloys under pressure. *Zh. Eksper. Teor. Fiz*., 59(5), 1494-1507.
5. Oelgart G., Schneider G., Kraak W. (1976). The semiconductor-semimetal transition in $Bi_{1-x}Sb_x$ alloys. *Phys.Stat.Sol*, 74(b), 1976, 75-78.
6. Brandt N.B., Semenov M.V., Falkovsky L.A. (1977). Experiment and theory on the magnetic susceptibility of Bi-Sb alloys. *J. Low Temp. Phys*., 27(1,2), 75-90.
7. Lenoir B., Cassart M., Michenaud J.-P. (1996). Transport properties of Bi-rich Bi-Sb alloys. *J. Phys. Chem. Solids*, 57(1), 89-99.
8. Rogacheva E.I., Drozdova A.A., Nashchekina O.N., Dresselhaus M.S., Dresselhaus G. (2009). Transition into a gapless state and concentration anomalies in the properties of $Bi_{1-x}Sb_x$ solid solutions. *Appl. Phys. Lett*., 94 (20), 202111.
9. Rogacheva E.I., Drozdova A.A., Nashchekina O.N. (2010). Percolation effects in semimetallic Bi-Sb solid solutions. *Phys.Stat. sol*, 207(A), 344–347.
10. Rogacheva E.I., Doroshenko A.N., Drozdova A.A., Nashchekina O.N., Men'shov Yu.V. (2020). Galvanomagnetic properties of polycrystalline $Bi_{1-x}Sb_x$ solid solutions in the concentration range x = 0-0.25. *Functional Materials*, 27(3), 488-496.
11. Rogacheva E.I. and Drozdova A.A. (2006). Thermoelectric properties of polycrystalline Bismuth-Antimony Solid Solutions. *J. Thermoelectricity*, 2, 22-28.
12. Doroshenko A.N., Rogacheva E.I., Drozdova A.A., Martynova K.V., Men'shov Yu.V.(2016). Thermoelectric properties of the polycrystalline Bi1-xSbx solid solutions in the concentration interval x = 0 – 0.25. *J. Thermoelectricity*, 4, 23-36.
13. Rogacheva E.I., Nashchekina O.N., Orlova D.S., Doroshenko A.N., Dresselhaus M.S. (2017). Influence of composition on the thermoelectric properties of Bi1−xSbx thin films. *J. Electronic Mater.* 46(7), 3821-3825.
14. Rogacheva E.I., Doroshenko A.N., Sipatov A.Yu. (2020). Electronic phase transitions in thin Bi1-XSbX films. *J. Thermoelectricity*, 2, 12-24.
15. Fu L., Kane C.L., Mele E.J. (2007). *Phys. Rev. Lett.*, 98, 106803.
16. Hsieh D., Qian D., Wray L., Xia Y.,. Hor Y.S, Cava R.J.,. Hasan M.Z. (2008). *Nature*, 452, 970.
17. Hasan M.Z. Kane C.L. (2010). *Rev. Mod. Phys*., 82, 3045.
18. Dresselhaus M.S. , Yu-Ming Lin, Koga T. , Cronin S.B. , Rabin O., Black M.R. , Dresselhaus G. (2001). In *Semiconductors and Semimetals, Recent Trends in Thermoelectric Materials Research* III, USA, San Diego, CA, Academic Press, 2001, 1–121.
19. Komnik Yu.F. (1979). *Fizika metalicheskikh plionok [Physics of metal films]*. Moscow: Atomizdat [In Russian].
20. Ogrin Y.F., Lutsky V.N., Yelinson M.I. (1966). Observation of quantum size effects in thin

bismuth films. *Sov. Phys. JETP Lett*., 3, 71-73.

21. Sandomirskii V.B. (1967). *Quantum size effect in semimetal films*. Soviet Phys. JETP, 25(1), 101-106.
22. Duggal P., Rup R., Tripathi P. (1966). Quantum size effect in thin bismuth films. *Appl. Phys. Let*., 9(8), 293-295.
23. Komnik Yu.F., Buchsztab E.I. (1968). Observation of the quantum and classical size effects in polycrystalline thin bismuth films. *Soviet Physics JETP*, 54, 34-37.
24. Traon JJ.Y.le, Combet H.A. (1969). Electrical conductivity and Hall effect in thin layers of bismuth between 4,2K and 300K. *J. Phys*., 30, 419-426.
25. Thornburg D.D., Wayman C.M. (1969). Quantum and classical size effects in the thermoelectric power of thin bismuth films. *Philos. Magaz*., 20(167), 1153-1161.
26. Lal A., Duggal V.P. (1970). Thermoelectric power of thin single crystal bismuth films. *Philos. Magaz*., 22(175), 189-191.
27. Hoffman R.A., Frankl D.R. (1971). Electrical transport properties of thin bismuth films. *Phys. Rev. B.*, 3(6), 1825-1833.
28. Komnik Yu.F., Andrievskii V.V., Buhshtab E.I. (1970). Features of the magnetoresistance of thin bismuth films. *Physics of the Solid State*, 12(11), 3266 – 3269.
29. Petrosyan V.I., Molin V.N., Dagman E.I., Tavger B.A., Skripkina P.A., Aleksandrov L.N. (1971). Features of quantum size effects in thin non-textured polycrystalline bismuth films obtained by the electric flash method. *Fizika Metallov i Metallovedenie*, 32, 725 – 730 [in Russian].
30. Garcia N., Kao Y.H., Strongin M. (1972). Galvanomagnetic studies of bismuth films in the quantum-size-effect region. *Phys. Rev. B*., 5(6), 2029-2039.
31. Subotowicz M., Jalochowski M., Mikolajczak B, Mikolajczak P. (1973). Measurements of the physical properties of thin Bi films from 180 to 40000 AA. *Phys. Stat. Sol. A*., 17(1), 79-87.
32. Abrasimov V.M., Yegorov B.N., Krykin M.A. (1973).Size effect of kinetic coefficients in polycrystalline bismuth films. *Sov. Phys. JETP*, 37(1), 113-116.
33. Inoue M., Yagi H., Tamaki Y. (1973). Anomalies in the Hall coefficient of bismuth films. Japan. *J. Appl. Phys*., 12, 310.
34. Mikolajczak P., Piasek W., Subotowicz M. (1974). Thermoelectric power in bismuth thin films. *Phys. Stat. Sol. A*., 25(2), 619-628.
35. Borzyak P.G., Vatamanyuk V.I., Kulyupin Yu.A. (1974). Peculiarties of the thickness dependences of the bismuth films structure and resistivity. *Phys. Stat. Sol. A*., 22, 3-6.
36. Baba S., Sugawara H., Kinbara A. (1976). Electrical resistivity of thin bismuth films. *Thin Solid Films*, 31, 329-335.
37. Bondar E. A., Vatamanyuk V.I., Chumak A.A. (1976). Thickness dependence of the current carrier concentration in bismuth films. *Thin Solid Films*, 34, 387-389.

38. Komnik Yu.F., Andrievsky V.V. (1977). Kinetic properties of electrons in bismuth thin films. *Thin Solid Films*, 42, 1-6.
39. Kochowski S., Opilski A. (1978). Concentration and mobility of charge carriers in thin polycrystalline films of bismuth. *Thin Solid Films*, 48, 345-351.
40. Saleh M., Buxo J., Dorville G., Sarrabayrouse G. (1979). Electrical and elastoresistance properties of evaporated thin films of bismuth. *Revue de Physique Applique*, 14, 405-413.
41. Asahi H., Kinbara A. (1980). Size effect in electrical properties of thin epitaxial bismuth films. *Thin Solid Films*, 66, 131-137.
42. Boxus J., Uher C., Heremans J., Issi J -P. (1981). Size dependence of the transport properties of trigonal bismuth. *Phys. Rev. B*., 23, 449–452.
43. Akhtar S.M., Khawaja E.E. (1985). A study of the resistivity and the. thermoelectric power of thin films of Sb and Bi. *Phys. Stat. Sol. A*., 87, 335-340.
44. Damodara Das V., Soundararajan N. (1987). Size and temperature effects on the Seebeck coefficient of thin bismuth films. *Phys. Rev. B*., 35(12), 5990-5996.
45. Chu H.T., Zhang W. (1992). Quantum size effect and electric conductivity in thin films of pure bismuth. *J. Phys. Chem. Solids*, 53, 1059.
46. Rogacheva E.I., Grigorov S.N., Nashchekina O.N., Lyubchenko S.G., Dresselhaus M.S. (2003). Quantum-size effects in n-type bismuth thin films. *Appl. Phys. Let*., 82(15), 2628-2630.
47. Rogacheva E.I., Lyubchenko S.G., Nashchekina O.N., Meriuts A.V., Dresselhaus M.S. (2009). Quantum size effects and transport phenomena in thin Bi layers. *Microelectronics Journal*, 40, 728-730.
48. Rogacheva E.I., Lyubchenko S.G., Drozdova A.A. (2009). Effect of magnetic field on galvanomagnetic properties of mica/Bi/EuS heterostructures. *Microelectronics Journal*, 40, 821–823.
49. Mustafaev Z., Fraiman B.S., Chudnovskiy A.F. (1971). Thermal conductivity of thin layers of bismuth. *Semiconductors*, 5(1), 242-246 [in Russian].
50. Okun I.Z., Fraiman B.S., Chudnovskiy A.F. (1972). Magnetoresistance of thin bismuth layers. *Semiconductors*, 6(4), 715-717 [in Russian].
51. Burchakova V.I., Gitsu D.V., Kozlovskiy M.I. (1972). Features of thermoelectric power of bismuth thin films. *Physics of the Solid State*, 14(3), 1972, 907-909 [in Russian].
52. Fuchs K. (1938).The conductivity of thin metallic films according to the electron theory of metals *Proc. Cambridge Philos. Soc*., 34, 100-108.
53. Sondheimer E.H. (1952). The mean free path of electrons in metals. *Adv. Phys*., 1(1), 1-42.
54. Savchenko A.K., Lutskiy V.N., Rilik A.S. (1981). About the influence of quantum corrections on the resistance of thin bismuth films. *Sov. Phys. JETP Lett*., 34(6), 367-371.
55. Buhshtab E.I., Komnik Yu.F., Butenko A.V. Andrievskiy V.V. (1982). Features of the magnetoresistance of thin bismuth films in the region of manifestation of quantum corrections.

*Sov. J. Low Temp. Phys*., 8(4), 440-445.

56. Komnik Yu.F., Buhshtab E.I., Butenko A.V. Andrievskiy V.V. (1982). Localization effects in bismuth films in a weak magnetic field. Sov. *J. Low Temp. Phys*., 8(12), 1289-1292.
57. Komnik Yu.F., Bukhshtab E.I., Butenko A.V., Andrievsky V.V. (1982). Separation of the electron localization and interaction in bismuth film resistance.*Solid State Communs*., 44(6), 865-867.
58. Fumio Komori, Shun-inhi Kobayashi, Wataru Sasaki (1983). The anti-localization effect in Bi thin films. *J. Phys. Soc. Japan*, 52(2), 368-371.
59. Woerlee P.H., Verkade G.C., Jansen G.M. (1983). An experimental investigation on weak localisation, spin-orbit and interaction effects in thin bismuth films. *J. Phys. C: Solid State Phys.*, 16, 3011-3024.
60. McLachlan D.S. (1983). Weak-localization, spin-orbit, and electron-electron interaction effects in two- and three-dimensional bismuth films. *Phys. Rev. B*., 28(12), 6821-6832.
61. Favennec M.M.E., Le Contellec M., Le Traon J.Y. (1972). Study of quantum size effects by elastroresistance, thermoelectric power and conductivity measurements in Bi and $Bi_xSb_{1-x}$. *Thin Solid Films*, 13(1), 73-79.
62. Favennec M.P., Le Contellec M. (1973). Quantum size effects in the thermoelectric power of Bi and $Bi_xSb_{1-x}$ thin films. *Solid State Communs*., 13(2), 141-146.
63. Komnik Yu. F., Bukhshtab E. I., Nikitin Yu. V. (1975). Quantum size effect in bismuth films with antimony adding. *Sov. J. Low Temp. Phys*., 1, 243–246.
64. Bukhshtab E. I., Komnik Yu. F., Nikitin Yu. V. (1978). Electrical properties of thin bismuth-antimony films. I. Changes in the properties with varying composition. *Sov. J. Low Temp. Phys*., 4(8), 474 – 479.
65. Komnik Yu. F., Nikitin Yu. V., Bukhshtab E. I. (1978). Electrical properties of thin bismuth-antimony films. II. Changes in the properties with varying thickness. *Sov. J. Low Temp. Phys*., 4(9), 538 – 544.
66. Komnik Yu. F., Nikitin Yu. V., Bukhshtab E. I. (1878). Electrical properties of thin bismuth-antimony films. III. Quantum size effect. *Sov. J. Low Temp. Phys*., 4(10), 591 – 595.
67. Nikitin Yu. V., Bukhshtab E. I., Komnik Yu. F. Electrical properties of thin bismuth-antimony films. IV. Temperature dependence, Sov. J. Low Temp. Phys., 4(11), 1978. 679 – 684.
68. Komnik Yu. F., Bukhshtab E. I., Nikitin Yu. V. (1978). Specific features of the galvanomagnetic properties of thin films of $Bi_{1-X}Sb_X$ in the semimetal and semiconductor regions. *Thin Solid Films*., 52, 361 – 364.
69. Damodara Das V., Meena N. (1981). Electrical properties of Bi80Sb20 alloy thin films, vacuum-deposited at different substrate temperatures. *J. Mater. Science*, 16(12), 3489–3495.
70. Tang M.Y., Dresselhaus M.S., A band structure phase diagram calculation of 2D BiSb films, Materials research society symposium proceedings, 886, 2006, 129134.

71. Mallik R.C., Damodara Das V. (2005). Study of structural-, and thickness-dependent thermoelectric and electrical properties of $Bi_{93}Sb_7$ alloy thin films. *J. Appl. Phys*. 98, 0237101-0237108.
72. Mallik R.C., Damodara Das V. (2005). Size- and temperature-dependent thermoelectric and electrical properties of $Bi_{88}Sb_{12}$ alloy thin films. *Vacuum*, 77(3), 275-285.
73. Rogacheva E.I., Orlova D.S., Dresselhaus M.S., Tang S. (2011). Size effects in Bi-Sb solid solutions thin films. *MRS Online Proceedings Library*, 1314, 1-6.
74. Rogacheva E.I., Orlova D.S., Nashchekina O.N., Dresselhaus M.S., Tang S. (2012). Thickness dependence oscillations of transport properties in thin films of atopological insulator $Bi_{91}Sb_{9.}$ *Appl. Phys. Lett*., 101, 023108(1-4).
75. Michenaud J-P., Issi J-P. (1972). Electron and hole transport in bismuth. *J. Phys. C:Solid State Phys*., 5, 3061-3072.
76. Rogacheva E.I., Nashchekina O.N., Tavrina T.V., Us M.A., Dresselhaus M.S., Cronin S.B., Rabin O. (2003). Quantum size effects in IV-VI quantum wells. *Physica E*, 17, 313-315.
77. Rogacheva E.I., Budnik A.V., Sipatov A.Yu., Nashchekina O.N., Dresselhaus M.S.(2015). Thickness dependent quantum oscillations of transport properties in topological insulator $Bi_2Te_3$ thin films. *Appl. Phys. Lett*. 106, 053103.

Submitted 21.09.2020