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The Effect of Phonon Drag of Charge Carriers in $In_{1-x}Ga_xSb$

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Abstract

The temperature dependencies of the thermal power a_0 and thermal conductivity κ in two samples of $In_{1-x}Ga_xSb$ ($x = 0.65$ and 0.45) doped by Te$\sim$ 0.001 at%, with electron concentration $n = 5.9 \cdot 10^{16}$ and $1.3 \cdot 10^{17}$ cm^{-3} (at 100K), have been investigated. It is shown that in $In_{0.35}Ga_{0.65}Sb$ a_0 increases with decreasing T below 50K. At 14K a_0 passes through maximum and it falls sharply with decreasing T. It is shown that the maximum value of a_0 is in agreement with the maximum value of κ. In $In_{0.55}Ga_{0.45}Sb$, starting from T = 4.2K, a_0 is shown to increase monotonically. For $In_{0.35}Ga_{0.65}Sb$, thermal power due to phonon drag a_{ph} is derived and its dependence on temperature, $\alpha_{ph}(T)$, is plotted. It is shown that when α_{ph} rises with decreasing T, $\alpha_{ph}(T)$ changes as $T^{-2.6}$; and when the curve falls, it is characterized by a power index of 2.8. These results for $In_{0.35}Ga_{0.65}Sb$ compare reasonably well to other semiconductors for solid solutions and are in good agreement with Herring theory.

1. Introduction

In semiconductors at low temperatures moreover the diffusion thermal power of electron gas α_0, is possible for the additional coupling of the thermal power connected by the phonon drag effect of the charge carriers. This additional thermal power component owes its origin to the effect in which the phonon and electron flow moving in the same direction affects the electron distribution. It is known that the phonon drag effect is observed in samples having high lattice thermal conductivity κ_L and when effective mass, m^*, of charge carriers is not excessively small. Since phonon drag is possible in semiconductors with small charge carrier concentration n and low T, according to Herring theory [1], the total thermal power of α_0 semiconductor with small n can be presented as $\alpha_0 = \alpha_d + \alpha_{ph}$, where α_d is the diffusion thermal power of electron gas, and α_{ph} is the thermal power due

to phonon drag of the carriers. To determine the temperature dependence of α_{ph}, one should assume that charge carriers are scattered on long-wave acoustic phonons (which have mobility with temperature dependence $U \sim T^{-3/2}$). Then, for cubic crystals, one must observe $\alpha_{ph} \sim T^{-3.5}$. Such a dependence is observed experimentally only for diamond [2], but for Ge, Si and p-InSb the dependence was weak, i.e. $\alpha_{ph} \sim T^{-(3\div 2.3)}$ [3]. The phonon drag effect is observed in GaSb doped by Ge and Si [4]. The beginning of the phonon drag effect on the $\alpha_0(T)$ curve is shifted to the low T region with increasing n. However, nothing has been reported about α_{ph} for the $In_{1-x}Ga_xSb$ system.

2. Results and Discussion

In this work measurements of α_0 and κ in two samples of $In_{1-x}Ga_xSb$ system (x=0.5) doped by ~ 0.001 at % Te is presented. The samples are cut from ingot and prepared by the method described in [5,6]. Both samples have n-type conduction. It is known that at zone level, due to mass transfer, it is difficult to obtain samples of solid solution with stable composition. Therefore the character of the Tellurium-doped $In_{0.5}$ $Ga_{0.5}Sb$ samples, i.e. main physical parameters such as *Eg,* ρ and m^* among others, vary with position within the ingot. The composition of investigated samples is determined *via* the lattice parameter constant $\overline{a}$, which has the dependence $\overline{a} \sim f$ *(mol*% GaSb), and is determined by x-ray structure analysis. The investigated samples are found to have the following compositions: $In_{0.35}Ga_{0.65}Sb$ and $In_{0.55}$ Ga $_{0.45}Sb$

The temperature dependencies of α_0 and κ are given in Fig. 1. As it can be seen, in $In_{0.35}Ga_{0.65}Sb$, beginning from 50K, α_0 increases with decreasing T. Maximum value of κ in In $_{0.35}Ga_{0.65}Sb$ is more then the maximum value of thermal conductivity in $In_{0.55}Ga_{0.45}$ Sb. In the $In_{0.35}Ga_{0.65}Sb$ sample, beginning with $T = 50$ K, the thermal power increases with decreasing T, and at $T = 14$ K, a_0 passes through a maximum, after which it monotonically decreases. In the $In_{0.55}Ga_{0.45}Sb$ sample, the thermal power decreases with decreasing T. So, in the $In_{0.35}Ga_{0.65}Sb$ sample there is the phonon drag effect of charge carriers. In this range the thermal power consists of two components, diffusion and phonon parts of α_0. The diffusion part can be determined by extrapolation of experimental data of thermal power in the low T range, as it can be seen in Fig. 2a (dot-dash curve). The temperature dependence of the diffusion part α_d has been calculated according to [7]:

$$\alpha_d = \frac{k_0}{e} - \left[\frac{I^1_{r+1,2}(\eta^*, \beta)}{I^0_{r+1,2}(\eta^*, \beta)} - \eta^*\right],$$

where $I^m_{n,p}$ are two-parameter Fermi integrals; η^* is the reduced chemical potential; $\beta = k_0T/E_g$ is a non-parabolic parameter, and r is the scattering mechanism parameter. These calculations allow one to determine the temperature dependencies of reduced chemical potentials (see bottom part of Fig. 1), allowing one to conclude the degree of carrier degeneracy in the 40-300K region. It can be seen that in In $_{0.55}Ga_{0.45}Sb$ the degeneracy is strong and in In $_{0.35}Ga_{0.65}Sb$ the partial degeneracy at low temperatures

is gradually removed with increasing T. Evaluating η^* in $In_{0.35}Ga_{0.65}Sb$ ($n = 6 \cdot 10^{16}$ cm^{-3}), the degree to which $\beta = k_0T/E_g$ is non-parabolic is considered Band gap E_g is taken from [8] to be 0.5 and 0.43 eV at temperatures 0 and 300K respectively. Thus after determination of $\alpha_0 - \alpha_{ph}$, which is equal to α_d, $\eta^*(T)$ is calculated with correction for the non-parabolicity of band dispersion.

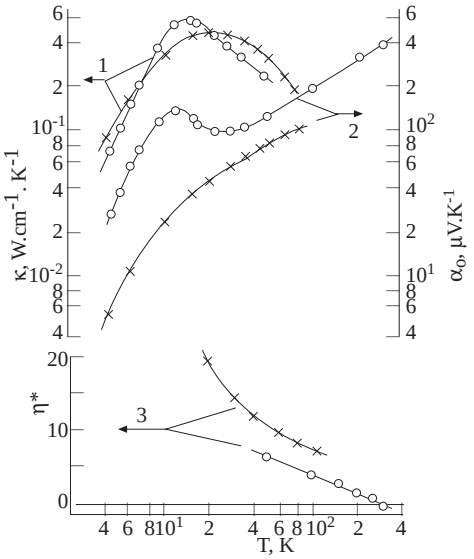

Figure 1. Dependence of thermal conductivity (1), thermal power (2) and reduced chemical potential (3) on temperature.
Samples: **0** - $In_{0.35}Ga_{0.65}Sb$
x - $In_{0.55}$ $Ga_{0.45}Sb$.

Figure 2b presents $a_{ph}(T)$, with both axes in logarithmic scale. The right part of the curve seems to be governed by exponential index equal to -2.6, in good agreement with Herring theory; the left side of the curve shows exponential index equal to 2.8. We note that, as in $a_{ph}(T)$ and $\kappa(T)$ for $In_{0.35}Ga_{0.65}$ Sb , degree index in the dip are close and are equal 2.8 and -2.6, respectively. Both curves of $\alpha_0(T)$ and $\kappa(T)$ passes through a maximum at $T_{max} \cong 14\ K$ for the $In_{0.35}Ga_{0.65}Sb$ sample. In both samples of $In_{1-x}Ga_xSb$ (x=0.35 and 0.55) the heat transport is realized mainly by the longwave phonons at $T < T_{max}$. According to [8,9] at low temperatures the phonons in $In_{0.35}Ga_{0.65}Sb$ are scattered mainly by the point defects, and in $In_{0.55}Ga_{0.45}Sb$ by the charge carriers. The maxima in $\kappa(T)$ (see Fig. 1) curves in investigated samples have been displaced on the temperature scale. This fact is due to the distinction of component contents and the distinction of the principal scattering mechanism of phonons (recall that the $\kappa(T)$ maximum in InSb takes place at $T \cong 8K$, while in GaSb it takes place at $T \cong 28K$ [8,9]).

To determine the scattering mechanism, diffusion thermal power of charge carriers for two values of r were calculated, results of which are given in Fig. 2a. We note that in

the temperature range 4.2-300K, Hall coefficient R changes very slightly, and does not depend on magnetic field H. These results indicate that only electrons take part in the physical effects. These results, together with experimental data for n and the effective mass of current carriers at the bottom of the conduction band for sample $In_{0.35}Ga_{0.65}Sb$ $(m^* - 0.0295m_0)$ [8], allow determination of the temperature dependence α_d using the following relationship [7]:

$$\alpha_d = \frac{k_0}{e}\left[r + 2 + \ln\frac{2\left(2\pi m_0^* kT\right)^{3/2}}{h^3 n}\right],$$

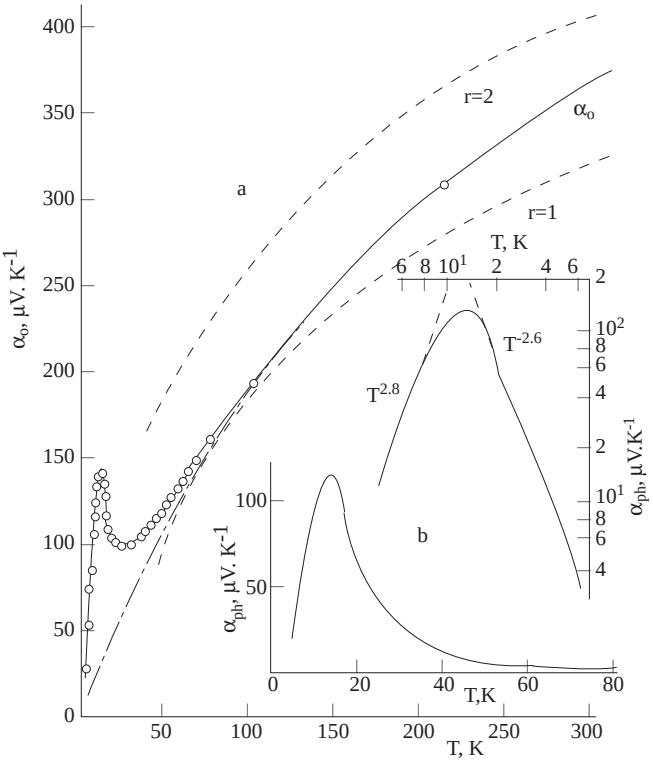

Figure 2. The temperature dependence of the thermal power in $In_{0.35}Ga_{0.65}Sb$.

a) The total thermal power. The dotted curves are calculated curves of diffusive thermal power of a_d at various scatter mechanisms (r=l is scatter by optical phonons; r=2 is scatter by charge impurities); the point-dotted curve is extrapolated diffusive thermal power in phonon drag region

b) The separated phonon contribution of thermal power

where r is the parameter for the scattering mechanism of the charge carriers, m_0^* is the effective mass of electrons at the bottom of the conduction band and n is electron

concentration. Calculations of α_d are performed for both cases of charge carrier scattering on impurity ions and optical lattice vibrations. As can be seen in Fig. 2a, $\alpha_0(T)$ and $\alpha_d(T)$ (the latter is calculated with the regard of scattering of charge carriers on impurity ions $r = 2$) lie parallel with $\alpha_d(T)$ above $a_0(T)$. Thermal power calculated with charge carriers scattering on optical thermal lattice vibrations of $(r = 1)$ in mind lies lower and is close to experiment. It is seen that below 160K, α_0 compares well with the calculated value of α_d at $r = 1$. Above 160K, the contribution from optical thermal vibrations is reduced, whereas the contribution from scattering on impurity ions increases. We note that the contribution of scattering of charge carriers on impurity ions at 20K is less than 10% and starting from 160K it increases with temperature. The displacement of α_0 between calculated curves for α_d at $r = 1$ and $r = 2$ indicate the equivalent effects of these mechanisms at 300K.

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