THE SCATTERING CHARACTER AND CONDUCTION MECHANISM OF CHARGE CARRIERS IN $Bi_{1-x}Sb_x$ ALLOYS

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The complex investigation of thermomagnetic phenomena in $Bi_{1-x}Sb_x$ system in wide temperature interval and concentrations in weak and strong magnetic fields has been carried out. Lorentz number $L_{ex}(T,n)$ and electron heat conduction K_{el} are obtained. It is seen that L_{ex} in wide interval of n and T is less than Zommerfeld value L_0. By comparison of experimental data with theory taking into consideration the non-elasticity influence on L_0 is established that non-elasticity is mainly caused by electron collision. The non-elastic scattering on polar optical phonons achieves 7% in average temperature interval. It is established that $R(T)$ increase in samples with strongly expressed electron gas is partially caused by non-parabolicity of conduction band of $Bi_{0.88}Sb_{0.12}$.

INTRODUCTION

The experimental and theoretical investigations of thermomagnetic and thermoelectric properties show that non-elastic scattering of charge carriers in narrow-band semiconductors strongly influences on kinetic effects caused by the presence of temperature gradient [1-11]. The analysis of these results shows that experimental definition of Lorentz number L_{el} and electron heat conduction component K_{el} is possible with the use of thermomagnetic and thermoelectric properties at optional classic magnetic fields including the low ones ($uH/c<<1$). This allows us to expand the fild of investigations of concentration and temperature dependences of Lorentz number L_{ex} (n,T) and electron heat conduction K_{el} (n, T) in detail.

The system of solid solutions $Bi_{1-x}Sb_x$ is the most suitable object for complex investigations of electric, thermoelectric and thermomagnetic properties of massive and thin-film samples of n- and p-type and also in mixed region of conduction [1-15]. In particular, the questions of scattering character revealing of charge carriers in wide temperature interval and concentration and also conduction mechanism in narrow-gap and non-gap compositions $Bi_{1-x}Sb_x$ take an interest. L_{ex} and K_{el} with different electron concentrations are defined in earlier investigated work [11] for three samples $Bi_{0.88}$ $Sb_{0.12}$.

In some semiconductor series the Hall coefficient $R(T)$ passes maximum or it increases with temperature in the case of strong electron gas degeneracy on comparison with the normal two-band case (when $R(T)$ has constant value). The physical causes of the given phenomenon are different. Some of them are: conduction of impurity band located in condition band [16,17], the presence of quazi-local impurity bands in forbidden band [18], the taking of degeneration of electron gas in case of electron scattering on ionized regions by impurities, influence of hard charge carriers, located in valency band. The $R(T)$ increase in Bi_{1-x} Sb_x system and its passing maximum the causes revealing of which also takes the interest.

EXPERIMENTAL RESULTS AND THEIR DISCUSSION

In work [11] the investigation of magnetic field influence on electron part of heat conduction $Bi_{0.88}$ $Sb_{0.12}$ for three samples with n=4,4.10^{18}cm^{-3} and n=3,7.10^{19}cm^{-3} has been carried out. As the scattering non-elasticity takes place in narrow-gap and non-gap semiconductors and semi-metals and non-elasticity parameter L_{ex}/L_0 enters in formulas of thermomagnetic and thermoelectric coefficients then the definition of K_{el} and L_{ex} is correct for data from Madji-Rig-Luk effect in classical strong magnetic fields $(uH/c>>1)$. However, the introduction of L_{ex}/L_0 relation of thermomagnetic and thermoelectric coefficients at carrying out of some experiment conditions described in [1,2] can be used for L_{ex} definition.

Let's consider the some of them. The value of electron heat conduction in strong magnetic field with taking into consideration of non-elasticity degree of L_{ex}/L_0 has the form:

$$K_{el}=\Delta K_{H\to\infty}=\frac{1+\left(\frac{uH}{c}\cdot\frac{L_{ex}}{L_0}\right)^2}{\left(\frac{uH}{c}\cdot\frac{L_{ex}}{L_0}\right)^2}.\Delta K \qquad (1)$$

from which it is followed that $K_{el}=\Delta K_{H\to\infty}(H)$ can be defined if we know the relation L_{ex}/L_0. One can define L_{ex} from (1) then introducing it in $K_{el}=L_{ex}\sigma T$ we can define the electron component of heat conduction.

The L_{ex}/L_0 value can be defined from the following dependence:

$$\Delta K(H)=\frac{\left(\frac{uH}{c}\cdot\frac{L_{ex}}{L_0}\right)^2}{1+\left(\frac{uH}{c}\cdot\frac{L_{ex}}{L_0}\right)^2}K_{el}, \qquad (2)$$

which is correct at arbitrary value H [4].

In this case we should select the value L_{ex}/L_0 up to coincidence of calculation and experimental ones as in the previous case and calculate $k_e=(L_{ex}/L_0)\sigma T$.

The analogous task is solved by investigation of longitudinal and transversal Nernst-Ettingausen effects.

$$\Delta\alpha_\infty=\Delta\alpha.\frac{1+\left(\frac{uH}{c}\cdot\frac{L_{ex}}{L_0}\right)^2}{\left(\frac{uH}{c}\cdot\frac{L_{ex}}{L_0}\right)^2} \qquad (3)$$

$$\frac{Q^{\perp}_{H\to 0}}{R\sigma}\frac{L_{ex}}{L_0}=\Delta\alpha_{\infty} \quad (4)$$

In (4) at weak fields ($uH/c<<1$) $Q^{\perp}_{H\to 0}$ has the constant value from which it follows:

$$\frac{L_{ex}}{L_0}=\frac{\Delta\alpha_{\infty}R\sigma}{Q^{\perp}_{H\to 0}} \quad (5)$$

Thus, measuring $\Delta K(H)$, $\Delta\alpha(H)$ at given values of H и $Q_{iz}^{\perp}$ at weak fields by formulas (2)-(5) as independent methods, L_{ex}/L_0 and electron and phonon parts of heat conduction are defined.

It is also known that transversal *N-E* dimensionless field ε_y and Rig-Leduk coefficient at inelastic scattering character pass maximum not at u$H/c=1$ as it happens at elastic scattering character, but at $uH/c>1$ values [4]:

$$-SH\left(\frac{uH}{c}\right)=\frac{\frac{uH}{c}\cdot\frac{L_{ex}}{L_0}}{1+\left[\frac{K_f}{L_0\sigma T}\right]\cdot\left[1+\left(\frac{uH}{c}\right)^2\left(\frac{L_{ex}}{L_0}\right)^2\right]\frac{L_0}{L_{ex}}} \quad (6)$$

and

$$\varepsilon_y=\frac{\Delta\alpha_{\infty}\cdot\left(\frac{uH}{c}\right)\cdot\left(\frac{L_{ex}}{L_0}\right)}{\frac{k}{e}\cdot\left[1+\left(\frac{uH}{c}\right)^2\left(\frac{L_{ex}}{L_0}\right)^2\right]} \quad (7)$$

From (6) and (7) it follows that values of SH and ε_y maximums are defined by L_{ex}/L_0 relation, in detail the maximum takes place at

$$\frac{uH}{c}\cdot\frac{L_{ex}}{L_0}=1 \quad (8)$$

then $\frac{uH}{c}=\frac{L_0}{L_{ex}}$. Therefore, the maximum position of these effects directly defines the inelasticity degree $\frac{L_{ex}}{L_0}$. in the investigated sample

The above mentioned results for $Bi_{1-x}Sb_x$ system are important ones. Firstly, the sample $Bi_{0.88}Sb_{0.12}$ with n=4,4·10^{18}cm^{-3} is the most suitable for affirmation of theory and earlier observable experimental data about maximum shifting $\varepsilon_y(uH/c)$ and $SH(uH/c)$ to the side of high values $(uH/c)>1$ (fig.1 and fig.2). They allow us to define L_{ex}/L_0 and K_{el} for samples n>4,4·10^{18}cm^{-3}, obtain the data about L_{ex} and K_{el} with high accuracy, extend the temperatures L_{ex} and K_{el} and concentration $L_{ex}/L_0(n)$ intervals. The complex measurement of above mentioned coefficients in crystals $Bi_{1-x}Sb_x$ for compositions with x=0,02; 0,04; 0,08 and 0,12 has been carried out with this aim. $L_{ex}/L_0(T, n)$ are calculated on the basis of experimental data by formulas (1)-(8) and are given in the table.

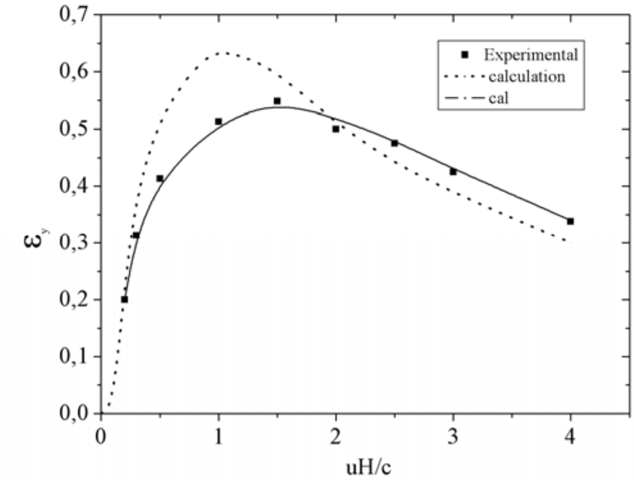

Fig.1. The dependence of Nernst-Ettinghausen dimensionless field *(*ε_y*)* on *uH/c* value. The points are experimental data. Curves are the calculation on formula (7) taking into consideration of elastic (hatch) and inelastic (solid line) electron scattering at T=105K.

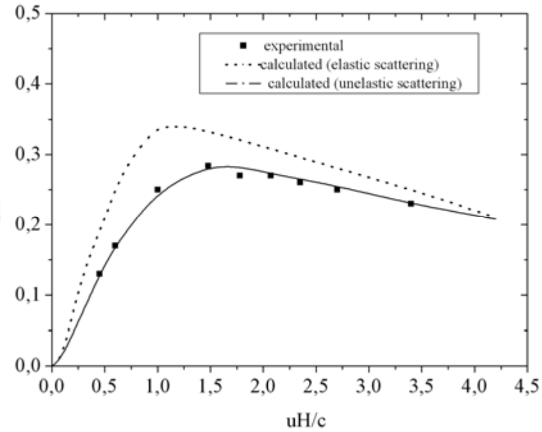

Fig.2. The dependence –SH on *uH/c* value for $Bi_{0.88}Sb_{0.12}$ samples with electron concentration n=4,4.10^{18}cm^{-3}. Curves are the calculation on formula (6) with taking into consideration of elastic (hatch) and inelastic (solid line) electron scattering at T=93K.

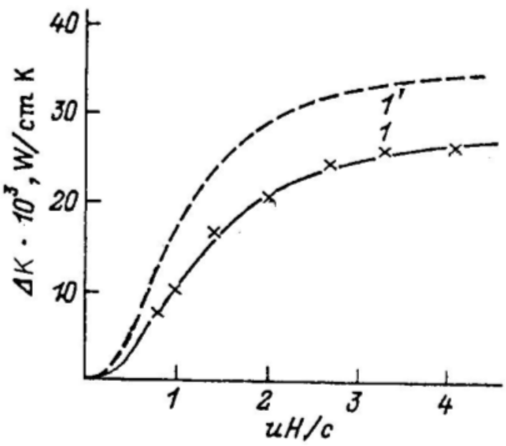

Fig.3. ΔK dependences on *uH/c* value for sample with concentration 5·10^{18}cm^{-3}. The points are experiment date, curve is calculation by formula (1) taking into consideration of elastic (hatch) and inelastic (solid line) electron scattering at T=93K.

Note that in calculative line *ΔK(H)* (fig.3) in the case of elastic character of electron scattering, the saturation is at *uH/c*≈5÷6 and at inelastic character is (8÷9), i.e. inelasticity decreases the Lorenz force action on electrons taking part in t6ransition of heat energy. It is clearly seen that ε_y at elastic scattering character passes through maximum at *uH/c*=1 and at inelastic scattering character at (*uH/c*)>1, moreover the curves of dependence of transversal effect *H-Э* calculated at elastic and inelastic scattering characters intersect after passing through maximum. This is also connected with the fact that in the case of inelastic scattering character the effective value of magnetic field $\frac{uH}{c}.\frac{L_{ex}}{L_0}$ is weaker than at elastic one.

At inelastic character the electron scattering the maximum of thermomagnetic effect *P-Л (-SH)* has the more fuzzy form. This is caused by the fact that relation $K_f/L_0\sigma T$ (formula (6)) influences on maximum position and increases under *H* action.

The theory of electron heat conduction and thermomagnetic phenomena in the case of inelastic scattering character of charge carriers is considered in works [3,4,7]. According to [3,6] at strong degeneration of electron gas (μ>>1) if the energy of longitudinal optical phonons is significantly less than the given charge carrier energy whereas it is by the order kT (μ>>hω₀, μ =kT) then Lorenz number L_{ex}/L_0 has the form in general:

$$\frac{L_{ex}}{L_0}=\left[1+\frac{W_{ee}}{W_0}+\frac{U}{U_{op}}\left(\frac{L_0}{L_{ex}}-1\right)_{op}\right]^{-1}, \tag{9}$$

where $W_0=(L_0\sigma T)^{-1}$ is heat resistance for elastic scattering, W_{ee} is heat resistance caused by collisions between electrons, u is experimental value of electron mobility, u_0 is mobility at carrier mobility on optic phonons. Consequently, the second summand is connected with taking into consideration of inelasticity because of collision between charge carriers and third one with scattering on polar optic phonons. As a result of calculation we obtain [7]:

$$\frac{W_{ee}}{W_0}=2\pi^4\frac{e^3(kT)^2(k_f\tau_r)^3un}{E_\infty^2\hbar^3k_F^3v_F^4} \tag{10}$$

where v_F is velocity, k_F is quazi-impulse on Fermi level $\tau_e=\left[\frac{\varepsilon_\infty}{4\pi.e^2\rho(\mu)}\right]^{1/2}$ is screening radius corresponding to dielectric constant ε_∞, $\rho(\mu)=\frac{3en\alpha_\infty}{\pi^2k^2T}$ is density of states, α_∞ is thermoelectromotive force in strong magnetic field, n is electron concentration. The calculation results L_{ex}/L_0 are given on fig.4 and 5 in the comparison with averaged values defined from (1) – (8) in the form of temperature and concentration dependences.

Note that experimental data of L_{ex}/L_0 *(T)* and $L_{ex}/L_0(n)$ below *T*<80K and *n*<4,4.10^{18} cm^{-3} are related to samples $Bi_{1-x}Sb_x$ - (*x*=0,02; 0,04; 0,08 and 0,12). The obtained results allow us to conclude that scattering inelasticity in $Bi_{0.88}Sb_{0.12}$ alloys in conditions of strongly degeneration of electron gas at *T*≤50-60K temperatures and n≥4,4·10^{18}cm^{-3} concentrations is mainly connected with electron collisions. The inelasticity part connected with electron scattering on polar optical phonons doesn't exceed 5-7% and reveals in 80-250K interval in *n*≤4,4.10^{18}cm^{-3} range. The inelasticity absence at *T*<30K in $Bi_{1-x}Sb_x$ alloys is connected with the fact that the Rutherford scattering on impurity ions having the purely elastic character is the main mechanism of electron scattering at such low temperatures.

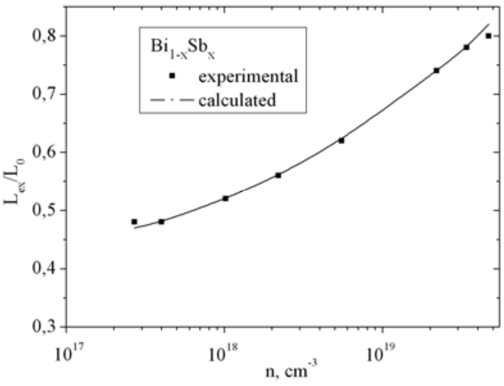

Fig.4. The dependence L_{ex}/L_0 on electron concentration in $Bi_{1-x}Sb_x$.

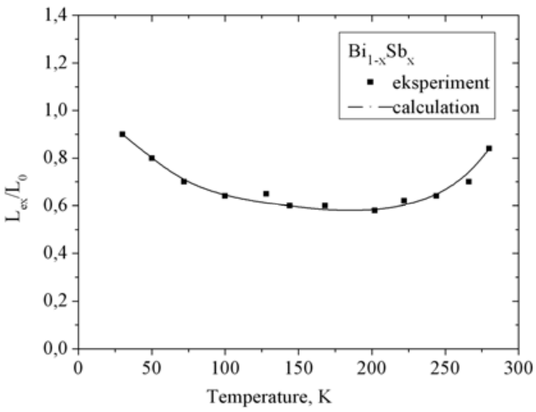

Fig.5. The dependence L_{ex}/L_0 on temperature in $Bi_{1-x}Sb_x$.

The temperature dependences K_f- and $K_{el}(T)$ in Bi single crystal are investigated in work [15] in which it is established that inelasticity in Bi reveals only at *T*≤30K. The inelasticity absence in pure Bi at *T*>30K is explained by simultaneous participation of electrons and holes in heat conductivity, i.e. by small part of K_{el}. One can suppose that if the above mentioned more accurate methods for L_{ex} definition and division of K_{el} and K_f, then one can expand the inelasticity temperature interval to the side of high temperatures, but at Bi doping by Te atoms one can probably obtain the valuable results on scattering character.

Thus we can conclude that above mentioned formulas for thermomagnetic effects obtained on the base of phenomenological theory [4] taking into consideration the inelasticity influence on kinetic phenomena caused by presence of temperature gradient, are very useful ones for treatment of experimental results of thermomagnetic and thermoelectric phenomena and play the determinative role at revealing of the part of scattering inelastic character ($\frac{L_{ex}}{L_0}$)

and for division of electron and phonon compounds in heat conductivity.

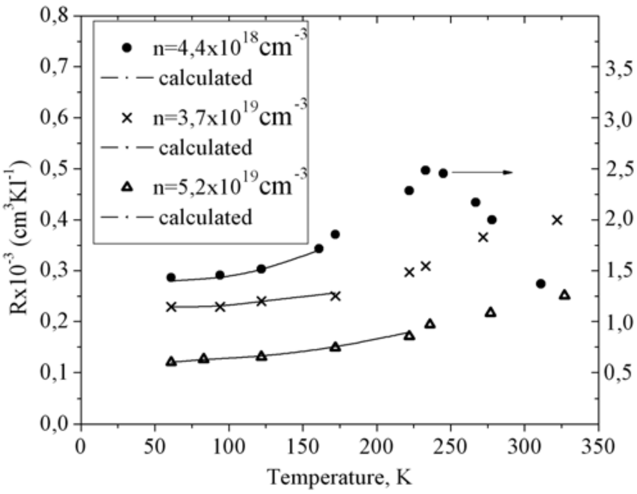

Fig.6. The temperature dependence of Hall coefficient *R*. 1 - n=4,4·10^{18}cm^{-3}, 2- 3,7·10^{19}cm^{-3}, 3 - 5,2·10^{19}cm^{-3}. Solid lines are calculation ones.

In the given work the temperature dependences *R(T)* in $Bi_{1-x}Sb_x$ are analyzed. *R(T)* for three samples with n_1=4,4·10^{18}cm^{-3}, n_2=3,7·10^{19}cm^{-3} and n_3=5,2·10^{19}cm^{-3}are presented on fig.6. It is seen that *R(T)* increases for n_2 and n_3 samples from *T*=140 and 155K and *R* for n_1 increases from *T*=90K and passes through maximum at *T*=240K.

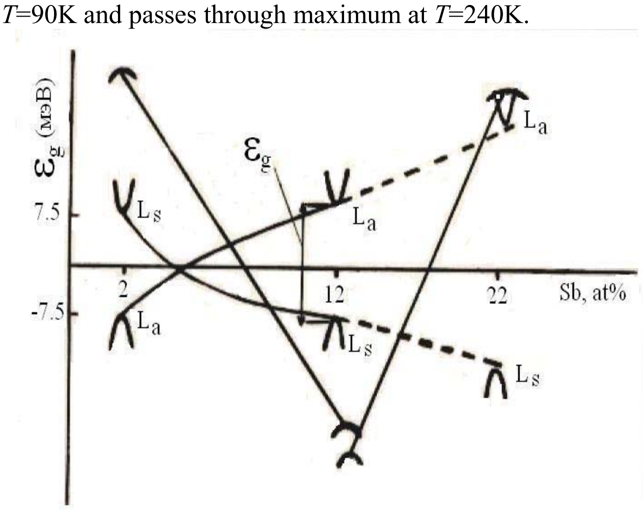

Fig.7. Zone diagram of $Bi_{1-x}Sb_x$ system at $T\rightarrow 0$.

For explanation of the presented data it is necessary to analyze the existing models and explain their suitability or uselessness for Bi_{1-x} Sb_x system. In [16,17] it is seen that in в GaAs and InP with n=10^{17}cm^{-3} the increase of *R* is observed as a result of conductivity presence on impurity band at *T*<100K, and *R* doesn't depend on *T* in samples with n>10^{18}cm^3. This is explained by the fact that impurity band merges with bottom of conductivity band with *n* increase. The passing of *R(T)* through maximum is explained by the fact that donor levels situated on distance ΔE from conductivity band behave themselves as traps of their electrons, Fermi level entries in this band in temperature interval when process of electron localization takes place and the conductivity on impurity band is carried out that leads to n decrease, i.e. to *R* increase. In the case of the presence of quasi-local levels situated in conductivity band, they beginning from temperature satisfying to $kT\geq\Delta E$ also play the role of traps for conductivity electrons. Consequently, R increases with temperature increase and concentration increases (*R* passes through maximum) at higher *T* when kT achieves the value enough for impurity ionization. The other important peculiarity is the fact that E_F concentration stabilizes at their coincidence with Fermi level, E_F is fixed on definite level and further impurity introduction or temperature increase don't lead to n growth. Such phenomenon is observed in PbTe doped by In atoms [18-21]. However in case of $Bi_{1-x}Sb_x$ the electron concentration increases proportionally to concentration of introduced impurity (before 5,2·10^{19}cm^3) at introduction of doping impurities (Te) not having the tendency to stabilization.

In the given work the attention to narrow width of prohibited band ε_{gL} (fig.7) and its temperature dependence is given. It is known that non-parabola degree is inversely to energy distance between conduction band L_s and easy hole band L_a $Bi_{1-x}Sb_x$. That's why the influence of strong non-parabola of conductivity band on Hall coefficient is considered. Hall coefficient has the following form in semiconductors with one charge type in strong magnetic field:

$$R = \frac{A_r}{en} \tag{11}$$

where $A_r = \dfrac{<\tau_m^2>}{<\tau_m>^2}$ is Hall factor, τ_m is relaxation time of charge carriers. As it is seen *R* change at n=const can take place because of the change of $A_r(T)$. In the case of nonquadratic scattering law in limits of A_r one-band model is expressed by following formula:

$$A_r\left(\eta^x, \beta\right) = \frac{I^0_{3/2} + I^0_{2r+1/2}}{(I^0_{r+1/2})^2} \tag{12}$$

It is seen that A_r strongly depends on non-parabola degree $\beta=kT/\varepsilon_g$ and on scattering parameter *r*. The calculation results for samples with n=3,7·10^{19}cm^{-3} and 5,2·10^{19}cm^{-3} show that Hall factor A_r growths beginning from *T*=140K and 155K correspondingly for given electron concentrations moreover the more strong dependence is observed at electron scattering on acoustic phonons. The analysis of obtained results shows that A_r decreases independently on scattering mechanism at constant temperature with *n* growth. $A_r\rightarrow 1$ at low temperatures in strongly doped samples. Also it is obtained that growth beginning of $A_r(T)$ with n increase to the side of high *T*. The obtained values of A_r evidence that the observable peculiarity *R(T)* is significantly connected with strong non-parabola of conductivity band of $Bi_{0.88}Sb_{0.12}$ composition. Nevertheless, the temperature dependence ε_{gL} significantly influences on A_r.

The zone diagram of Bi_{1-x} Sb_x for $T\rightarrow 0$ is presented on fig.7. It is seen that L_S and L_a terms are mutually inverse ones. In conduction band in *L* point Bi has term L_s but valence band top has term L_a whereas Si has inverse term position.

According to this the transition into gapless state (in *L* point of Brillun band) is observed in Bi_{1-x} Sb_x alloys at some $x=x_0$. L_n monotonously goes up at *x* increase up to 0,04 and L_S goes down, moreover energy crack decreases up to $\varepsilon_{g1}=0$, later the term inversion takes place and terms remove from each other at further increase of Sb content. The temperature influences on zone diagram.

The given problem isn't discussed enough in papers probably because of it isn't big one. However, it can influence on galvanomagnetic effects in non-gap and narrow-gap states. That's why at *R(T)* calculations the influence of temperature dependence ε_{g1} is used.

$$\varepsilon_{g1} = -15.7 + 2.66.10^{-3}T + 2.133.10^{-4}T \qquad (13)$$

Substituting the obtained data of $A_r(T)$ in (13) we calculate *R(T)*. The agreement of experimental data with calculative ones is satisfactory one for sample with n=5,2.10^{19}cm^{-3} and for sample with n=4,4.10^{18}cm^{-3} this agreement is worse that requires the further investigations.

Table.

The dependence of inelastic scattering proportion (L_{ex}/L_0) in Bi_{1-x} Sb_x.

x	T,K	$n\cdot10^{18}$cm^{-3}	u,cm^2/Vs	L_{ex}/L_0					
				ΔK_∞	ΔK	$\Delta\alpha(H)$	ε_y	$-SH$	$\Delta\alpha_\infty R\sigma/Q^{\perp}_{H\to0}$
0.02	90	0.3	25000	0.65	0.63	0.62	0.13	0.65	0.63
	200			0.63	0.65	0.67	0.65	0.62	0.65
	300			0.70	0.7	0.80	0.81	0.60	0.81
0.04	92	0.5	24000	0.67	0.65	0.66	0.63	0.66	0.65
	205			0.65	0.60	0.62	0.65	0.63	0.63
	300			0.73	0.75	0.77	0.8	0.82	0.87
0.08	95	1	22000	0.68	0.63	0.65	0.63	0.63	0.65
	203			0.68	0.65	0.67	0.65	0.67	0.63
	300			0.75	0.77	0.81	0.80	0.81	0.82
0.12	93	4.4	20000	0.81	0.8	0.82	0.75	0.76	0.75
	120			0.23	0.76	0.80	0.70	0.72	0.71
	205			0.75	0.71	0.75	0.65	0.60	0.67
0.12	35	37	8000	1.01	1	—	—	—	—
	70			0.88	0.85	—	—	—	—
	102			0.72	0.76	0.66	0.70	0.70	0.65
	130			0.69	0.70	0.71	0.65	0.68	0.61
	205					0.72	0.60	0.60	0.55
0.12	97	52	380	0.77	0.75	0.73	0.70	0.71	0.65
	115			0.71	0.70	0.70	0.70	0.63	0.62
	200			0.62	0.60	0.67	0.65	0.60	0.6
	300			0.8	0.60	0.80	0.80	—	0.82

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$Bi_{1-x}Sb_x$ XƏLİTƏLƏRİNDƏ YÜKDAŞIYICILARIN KEÇİRİCİLİK MEXANİZMİ VƏ SƏPİLMƏ XARAKTERİ

Geniş temperatur və konsentrasiya intervalında, güclü və zəif maqnit sahələrdə $Bi_{1-x}Sb_x$ sistemində termomaqnit xassələri kompleks tədqiq edilmişdir. $L_{exp}(T,n)$ - Lorens ədədi və k_e - istilikkeçirmənin elektron hissəsi təyin edilmişdir. Geniş temperatur və konsentrasiya intervalında L_{exp}-in zommerfeld qiymətindən az olması göstərilmişdir. L_o-a qeyri elastikliyin təsirini nəzərə alan nəzəriyyə ilə eksperimental nəticələrin analizi göstərmişdir ki, qeyri elastiklik əsasən elektronlararası qarşılıqlı toqquşma ilə əlaqədardır. Orta temperatur oblastında polyar optik fononlardan qeyri elastikliki səpilmə 7%-ə çatır. Elektron qazının güclü cırlaşması olan nümunələrdə *R(T)*-nin artmasının $Bi_{1-x}Sb_x$-də keçirici zonanın qeyri-parabolikliyi ilə əlaqədar olması təyin edilmişdir.

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О ХАРАКТЕРЕ РАССЕЯНИЯ И МЕХАНИЗМЕ ПРОВОДИМОСТИ НОСИТЕЛЕЙ ЗАРЯДА В СПЛАВАХ $Bi_{1-x}Sb_x$

Проведено комплексное исследование термомагнитных явлений в системе $Bi_{1-x}Sb_x$ в широком интервале температур и концентраций в слабых и сильных магнитных полях. Определены число Лоренца $L_{ex}(T,n)$ и электронная теплопроводность K_{el}. Показано, что L_{ex} в широком интервале *n* и *T* меньше зоммерфельдовского значения L_0. Сопоставлением экспериментальных данных с теорией, учитывающей влияние неупругости на L_0 установлено, что неупругость обусловлена, в основном, межэлектронным столкновением. В области средних температур неупругое рассеяние на полярных оптических фононах достигает 7%. Установлено, что возрастание *R(T)* в образцах с сильно вырожденным электронным газом частично обусловлено непараболичностью зоны проводимости состава $Bi_{0.88}Sb_{0.12}$.

Received: 16.06.09