ABSORPTION OF TRANSVERSE ULTRASONIC WAVES IN INDIUM ANTIMONIDE

JAROSLAV KOVÁŘ*, Žilina

The present paper deals with experimental investigation of frequency and temperature dependences of transverse acoustic waves in the [111] and [110] direction, respectively. Absorption is mainly due to internal friction (viscosity). From experimental values of the absorption coefficient for pure slow and fast transverse waves in the [110] direction and using the theoretical relations of de Vault, the following viscosity coefficients were found for InSb at room temperature: $\eta_{11} = 8.78 \times 10^{-2}$ g cm^{-1}s^{-1}, $\eta_{12} = 6.70 \times 10^{-2}$ g cm^{-1}s^{-1}, $\eta_{44} = 1.15 \times 10^{-2}$ g cm^{-1}s^{-1}. With these values the attenuation of transverse waves in the [111] direction was computed and a good agreement with experimental results was found. The knowledge of viscosity coefficients enables also to determine that part of absorption, for which the internal friction is responsible in the case of longitudinal waves in the [111] and [110] directions. It was shown that the part proportional to the viscosity is in both cases approximately one third of the measured value at room temperature, which means that the longitudinal waves in InSb are more damped by thermal conductivity then by viscosity.

The temperature dependence of the absorption in the range of 200°K — 300°K follows the temperature dependence of the specific heat in accordance with the theory of transverse waves attenuation in dielectric crystals.

I. INTRODUCTION

The attenuation of longitudinal accoustic waves in In Sb has been investigated in papers [1—4]. For a complete understanding of the dominant reason for the attenuation it is necessary to investigate also the frequency and temperature dependences of transverse acoustic waves.

From the phenomenological point of view [5] longitudinal acoustic waves in ideal dielectric crystals are damped by thermal conduction and internal friction of viscosity, while for the absorption of transverse waves only the internal friction is responsible. Since the absorption on the conduction electrons

* Katedra fyziky Vysokej školy dopravnej, ŽILINA, Marxa—Engelsa 25.

in InSb in the absence of outside fields is negligible, we can apply the theory of absorption in perfect dielectric crystasl also to perfect single crystals of InSb.

By examining the transverse waves attenuation for various crystalographic directions and known theoretical relations, it is possible to determine the viscosity coefficients and by the use of them to determine that part of the longitudinal waves for which the thermal conductivity is responsible. This is the main purpose of this paper.

II. ABSORPTION OF TRANSVERSE WAVES

The phenomenological theory gives for the absorption coefficient due to internal friction the relation of the type

$$\alpha = \frac{\omega^2}{2\varrho v^3} \eta,\tag{1}$$

where ω is the angular frequency of the acoustic wave, ϱ is the density, v is the velocity of the wave and η characterizes the viscosity. The quantities v and η depend on the directions of propagation of the wave. In cubic crystals the viscose properties are in the first approximation characterized by the three viscosity coefficients η_{11}, η_{12}, η_{44} in a similar way as elastic properties are determined by the three coefficients c_{11}, c_{12} and c_{44}.

The quantities ϱv^2 and η for the examined waves can be expressed through elastic and viscosity coefficients in the following way:

For a transverse wave parallel to the [111] direction

$$\varrho v^2 = \frac{1}{3}(c_{11} - c_{12} + c_{44}), \quad \eta = \frac{1}{3}(\eta_{11} - \eta_{12} + \eta_{44}).\tag{2}$$

For a transverse wave parallel to the [110] direction and polarized in the [001] direction

$$\varrho v^2 = c_{44}, \quad \eta = \eta_{44}.\tag{3}$$

For a transverse wave parallel to the [110] direction and polarized in the [110] direction

$$\varrho v^2 = \frac{1}{2}(c_{11} - c_{12}), \quad \eta = \frac{1}{2}(\eta_{11} - \eta_{12}).\tag{4}$$

For a longitudinal wave parallel to the [111] direction

$$\varrho v^2 = \frac{1}{3}(c_{11} + 2c_{12} + 4c_{44}), \quad \eta = \frac{1}{3}(\eta_{11} + 2\eta_{12} + 4\eta_{44}).\tag{5}$$

For a longitudinal wave parallel to the [110] direction

$$\varrho v^2 = \frac{1}{2}(c_{11} + c_{12} + 2c_{44}), \quad \eta = \frac{1}{2}(\eta_{11} + \eta_{12} + 2\eta_{44}).\tag{6}$$

III. EXPERIMENTAL RESULTS

The measurements of the transverse waves attenuation were done on three samples. Electron concentration, mobility and other parameters of these samples are in Table 1.

Table 1

No	Type	Doping	Orient.	T [°K]	n [cm^{-3}]	u [cm^{2}V^{-1}s^{-1}]
1	N	Te	111	300	4.6×10^{12}	2.17×10^4
2	N	Te	111	77	4.5×10^{15}	1.3×10^5
3	N	Te	110	77	6.8×10^{14}	3.5×10^5

The frequency dependence of transverse waves attenuation in these samples can be seen in Fig. 1. The experimental results for all three samples show the
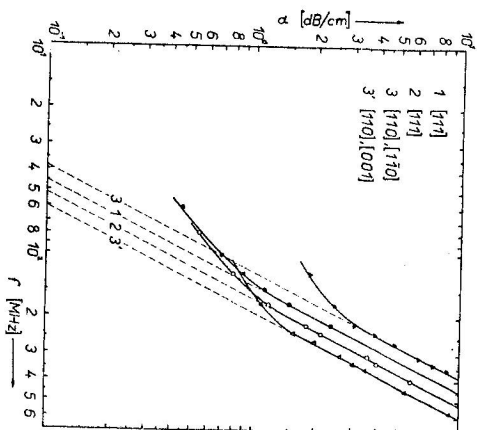

1   1 [111]
2   2 [111]
3   3 [110],[1̄10]
3' [110],[001]

Fig. 1. Dependence of the attenuation coefficient on frequency at 300 °K for transverse waves. The first bracket indicates the direction of propagation, the second the polarization of the wave.

dependence of the type $\alpha \sim \omega^2$. Deviations from the quadratic dependence set in at frequencies lower than 170 MHz and are not due to the real absorption in the samples but represent other losses like: a) diffraction losses, b) losses in the bond, c) losses due to the fact that a Y-cut transducer generates apart from a transverse wave to a small extent also a longitudinal wave because of the discontinuity of conditions on the sample — transducer boundary. All these factors influence the results of measurement especially in the range

of lower frequencies, while at high enough frequencies they can be neglected. A more detailed examination of these losses or their estimation has not been done, since it was not necessary for the purpose of the present paper. The determination of viscosity coefficients has been done from measurements, which are not appreciably influenced by the above mentioned losses.

The measurement of the attenuation of a transverse wave parallel to the [110] direction and polarized in the [001] direction enables according to the relations (1) and (3) to determine the coefficient η_{44} and the measurement for a transverse wave travelling in the same direction but polarized in the [110] direction enables according to relations (1) and (4) to determine the quantity (η_{11} — η_{12}).

According to the theory of De Vault [6] the following relation between the coefficients η_{11} and η_{44} holds

$$\frac{\eta_{11}}{\eta_{44}} = \frac{I_{11} - \gamma^2}{I_{44}},$$

where γ is the Grüneisen constant, I_{11} and I_{44} are quantities which can be computed if the elastic coefficients of the second and the third orders are known. For γ we have used the value 0.58 [7] and for the elastic coefficients we have used the values from [8]. Then we have computed I_{11} and I_{44} from the approximative formula given by De Vault [6] and we have obtained $I_{11} = 1.68$, $I_{44} = 0.175$. This enables us to determine all three viscosity coefficients for InSb. Their values at room temperature are: $\eta_{11} = 8.78 \times \times 10^{-2}$g cm^{-1}s^{-1}, $\eta_{12} = 6.70 \times 10^{-2}$g cm^{-1}s^{-1}, $\eta_{44} = 1.15 \times 10^{-2}$g cm^{-1}s^{-1}.

Using these values, the absorption of a transverse wave parallel to the [111] direction has been computed according to relations (1) and (2), which fits the experimental data gained for sample 1. The measured values of sample 2 for the same wave, obtained experimentally, are somewhat smaller. The very good agreement of computed and measured values on sample 1 should be, however, considered rather accidental, since the approximately 10 % mistake could not be avoided by attenuation measurements and also approximative theoretical formulae have been used in computations. Nevertheless, we can conclude that formula (1) can well explain the measured absorption of transverse waves in InSb and the determined values of viscosity coefficients are reasonable.

This enables us to estimate also the contribution of internal friction to the absorption of longitudinal waves parallel to the [110] and [111] directions, respectively. For the frequency of 175 MHz of a longitudinal wave parallel to the [110] direction, the absorption due to internal friction at room temperature has been computed as 1.6 dB cm^{-1}, while the measured value is

4.6 dB cm⁻¹, which means that the absorption of a longitudinal wave due to thermal conductivity is approximately twice the absorption due to viscosity. Similarly it is also for the longitudinal wave parallel to the [111] direction where for the same frequency we have measured the absorption 4.0 dB cm⁻¹ and by the use of here determined viscosity coefficients we have computed the value 1.38 dB cm⁻¹ as a contribution corresponding to the internal friction. Again the thermal conduction gives approximately twice larger absorption than viscosity.

Apart from the investigation of frequency dependences of transverse waves, the temperature dependence in the range of 180 °K to 300 °K have been determined. The experimental results are in Fig. 2.
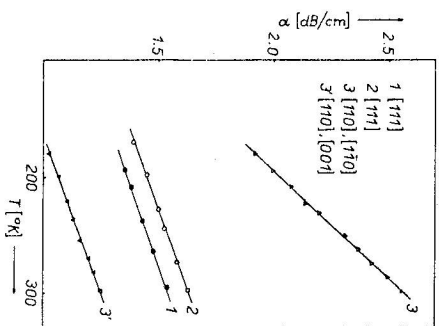

Fig. 2. Dependence of the attenuation coefficient on temperature at 175 MHz for transverse waves. The first bracket indicates the direction of propagation, the second bracket indicates the polarization of the wave.

According to the theory of the absorption of transverse waves in perfect dielectrics [6] for frequencies for which the relation $\omega\tau \ll 1$ holds, τ being the relaxation time for thermal phonons, the absorption is given by the formula

$$\alpha = \frac{\omega^2}{2\varrho v^3}\,\tau T C_v l .$$

Comparing this relation to the phenomenological formula (1) we get

$$\eta = \tau T C_v l ,$$

where C_v is the heat capacity of the unit volume, l can be computed when the elastic constants of the second and the third orders are known. Since in the investigated temperature range the relaxation time is approximately proportional to T^{-1} and the quantity l similarly as the Grüneisen parameter γ does not depend appreciably on the temperature in the range above the Debye

temperature (for InSb 202.5 °K), we can expect that the temperature dependence of the viscosity η and also the absorption coefficient of transverse waves will be determined mainly by the temperature dependence of the heat capacity. The character of the C_v versus the T dependence according to measurements done by Piesbergen [9] is shown in Fig. 3, from which it can be seen that in the range of 200 °K to 300 °K C_v similarly as α increases approximately linearly with increasing temperature.
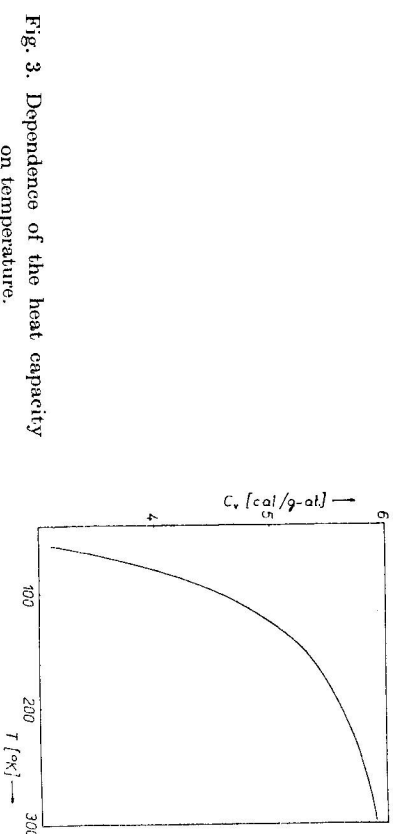

Fig. 3. Dependence of the heat capacity on temperature.

Therefore the formula (1) can explain well also the temperature dependence of transverse waves attenuation in InSb.

IV. CONCLUSION

The results of the measurements of the longitudinal [2] and transverse waves attenuation in InSb point to the fact that it is mainly the interaction with thermal phonons which is responsible for the attenuation of acoustic waves in the examined temperature range. Experiments show that the conclusions of some authors stating that at higher temperatures the attenuation converges to a constant value cannot be generalized. In InSb in the range above the Debye temperature the attenuation of longitudinal waves in good single crystals decreases with increasing temperature [2], while the attenuation of transverse waves, as we have shown in this paper, still increases.

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