THE SCATTERING OF CURRENT CARRIERS ON LONG-WAVE ACOUSTIC PHONONS IN $In_{1-x}Ga_xSb$ (x=0.3÷0.7) AT LOW TEMPERATURES

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The investigations of thermopower(α) and total thermal conduction(χ_{tot}) in solid solutions $In_{1-x}Ga_xSb$(x=0.30÷0.70) in temperature interval5÷300 K, are carried out. K $\alpha(T)$ and $\chi_{t_ot}(T)$ pass through maximum in interval~20÷25 and ~30÷40 K. $\chi_{tot}(T)$ maximum is explained by Callaway theory and α(T) maxima are connected with hole scattering on long-wave acoustic phonons. It is established that the shift of maxima $\alpha(T)$ and $\chi_{tot}(T)$ and also the dependence of phonon thermopower α_{ph} on T in $\alpha_{ph}\sim T^{-3.4}$ form are in accordance with Herring theory.

Keywords: thermopower, thermal conduction, scattering, effective mass, relaxation time.
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INTRODUCTION

Last time the investigations of semiconductor physical properties having the small width of forbidden band, small effective mass and big carrier mobility are intensively carried out. The one of such semiconductors is $A^{III}B^{V}$ – $A^{III}B^{V}$ solid solution. One can form high-sensitive thermogenerators on their base. The investigation of kinetic properties of $A^{III}B^{V}$–$A^{III}B^{V}$ solid solutions is of the big interest. $A^{III}B^{V}$–$A^{III}B^{V}$ solid solutions are obtained on the base of binary compounds $A^{III}B^{V}$и $A^{III}B^{V}$. The additional thermopower which appears because of charge carriers on long-wave acoustic phonons (phonon drag) is often observed at investigation of thermopower in $A^{III}B^{V}$and $A^{III}B^{V}$ compounds. The realization of new effect takes place at approximation of electron wave numbers to phonons that is satisfied as $\kappa \approx q$ (κ and q are wave numbers of electrons and phonons correspondingly) or electron wave length are equal to phono wavelength which are observed at low temperatures. $A^{III}B^{V}$ and $A^{III}B^{V}$ samples have *p*-type conduction. That's why solid solutions also have p-type conduction. For analysis of obtained results it is necessary to emphasize the hole (χ_h) and phonon (χ_{ph}) thermal conduction components such as $\chi_{ph} = \chi_{tot} L\sigma T$ where L is Lorentz number (L=2.44 ·10^{-8} Vt·Om/K) and σ is electric conduction. At low temperatures χ_{ph} is small enough, i.e. in this region T thermal conduction is totally supplied by phonons, then $\chi_{ph} \approx \chi_{tot}$. In samples with temperature decrease both the thermal conduction χ_{ph} and phonon thermopower α_{ph} increasing take place. Such observation takes place when the increasing limit χ_{ph} forms the sample boundary limiting the free phonon length l_{ph}.

The phonon drag is observed at low temperatures in $A^{III}B^{V}$ and $A^{III}B^{V}$ compounds [1]. One can expect that given effect also takes place in these solid solutions. The coefficients of thermopower and thermal conduction in $In_{1-x}Ga_xSb$ (x=0.30÷0.70) in temperature interval 5÷300K (fig. 1 and 2) are investigated for this purpose. As it is seen from fig.1 and 2, $\alpha(T)$ in~20÷25K interval and $\chi_{t_ot}(T)$ in ~30÷40K interval pass maximum. Such observation takes place when the increase limit χ_{ph} forms the sample boundary limiting the free phonon length l_{ph}. As it is known, in crystal thermal conduction takes place whole phonon spectrum for which the effective mean free path $\bar{l}_{ph}$ is less than phonons have taking part in drag process as $\bar{l}_{ph} \ll l_{ph}$ then $\alpha_{ph}(T)$ maximum in comparison with $\chi_{ph}(T)$ maximum should be shifted to the side of low temperatures. As the maximum position depends directly on investigated sample size, for experimental question solution it is necessary to carry out χ_{ph} and α_{ph} measurements on the one and the same sample. The given question is discussed for different materials in several works [1-5]. In these woks it is revealed that $\chi_{ph}(T)$ and α_{ph}(T) maxima coincide at low temperature shift. As phonon thermopower is observed in *p*-InSb and *p*-GaSb [4] samples then it is expected that this effect can be also observed in $In_{1-x}Ga_xSb$ solid solutions which are obtained on their base. Here one moment presents interest by the fact that hole concentration and hole effective mass strongly differ from crystal *p*-InSb *and* *p*-GaSb. These distinctions should lead to the maximum shift in $\alpha(T)$ and $\chi_{ph}(T)$ in $In_{1-x}Ga_xSb$ in comparison with *p*-InSb and *p*-GaSb. From this point of view it is necessary to investigate $\alpha(T)$ and $\chi_{ph}(T)$ temperature dependences on composition dependence in $In_{1-x}Ga_xSb$ at low temperatures.

From above mentioned it is followed that the given work is dedicated to investigation of $\chi_{ph}(T)$ and $\alpha(T)$ in $In_{1-x}Ga_xSb$ (x=0.3÷0.70) at low temperatures.

EXPERIMENT TECHNIQUE

The measurement of coefficients of thermopower and thermal conduction are carried out in the crystal taken for measurement of kinetic coefficients in region 5÷300 K [6]. The temperature measurements in interval 5÷40 K are carried out by resistance carbon thermometer. The solid solution InSb-GaSb is obtained by the method zone leveling at different velocities [7]. The temperature dependences α and χ_{ph} for four samples of $In_{1-x}Ga_xSb$ are shown in Fig.1,2.

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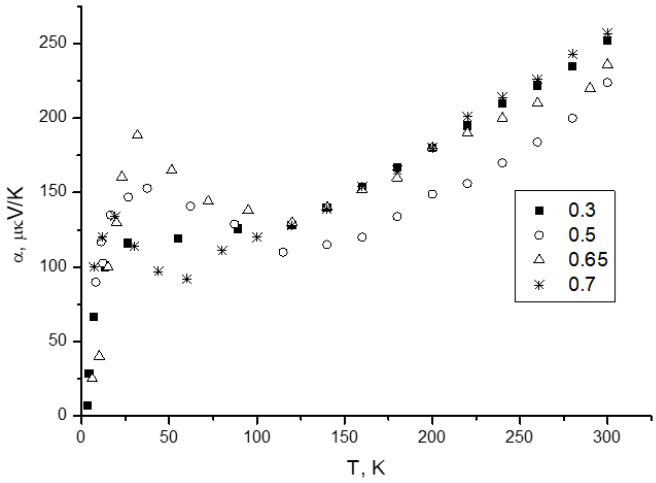

Fig.1. Temperature dependence of thermopower in $In_{1-x}Ga_xSb$ (x=0,3÷07) , where:
■- x=0.3; 0-(x=0.5); Δ- (x=0.65); ∗ – (x=0.7)

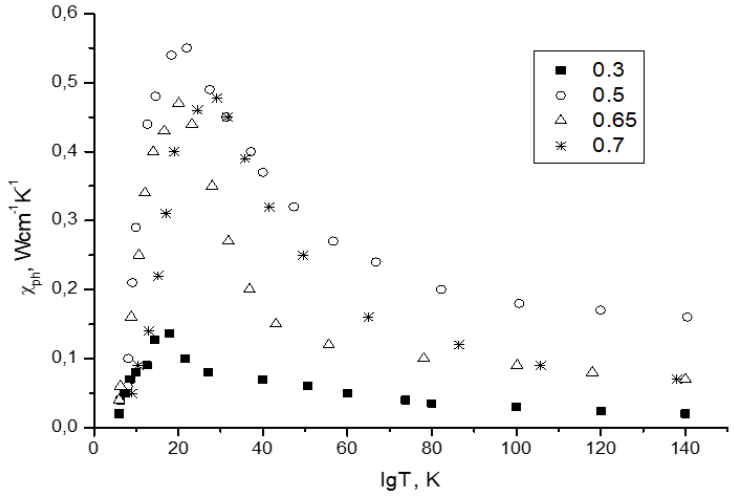

Fig.2. Temperature dependence of thermal conduction in $In_{1-x}Ga_xSb$ (x=0.3÷0.7)
■- x=0.3; 0-(x=0.5) ; Δ- (x=0.65); ∗ – (x=0.7)

As it is seen, in $In_{1-x}Ga_xSb$ thermopower increases going through maximum at T~20÷25 K beginning from 100K with temperature decrease. The thermal conductivity coefficient values χ_{ph} is significantly lower than in $A^{III}B^{V}$ crystals, the temperature motion χ_{ph} in region 90-300K isn't strong, maximum is situated in temperature interval T~30÷40K .

RESULT'S ANALYSIS

From fig.1 it is seen that $\alpha(T)$ goes through maximum in $In_{1-x}Ga_xSb$ solid solutions at temperature T~20÷25 K. $\alpha(T)$ increase at T<100 K can be accepted as phonon drag effect $\alpha_{ph}(T)$. α_{ph} exceeds diffusion component α_d beginning from T≈100 K. The hole part of thermal conductivity in $In_{1-x}Ga_xSb$ is small one, then curve $\chi_{tot}(T)$ also can be accepted as phonon part $\chi_{ph}(T)$ at T <100K because of electric conduction σ(Fig.3).

This shows that in $In_{1-x}Ga_xSb$ α_{ph} maxima to the side of low T than χ_{ph}(~45K) maxima, i.e. the theory prediction realizes. The analysis in limits of Kalavey theory [8] which allows all possible scattering mechanisms takes place by $\chi_{ph}(T)$ data. One can suppose that maximum $\chi_{ph}(T)$ at T~40-50K is caused by scattering of phonons on boundaries, point defects and phonons (umklapp and normal processes). The qualitative correlation allows us to conclude that in $In_{1-x}Ga_xSb$ there are enough quantity of eigen defects leading to intensive phonon scattering. χ_{ph} decrease in T~100-300 K interval takes place because of the influence of normal processes on χ_{ph} value. From $\chi_{ph}(T)$ curves, it is seen that increases on $\chi_{ph} \infty T^{2.2}$ law up to $\chi_{ph}(T)$ maximum. From general theory of thermal conduction, it follows that $\chi_{ph} \infty T^3$ condition satisfies. Besides, such distinction is connected with the fact that at low temperatures the phonons scatter on big effective mass of charge carrier especially on samples with p-type conduction. This type of scattering is especially intensive at low temperatures - 9-11].

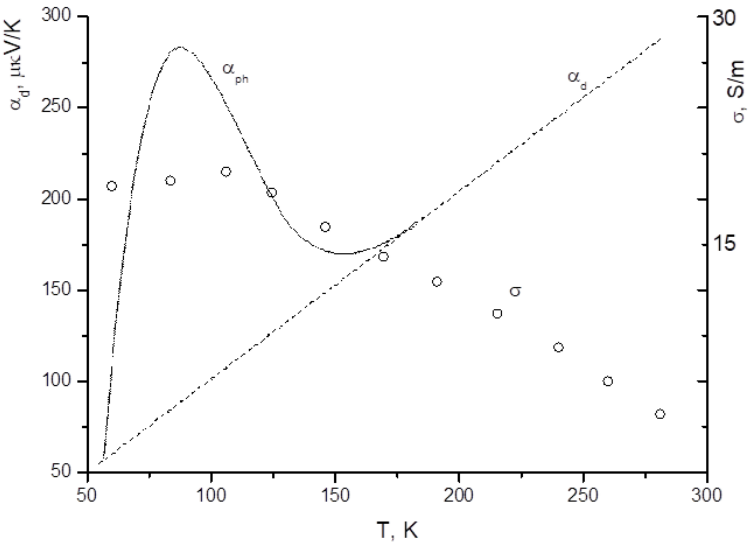

Fig.3. Calculation values $\alpha_{ph}(T)$, $\alpha_d(T)$ and experimental value σ(T) in $In_{1-x}Ga_xSb$

For theoretical analysis of $\alpha_{ph}(T)$ one should use Herring theory according to which α_{ph} value is defined by formula [12]:

$$\alpha_{ph} = \frac{k_0}{e}\frac{m^* V_0^2 <\tau_{ph}>}{3k_0 T \tau_e} - \qquad (1)$$

where κ_0 is Boltzmann constant, m^* is effective mass of charge carrier, V_0 is group velocity of long-wave phonons interacting with charge carriers (velocity of sound), τ_e is relaxation time of charge carrier is caused only by this process of interaction, $<\tau_{ph}>$ is averaged relaxation time of long-wave phonons defined by their interaction with whole crystal phonon spectrum, with defects of charge carriers and crystal boundaries. From formula [1] it is seen that of $<\tau_{ph}>$ big value, i.e. high thermal conductivity is formed for drag effect appearance at not small effective mass of charge carriers. In this case α_{ph} temperature motion is defined by τ_{ph}/т temperature motion. $<\tau_{ph}(\text{т})>$ dependence by Herring is caused by crystal symmetry [12].

For $\alpha_{ph}(T)$ calculation in approximation of relaxation time in the dependence on scattering on long-wave acoustic phonons is defined by following way. The averaged relaxation time of long-wave phonons is expressed by formula [13,14].

$$<\tau_{ph}(\text{т})> = \frac{1}{4\text{к}^4}\int_0^{2\text{к}} \tau_{ph} q^3 dq \quad , \qquad (2)$$

where

$$\tau_{ph}^{-1} = \frac{\hbar q}{\rho_0}\left(\frac{k_0 T}{\hbar V_0}\right)^4 V_0 \quad , \qquad (3)$$

here ρ_0 is crystal density. Substituting the (3) expression in formula (2) for the definition of averaged relaxation time of long-wave phonon we obtain:

$$<\tau_{ph}> = \frac{2\rho_0}{3\sqrt{2m^* k_0 T}}\left(\frac{\hbar V_0}{k_0 T}\right)^4, \qquad (4)$$

Taking under consideration formula (4) for averaged absorption mean free path of long-wave phonons we obtain the following expression

$$l = \frac{2\rho_0}{3\sqrt{2m^* k_0 T}}\left(\frac{\hbar V_0}{k_0 T}\right)^4 V_0 \quad , \qquad (5)$$

For τ_e definition including in formula (4) and for charge scattering the carriers on acoustic phonons at standard band has the form [15]:

$$\tau_{ac}(T) = \frac{9\pi}{2}\frac{\rho V_0^2 \hbar^4}{C^2 (2m^* k_0 T)^{3/2}} \qquad (6)$$

C is constant where it connects with deformation of E_d lattice deformation potential by following way $E_d = \frac{2}{3}C$ [15]. Substituting ρ, V_0, C, m^* values in formula (5), we define $\tau_e(T)$. Taking under consideration $<\tau_{ph}>$ and τ_e in formula (1) we define $\alpha_{ph}(T)$. The general thermopower is equal to sum of partial phonon and diffusion thermopower (α_d) as

$$\alpha = \alpha_{ph} + \alpha_d$$

where $\alpha_d = -\frac{\kappa_0}{e}\left[r + 2 + \ln\frac{2(3\pi m^* k_0 T)^{3/2}}{\hbar^3 n}\right]$. Here r is scattering mechanism parameter, n is charge carrier concentration.

The calculative data of $\alpha_{ph}(T)$ and $\alpha_d(T)$ for sample $In_{0.5}Ga_{0.5}Sb$ (where V_0= $5.2\cdot10^5$ cm/c, ρ_0=5.66 gr/cm^3, m^*=0.340m$_0$, E_d=45 eV) are presented in Fig.3.

As it is seen from fig.3 the theoretical calculation of maximum value $\alpha_{ph}(T)$ in comparison with experimental one is in two times bigger.

This can be connected with two reasons:

1) the shifted scattering (acoustic ions) takes place in this temperature region,
2) the hole gas is strongly degenerated. For confirmation of second preposition the chemical

potentials at $T \leq 20$ K are defined by formula [15]:

$$\alpha = -\frac{k_0}{e}\left[\frac{F_{r+2}}{F_{r+1}} - \mu^*\right] \quad , \qquad (6)$$

μ^* is given chemical potential, $F(\mu^*)$ is one-parameter Fermi integral. The obtained data are given in the table.

Table

The band parameters in $In_{1-x}Ga_xSb$

x	P, cm^{-3} 10^{16}	$\eta^*(T=15\ K)$	m^*	E_g, eV (T=0 K)	μ, $cm^2/V{\cdot}s$ T=15 K	E_d, eV
0.20	4,5	14	0.363 [13]	0.285[13]	2800	42
0.50	5.0	16	0.340 [16]	0.370[16]	2764	45
0.65	6.30	19	0.376[13]	0.368 [13]	2500	47
0.7	6.80	21	0.389[13]	0.775[13]	1782	50

P is hole concentration, m^* is effective mass of holes, E_g is forbidden band width, μ is hole mobility, E_d is deformation potential.

The comparison of experimental and calculative data of $\alpha_{ph}(T)$ and table data show that this effect is strongly emphasized at removal of hole gas degeneration, i.e. the hole drag on long-wave acoustic phonons more intensively changes in the dependence on crystal symmetry [12]. For general dependence α_{ph} (T) hasn't universal form in the region of its increase up to maximum.

The theoretical calculation shows that we should take charge carrier scattering on lattice acoustic oscillations for $\alpha_{ph}(T)$ definition.

From theory, it is followed that significantly bigger effective mass of charge carriers, absence of electron gas degeneration and big value of $<\tau_{ph}>$ long-wave phonons in $In_{1-x}Ga_xSb$ cause the strong effect of hole increasing by phonons. The rest values of formula (1) weakly depends on temperature.

The analysis of other crystals shows that the given drag effect shows that α_{ph} should depend on T as $\alpha_{ph} \infty T^{-3,5}$ for cubic crystals and depend on as $\alpha_{ph} \infty T^{-3}$. Inn temperature interval the charge carries scatter on ions, drag effects weakens and it influences on $\alpha_{ph}(T)$ dependence. If the phonon free path length achieves the sample minimum sizes ($\tau_{ph} = const$), temperature motion of $\alpha_{ph}(T)$ is defined by $1/T\ \tau_e$ value change on temperature at $\tau_e \infty T^{-3/2}$, $\alpha_{ph} \infty T^{-0.5}$.

$In_{1-x}Ga_xSb$ solid solutions are related to the number of diamond-like structure [17]. According to this the calculation shows that α_{ph} dependence on T has the form $\alpha_{ph} \sim T^{-3.4}$. In experiment this fact is designated as $\alpha_{ph} \sim T^{-3}$. Probably these distinctions in this temperature region are connected with the fact that there is additional scattering mechanism.

Thus, the going through $\alpha_{ph}(T)$ maximum at $\alpha_{ph}(T)$ temperature interval in $In_{1-x}Ga_xSb$ solid solutions totally agrees by Herring theory as charge carrier drag by phonons caused by unique scattering mechanism of long-wave phonons.

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