ISSN 1027-5495. Functional Materials, 27, No.3 (2020), p. 488-496.
doi:https://doi.org/10.15407/fm27.03.488 

# Galvanomagnetic properties of polycrystalline $Bi_{1-x}Sb_x$ solid solutions in the concentration range $x = 0–0.25$

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*Received June 22, 2020*

The dependences of the Hall coefficient, electrical conductivity, magnetoresistance, electron and hole concentration and mobility on the $Bi_{1-x}Sb_x$ solid solution composition in the concentration range $x = 0–0.25$ at 77 and 300 K in magnetic fields 1 T and 0.05 T were obtained. It was shown that all the dependences exhibit a distinct nonmonotonic oscillating behavior at both temperatures and in both magnetic fields. The presence of concentration-dependent anomalies of galvanomagnetic properties is attributed to critical phenomena accompanying the percolation-type transition from dilute to concentrated solid solutions and electronic phase transitions: a transition to a gapless state, the semimetal — semiconductor transition, and indirect — direct band gap semiconductor transition.

**Keywords**: Composition, temperature, magnetic field, Hall coefficient, electrical conductivity, magnetoresistance, charge carrier mobility, percolation, electronic phase transition.

**Гальваномагнітні властивості полікристалічних $Bi_{1-x}Sb_x$ твердих розчинів у діапазоні концентрацій $x = 0–0,25$.** *Е.І.Рогачова, А.Н.Дорошенко, А.А.Дроздова, О.Н.Нащекіна, Ю.В.Меньшов*

Одержано залежності коефіцієнта Холла, електропровідності, магнетоопору, концентрації та рухливості електронів і дірок від складу твердого розчину $Bi_{1-x}Sb_x$ у концентраційному інтервалі $x = 0–0.25$ при температурах 77 та 300 К у магнітних полях 1 Тл та 0.05 Тл. Показано, що усі залежності мають чітко виражений немонотонний осцилюючий характер як при різних температурах, так і при різних магнітних полях. Наявність концентраційних аномалій гальваномагнітних властивостей пов'язується із критичними явищами, що супроводжують перколяційний перехід і електронні фазові переходи у безщілинний стан, напівметал — напівпровідник, непрямозонний — прямозонний напівпровідник.

Получены зависимости коэффициента Холла, электропроводности, магнетосопротивления, концентрации и подвижности электронов и дырок от состава твердого раствора $Bi_{1-x}Sb_x$ в концентрационном интервале $x = 0–0.25$ при температурах 77 и 300 К и в магнитных полях 1 Тл и 0.05 Тл. Показано, что все зависимости имеют отчетливо выраженный немонотонный осциллирующий характер как при различных температурах, так и при различных магнитных полях. Наличие концентрационных аномалий гальваномагнитных свойств связывается с критическими явлениями, сопровождающими перколяционный переход и электронные фазовые переходы в бесщелевое состояние, полуметалл — полупроводник, непрямозонный — прямозонный полупроводники.

## 1. Introduction

$Bi_{1-x}Sb_x$ solid solutions between two semimetals — Bi and Sb — keep attracting the interest of researchers due to new physical effects discovered in them, which are important not only from a purely scientific point of view, but also from the point of view of their practical use in various fields of science and technology. $Bi_{1-x}Sb_x$ are among the best thermoelectric materials operating at temperatures below 150–200 K [1, 2]. Recently, the interest in studying the properties of $Bi_{1-x}Sb_x$ crystals and thin films has increased due to the observation of the special properties characteristic of 3D-topological insulators in $Bi_{1-x}Sb_x$ [3–5] and assumptions about the possibility of using these properties to create efficient spintronic and TE materials [3–6].

The similarity of both crystalline and electronic structures of Bi and Sb [7] accounts for their unlimited solubility in each other and the formation of a continuous series of solid solutions. This makes it possible to study the effect of the composition on the crystal structure, energy spectrum, and physical properties of solid solutions in more detail over a wide concentration range. In this sense, $Bi_{1-x}Sb_x$ solid solutions are excellent model objects for solid state physics. Another attractive property of $Bi_{1-x}Sb_x$ is a high sensitivity of its properties to the effects of external factors — temperature, magnetic field, etc., which is of special interest from the point of view of practical applications in thermoelectricity, spintronics, quantum computers, etc. On the other hand, such a high susceptibility may be undesirable when it comes to ensuring the resistance of a material to certain external influences.

Although a rhombohedral structure is preserved over the entire $Bi_{1-x}Sb_x$ concentration range, the band structure of $Bi_{1-x}Sb_x$ solid solutions changes in a complex way (Fig. 1) [8–15]. Bi and Sb exhibit semimetallic properties: in Bi, the electron $L_s$-band $T$-band of "heavy" holes overlap, and in Sb, there is an overlap between the $H$-band of "heavy" holes and the electron $L_\alpha$-band. 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 is realized, which is followed by an inversion of the $L_s$ and $L_\alpha$ bands. Then, the gap between the $L_s$ and $L_\alpha$ bands increases again as $x$ continues to increase. Simultaneously with the increase in $x$, the top of the $T$ valence band shifts downward in energy, the overlap of $T$ and $L_s$ bands decreases, and at $x = 0.06 \div 0.07$, the band overlap disappears and a semimetal — indirect semiconductor transition occurs. The band gap of a semiconductor is determined by the distance between the $T$ and $L_\alpha$ bands. With further increase in $x$, the $T$ valence band top continues to shift downward in energy, at $x = 0.08 \div 0.09$, the tops of $T$ and $L_s$ valence bands coincide, and in the range $x \cong 0.09 \div 0.15$ the band gap represents the distance between the $L_s$ and $L_\alpha$ bands, i.e. semiconductor becomes a direct-gap one. At $x = 0.15 \div 0.17$, the tops of the $L_s$ and $H$ bands coincide, the semiconductor becomes indirect-gap again, and up to $x \sim 0.22$, the band gap is defined by the distance between the $L_\alpha$ and $H$ bands. The maximum value of the energy gap (~ 0.025 eV) in the semiconductor region is reached near $x = 0.16$, after which the band gap decreases. At $x \sim 0.22$, the tops of the $H$ and $L_\alpha$ bands coincide, a semiconductor — semimetal transition occurs, and then at $x > 0.22$, $Bi_{1-x}Sb_x$ solid solutions become semimetallic again.

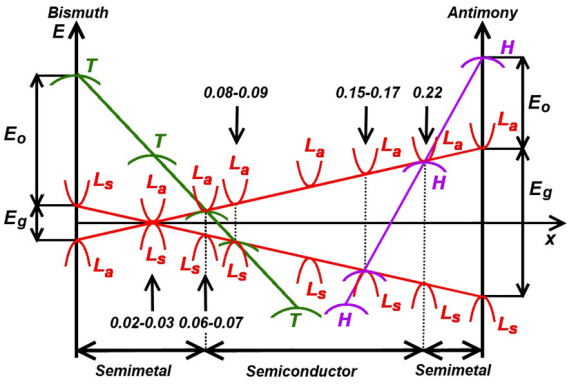


Fig. 1. The energy band structure of the $Bi_{1-x}Sb_x$ solid solutions.

Thus, according to the energy band diagram, the Bi-based semimetallic region is much narrower ($x = 0.0$–$0.1$) than the Sb-based semimetallic region ($x = 0.22 \div 1.0$), so all electronic phase transitions take place in the region $x = 0 \div 0.22$.

Most of the studies dealing with the $Bi_{1-x}Sb_x$ electronic structure and galvanomagnetic properties were carried out on single crystals [9, 11, 12, 15–24], although the number of studies related to the transport properties of cast or pressed polycrystalline samples is currently increasing

[25–59] due to the increasing application of these materials in thermoelectricity and other fields of technology.

To date, it has been found that the concentration dependences of the electrical conductivity $\sigma(x)$ and Hall coefficient $R_H(x)$ are continuous curves with a minimum of $\sigma$ and a maximum of $R_H$ in the semiconductor region [16–26]. The behavior of the concentration dependence of the charge carrier mobility $\mu(x)$ was differently described by different authors. According to [12, 20, 26, 35], as $x$ increases up to ~ 0.3, $\mu$ decreases. At the same time, the authors of [16, 21, 36] reported an increase in $\mu$ with increasing $x$. In [11, 15], it was suggested that interband hole scattering during transitions between the bands of "light" and "heavy" holes takes place reaching its maximum in the range $x = 0.09–0.16$ and decreasing with increasing temperature.

It should be noted that in practically all mentioned works, the alloys studied significantly differed in composition. Only in [45–53], did we investigate in detail the dependences of transport characteristics of $Bi_{1-x}Sb_x$ polycrystals with $x < 0.12$ on the Sb concentration. In the isotherms of properties, we discovered anomalous regions near compositions $x = 0.01$, 0.03, and 0.06. We attributed the presence of these concentration — dependent anomalies to critical phenomena accompanying the percolation-type transition from dilute to concentrated solid solutions, the transition to a gapless state, and the semimetal-indirect gap semiconductor transition, respectively. In [54], in the room temperature $\sigma(x)$ and $R_H(x)$ dependences, we found another anomaly near $x = 0.08$ and attributed it to the manifestation of another electronic phase transition associated with the transition from an indirect gap to a direct gap semiconductor. It should be pointed out, however, that the compositions of $Bi_{1-x}Sb_x$ polycrystals studied in [45–54] and preparation technologies (e.g. cast or pressed samples, different annealing times) differed, which complicates the comparison of the results. Besides, the concentration, temperature and magnetic field dependences of magnetoresistance, electron and hole mobility components in a wide range of compositions have not been studied using samples obtained under identical conditions.

The purpose of this work was to detect the presence of the electronic phase transitions in $Bi_{1-x}Sb_x$ polycrystals in the composition range $x = 0 \div 0.25$ through their manifestation in the concentration dependences of galvanomagnetic properties at different temperatures and in different magnetic fields.

It follows from the results obtained in this work that for the $Bi_{1-x}Sb_x$ solid solutions in the concentration range $x = 0 \div 0.25$, a non-monotonic behavior of the concentration dependences of galvanomagnetic properties occurs both at 300 K and 77 K, both in a weak and in a strong magnetic field.

## 2. Experimental

Measurements of galvanomagenitc properties were carried out on parallelepiped-shaped polycrystalline samples, 10×3×2 mm$^3$ in size, cut from ingots obtained by the method described in detail in [54]. All 30 studied samples of various compositions ($x = 0–0.25$) were prepared in the same technological cycle in order to ensure the identical conditions of preparation. $R_H$, $\sigma$, and magnetoresistance $\Delta\rho/\rho$ (where $\rho$ is the resistivity) were measured by the standard dc method at 300 K and 77 K, in magnetic fields of induction $B$ of 0.05 T and 1.0 T. Due to the high charge carrier mobility $\mu$, characteristic of $Bi_{1-x}Sb_x$ crystals, the critical magnetic field $B_C$, which separates the weak and strong magnetic field regions, is sufficiently small. In connection with this, for the correct interpretation of the results of galvanomagnetic measurements of $Bi_{1-x}Sb_x$ solid solutions, it is necessary to know the value of $B_C$. According to [55, 56], in which the $B_C$ values were determined for $Bi_{1-x}Sb_x$ alloys in the studied concentration range $x = 0–0.25$, the magnetic field of 0.05 T can be considered weak and the magnetic field of 1.0 T strong. The measurement error for $\sigma$, $R_H$ and $\Delta\rho/\rho$ did not exceed 5 %.

The electron $n$ and hole $\rho$ concentrations and electron $\mu_n$ and hole $\mu_p$ mobilities were calculated using the equations that take into account the presence of two types of charge carriers — electrons and holes [57, 58]:

$$R_H = \frac{p\mu_p^2 - n\mu_n^2}{e(p\mu_p + n\mu_n)^2}, \qquad (1)$$

$$\sigma = e(p\mu_p + n\mu_n), \quad \Delta\rho/\rho = \mu_n\mu_p B^2.$$

If we assume that the concentration of electrons $n$ is equal to the concentration of holes $p$, and the mobilities of electrons and holes are different, which is typical for Bi and $Bi_{1-x}Sb_x$ solid solutions [57–62], then $R_H$, $\sigma$ and $\Delta\rho/\rho$ values can be determined from the equations:

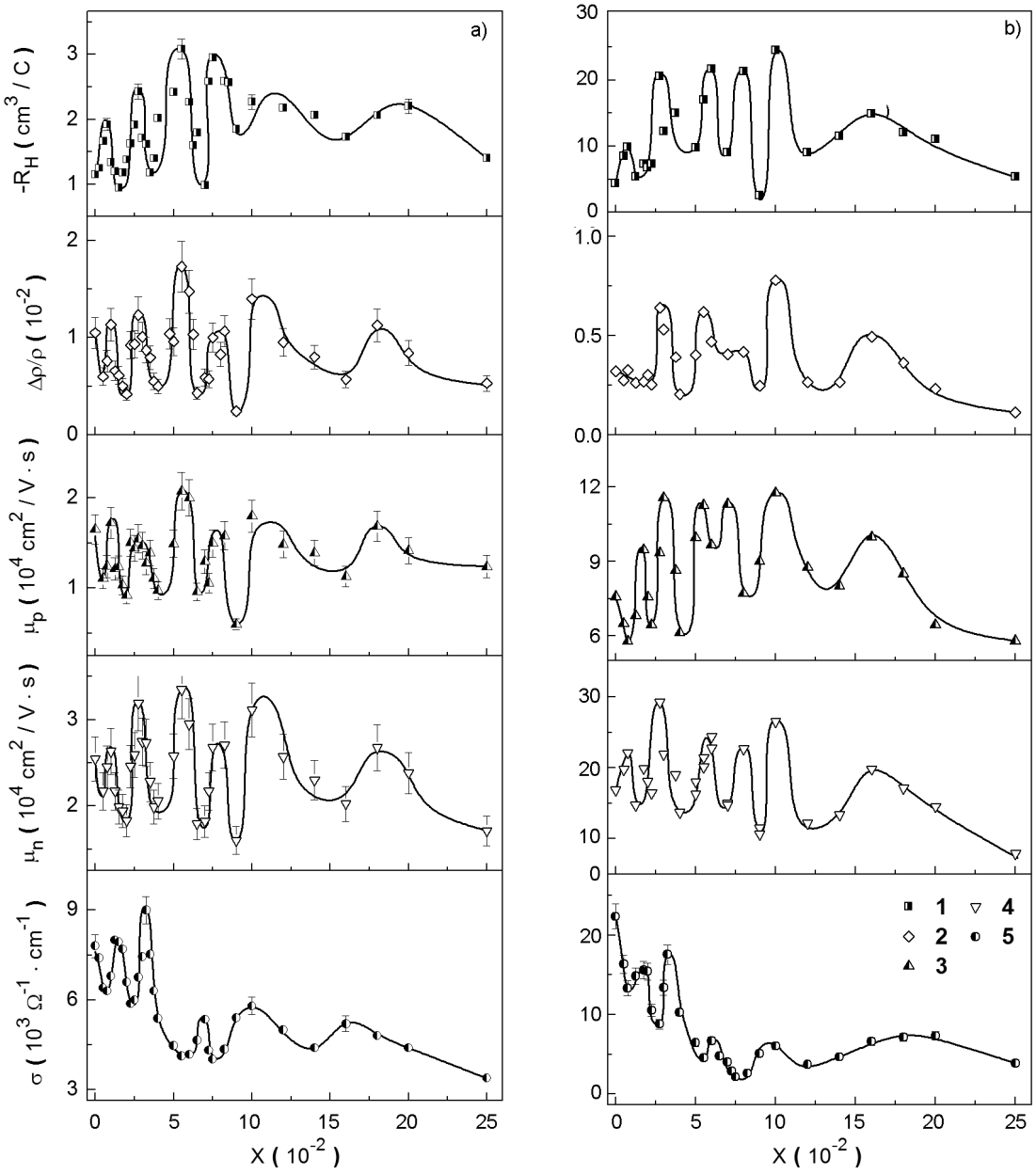


Fig. 2 The dependences of the Hall coefficient $R_H$ (*1*), magnetoresistence $\Delta\rho/\rho$ (*2*), hole mobility $\mu_p$ (*3*), electron mobility $\mu_n$ (*4*), electrical conductivity σ (*5*) on composition of the $Bi_{1-x}Sb_x$ solid solutions at 300 K (a) and 80 K (b). Solid lines are guides to the eye.

$$R_H = \frac{1}{en}\frac{\mu_p - \mu_n}{\mu_p + \mu_n}, \qquad (2)$$

$$\sigma = en(\mu_n + \mu_p), \quad \Delta\rho/\rho = \mu_n\mu_p B^2.$$

Using equations (2) and the results of measurements of σ, $R_H$ and $\Delta\rho/\rho$, the values of $n = p$, $\mu_n$ and $\mu_p$ were calculated for two different values of $B$.

### *3. Results and discussions*

In Fig. 2, a,b, the dependences $\sigma(x)$, $R_H(x)$, $\Delta\rho/\rho(x)$, $\mu_n(x)$, $\mu_p(x)$ dependences measured in this work at 300 K (a) and 77 K (b) are shown. A negative sign of $R_H$ indicates that all samples exhibited an electronic conductivity. This can be explained by the fact that the electron mobility $\mu_n$ exceeds almost three times the hole mobility $\mu_p$ [16, 18, 59, 60], and the sign of $R_H$ for

Bi and $Bi_{1-x}Sb_x$ solid solutions is determined by $\mu_n$ value (Eq. 2).

From Fig. a,b it can be seen that both at 77 K and at 300 K, as x increases up to 0.1, a tendency is observed to decrease in σ and to increase in $R_{H/}$, $\Delta\rho/\rho$, $\mu_n$, and $\mu_p$ also exhibit a tendency to increase with increasing $x$, although not so pronounced. It can also be seen that all the dependences both at 300 K and at 77 K and both at $B = 1$ T and $B = 0.05$ T have a distinct oscillating character. The positions of the extrema and their number are mostly the same for different kinetic coefficients and for both 300 K and 77 K. Meanwhile, as noted above, according to different authors, it was previously believed that the $\sigma(x)$, $\mu(x)$ and $R_H(x)$ dependences are continuous curves. However, contrary to the results reported by other authors we observed oscillations in the concentration dependences of the properties, whose the presence we attribute to the manifestation of critical phenomena accompanying the electronic phase transitions in $Bi_{1-x}Sb_x$ solid solutions [45–54].

Let us consider the obtained concentration dependences of kinetic coefficients in more detail. The introduction of the first portions of Sb in Bi (to $x \sim 0.005$) leads to an increase in $R_H$ and a decrease in σ, $\Delta\rho/\rho$, $\mu_p$ and $\mu_n$ both at 77 and 300 K. The decrease in charge carrier mobility under the introduction of an impurity is typical for solid solutions, since foreign atoms are centers of local distortions in the crystal lattice and centers of electron and hole scattering. This also manifests through a decrease in magnetoresistance, since $\Delta\rho/\rho \sim \mu_p \mu_n$ (Eq. 2). The increase in $R_H$ in the indicated composition range is usually associated with a decrease in the concentration of charge carriers as a result of a decrease in the overlap of $T$ and $L_s$ bands.

Under further increase in the Sb concentration, in the range $x = 0.005–0.015$, anomalies are observed in the isotherms of the galvanomagnetic properties (Fig. 1, 2), such as a sharp decrease in $R_H$ and an increase in σ, $\Delta\rho/\rho$, $\mu_p$. and $\mu_n$. We observed such anomalies in the $\sigma(x)$, $R_H(x)$ and $(\Delta\rho/\rho)(x)$ dependences in $Bi_{1-x}Sb_x$ solid solutions subjected to other heat treatments [45, 46, 50] and interpreted them as the manifestation of critical phenomena accompanying the percolation-type [63, 64] phase transition from dilute to concentrated solid solutions. It was assumed that there is a critical concentration (percolation threshold) at which a continuous chain of interconnected impurity atoms, the so-called "infinite cluster", is formed. A gradual increase in the density of the cluster with increasing impurity concentration (in this case — Sb) is accompanied by the appearance of anomalous regions in the concentration dependences of various physical properties.

A further increase in Sb concentration to $x \sim 0.1$ leads to the appearance of new peaks in the $\sigma(x)$, $R_H(x)$, $(\Delta\rho/\rho)(x)$ dependences at 300 K and 77 K (Fig. 2 a,b), which we attribute to i) transition to a gapless state ($x = 0.02–0.03$), ii) semimetal — indirect-gap semiconductor transition ($x = 0.05–0.06$) and iii) indirect-gap — direct-gap semiconductor transition ($x = 0.08–0.09$). These results are in good agreement with the results that we obtained earlier [45, 46, 50, 54] for alloys in the concentration range $x < 0.1$, in which we measured the $\sigma(x)$, $R_H(x)$ and $(\Delta\rho/\rho)(x)$ dependences for $Bi_{1-x}Sb_x$ solid solutions obtained using a different heat treatment. In the present work, we additionally investigated the $\mu_p$ and $\mu_n$ dependences on the composition $x$. It is seen that similar concentration anomalies are also observed in the $\mu_n(x)$ and $\mu_p(x)$ dependences, which is another convincing confirmation of the existence of critical phenomena accompanying the above mentioned electronic phase transitions to a gapless state, the semimetal — indirect gap semiconductor, and the indirect gap — a direct gap semiconductor transitions.

It is seen from Fig. 2 that apart from the peak associated with the indirect gap — a direct gap semiconductor transition ($x = 0.08–0.09$), when the $T$-band top coincides with the $L_s$-band top (Fig. 1), another two maxima are observed both at 300 K and at 80 K (Fig. 2 a,b). The maxima positions correspond to $x = 0.125$ and $x = 0.18$ at 300 K, and to $x = 0.1$ and $x = 0.16$ at 77 K.

The behavior of the kinetic properties of $Bi_{1-x}Sb_x$ solid solutions in the concentration range $x = 0.09–0.25$ can be expected to be non-monotonic if we take into account the $Bi_{1-x}Sb_x$ band structure (Fig. 1). The indicated composition range includes the direct-gap ($x = 0.09–0.16$) and indirect-gap ($x = 0.16–0.22$) semiconductor regions, as well as the semimetallic region ($x > 0.22$). It should be noted that the character of the dependences of the kinetic coefficients on the composition in the region $x = 0.09–0.25$ depends on a number of factors. These factors include 1) a contribution to the kinetic coefficients of the $T$-band with heavy holes

even when the transition at $x = 0.08–0.09$ has already occurred, 2) a change in the band gap width within the semiconductor region (initial growth and subsequent decrease after $x = 0.16–0.17$), which should lead to a change in charge carrier concentration, 3) a change in the contribution to the kinetic coefficients of the $H$-band with heavy holes as the $H$-band top goes down in energy, 4) an indirect gap semiconductor — semimetal transition at $x \sim 0.22$ and a change in the contribution of light and heavy $H$-band holes to the conductivity. These factors can influence different kinetic coefficients in different ways. These features of the $Bi_{1-x}Sb_x$ band structure complicate the analysis of changes in kinetic coefficients with increasing $x$.

Based on the $Bi_{1-x}Sb_x$ band diagram (Fig. 1), it can be assumed that the extrema in these curves in the composition region near $x = 0.16$ appear when the tops of "heavy" $H$ and "Light" $L_s$ valence bands coincide, when the maximum value of the energy gap in the semiconductor region is reached and a transition from direct gap to indirect gap semiconductor occurs, with the redistribution of charge carriers from the $L_s$ of the valence band to the $H$-band. The shift in the positions of the maxima/minima points with a change in temperature can be explained by a temperature dependence of $Bi_{1-x}Sb_x$ energy spectrum parameters. The composition corresponding to the direct-gap — indirect-gap semiconductor transition at 300 K shifts to the region of larger $x$.

The origin of a sharp decrease (especially at 77 K) in $R_H$, $\Delta\rho/\rho$, $\mu_p$ and $\mu_n$ in the vicinity of $x = 0.1$, when the transition to the region of direct-gap semiconductors has already occurred at $x = 0.08–0.09$, is not entirely clear, although some explanations can be suggested. It is known that the band of "light" holes is characterized by a large nonparabolicity and this leads to the strong dependence of the band parameters on external factors — temperature, magnetic field, composition, sample preparation technology, etc. One should also take into account possible interband scattering processes, which are the most intense in the concentration range $x = 0.09–0.16$ [11, 15], i.e. in the direct-gap semiconductor region. This is a possible explanation of the sharp change in the Hall coefficient and other parameters at $x = 0.1$, occurring after moving into the direct-gap semiconductor region. However, for an unambiguous explanation, additional theoretical and experimental studies are necessary that would take into account the contribution of the $T$-band with heavy holes to the conductivity, contribution of interband scattering processes and other factors.

The positions of the extrema for different kinetic coefficients may be shifted relative to one another due to possible differences in the behavior of concentration dependences for those coefficients. However, for almost all of the studied coefficients, the positions of the maxima/minima points almost coincided. This was another confirmation of the existence of phase transitions, especially taking into account that such properties as electrical conductivity, Hall coefficient, and magnetoresistance were measured independently of each other.

It is of interest to clarify the question of whether the concentration anomalies of kinetic coefficients in a strong magnetic field, when $\mu B >> 1$, will be observed. It is known that in a weak magnetic field the charge carrier cyclotron radius significantly exceeds the electron or hole mean free path, the Lorentz force slightly changes the movement of charge carriers and galvanomagnetic properties are mainly determined by the type of scattering processes. In strong magnetic fields ($\mu B >> 1$), vice versa, the charge carrier motion is completely controlled by the Lorentz force, and the galvanomagnetic properties depend mainly on the specific features of the electron energy spectrum [57, 58]. The type of scattering is determined mainly by the lattice subsystem of the crystal, while the electronic spectrum is determined by the electronic subsystem. But, of course, both subsystems are closely interrelated.

Fig. 3 shows the $R_H$ and $\Delta\rho/\rho$ dependences at 300 K, both in a weak ($B = 0.05$ T) and in a strong ($B = 1.0$ T) magnetic fields. It can be seen that in the concentration range $x < 0.1$, all the dependences in both the weak and strong magnetic fields exhibit a similar oscillating behavior and that the positions of maxima/minima coincide. This indicates that the band structure also determines the character of scattering of charge carriers, and therefore the concentration anomalies of properties look identical. However, in the concentration range $x = 0.1–0.25$, the behavior of the dependences differs: although the oscillations are observed in both cases, but the positions of maxima and minima do not coincide. This is similar to what is observed in this concentration range under decreasing temperature. Thus

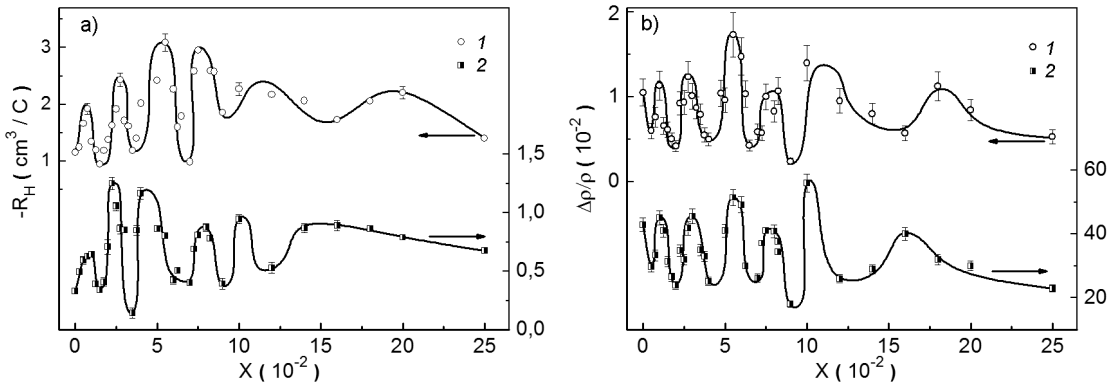


Fig. 3. The dependences of the Hall coefficient $R_H$ and magnetoresistence $\Delta\rho/\rho$ on the composition of $Bi_{1-x}Sb_x$ solid solutions at 300 K (*1* — $B = 0.05$ T; *2* — $B = 1$ T). Solid lines are guides to the eye.

the effect of increasing magnetic field on the concentration dependences is similar to that of decreasing temperature.

The small number of studied compositions in the range $x = 0.16 \div 0.25$ makes it impossible to identify the indirect-gap semiconductor — semimetal transition.

It follows from the data obtained that the oscillatory behavior of the $R_H$ and $\Delta\rho/\rho$ dependences on the composition of $Bi_{1-x}Sb_x$ solid solutions measured in a strong magnetic field ($B = 1$ T), is not associated with the magnitude of the magnetic field, but is caused by other factors.

Thus, it was shown that the existence of the anomalies in the behavior of galvanomagnetic properties of $Bi_{1-x}Sb_x$ solid solutions as a function of Sb concentration does not depend on either temperature or magnetic field. The non-monotonic character of the dependences of the galvanomagnetic properties on the composition is attributed to the occurrence of concentration-induced phase transitions from dilute to concentrated solid solutions, as well as phase transitions associated with qualitative changes in the $Bi_{1-x}Sb_x$ energy spectrum under increasing Sb concentration.

## 4. Conclusions

A detailed study of the concentration dependences of the Hall coefficient, electrical conductivity, magnetoresistance, hole and electron mobilities of the $Bi_{1-x}Sb_x$ polycrystalline samples ($x = 0$–$0.25$) at 77 and 300 K and in magnetic fields 0.05 and 1.0 T was carried out. Based on the results obtained in this work, the following conclusions have been made.

It was established that in the concentration range $x = 0$–$0.25$, the dependences of the galvanomagnetic properties on the composition of the solid solution exhibit a non-monotonic oscillating behavior. The anomalous behavior of the concentration dependences of electrical conductivity, Hall coefficient, magnetoresistance, electron and hole mobility was observed in the vicinity of compositions $x = 0.01$, 0.03, 0.07, 0.08, 0.1, and 0.16.

The oscillations in the dependences of kinetic coefficients were observed both at 77 K and 300 K, and in magnetic fields of 0.05 T and 1.0 T, which indicates the stability of this phenomenon with respect to the temperature and magnetic field in the studied temperature and magnetic field ranges.

The behavior of the dependences of galvanomagnetic properties on the composition is preserved both in weak to strong magnetic fields (up to 1 T).

Attribute the non-monotonic character of the dependences of the kinetic characteristics of $Bi_{1-x}Sb_x$ solid solutions on Sb concentration to a percolation-type transition in the region of very low impurity concentrations, to changes in the band structure under changing composition (redistribution of charge carriers over different energy bands ($L$, $T$, $H$) and consequently, changes in the relative contribution to conductivity of charge carriers from different energy bands, large nonparabolicity of the band of light holes, interband scattering) and to qualitative changes in the $Bi_{1-x}Sb_x$ energy spectrum at certain critical compositions (the transition to a gapless state, manifestation of the gapless state, semimetal — semiconductor transition, indirect band — direct band semiconductor transition).

Assume that the maxima and minima in the concentration dependences of the properties near $x = 0.1$ and 0.16 appear because at these concentrations the tops of the $T$-

and $H$-bands coincide with the tops of the LS bands.

The experimental results obtained in this work are interesting not only for the physics of electronic phase transitions and 3D Dirac semimetals but also from the point of view of potential applications of these materials in thermoelectric, spintronic and magnetoelectronic devices.

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

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