Peculiarities in the amplification of ultrasound in n-InSb in strong magnetic fields

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It is demonstrated experimentally that, in order to account for the phenomenon of ultrasonic amplification in n-InSb at T = 77°K in a wide frequency range and over a large interval of electric fields, it is necessary to take into proper consideration both the loss component of the relaxation time of the electrons with respect to the momentum and the electron-temperature wave accompanying the ultrasonic wave.

The collision-free mechanism of electron amplification of sound (amplification of sound waves of the Landau type) plays a fundamental role in n-InSb crystals at temperatures of liquid nitrogen and at frequencies ≥ 0.5 GHz. This means that the condition

$$ql > 1, \tag{1}$$

is satisfied at such frequencies, where q is the wave number of the sound and l is the mean free path of the electrons.

A number of researches[1,2] have been devoted to this phenomenon, in which excellent agreement has been noted with the theories of[3]; the value of the electron temperature T_e has been estimated from curves of the sound amplification. However, the picture of the phenomenon of amplification becomes complicated in the case of widening the frequency range of investigation and in the use of large values of the drift velocity, and the simple approach of[3] turns out to be inapplicable. Clarification of the peculiarities of sound amplification over a wide range of frequencies and electric fields is the purpose of the present work.

Before considering and discussing the principal results of the experiment, we pause briefly to discuss the method of measurement.

The measurements were carried out on n-InSb crystals ($n = 1.9 \times 10^{14}$ cm^{-3}, $\mu = 7 \times 10^5$ cm^2/V-sec at T = 77°K) in the frequency range 0.4–3.0 GHz. Samples measuring $1.5 \times 1.5 \times 7.0$ mm were cut along the [110] axis. Epitaxial film transducers of CdS were grown on the ends of the samples by means of a gas-transport reaction. These assured the excitation in the crystal of piezo-active shear ultrasonic waves according to a scheme previously described in[5]. The double conversion losses did not exceed 50 dB over the frequency range investigated.

The electron drift velocity v_d was found from the value of the total current through the sample I, $v_d = I/neS$, where n is the concentration of electrons, e the electron charge, and S the cross-section area of the crystal. To ensure linear amplification of the ultrasound, the intensity of the sound signal at the input was always kept to a minimum; the value of the sound signal exceeded by 5–6 dB the noise level of the receivers P5-3 and P5-4, the sensitivity of which was ~120 dB/W. Errors in the determination of the coefficient of electronic amplification of the ultrasound did not exceed ±0.5 dB/cm.

Let us trace the effect of heating of the electrons by the electric field, which causes carrier drift, on the amplification. The experimental dependences of the gain G on the electron drift velocity for a number of frequencies are shown in Fig. 1. It is seen from the drawing that at the frequency f = 0.5 GHz, the dependence has a clearly noticeable superlinear character, beginning with the velocity $v_d/v_s \approx 70$–80. At the frequency f = 3.0 GHz, the dependence is sublinear. The remaining two curves illustrate the intermediate case. Such a character of the dependence of G on v_d/v_s was noted in[2,4,6] and is in excellent qualitative agreement with the theoretical conclusions.

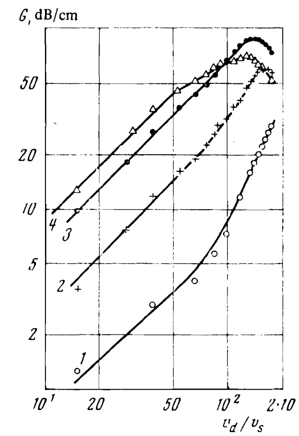

FIG. 1. Dependence of the electronic gain of ultrasound on the drift velocity of the electrons: 1 – f = 0.51 GHz; 2 – f = 0.96 GHz; 3 – f = 1.48 GHz; 4 – f = 3.0 GHz.

Actually, in accord with[3], the gain G in the case $ql \gg 1$ is determined by the expression (in dB/cm)

$$G = 4.34K^2 q \left(\frac{\pi m v_s^2}{2kT_e}\right)^{1/2} \frac{v_d/v_s}{q^2 r_D^2 (1 + q^{-2} r_D^{-2})^2}. \tag{2}$$

Here K^2 is the square of the electromechanical coupling coefficient, m the effective mass of the electron, v_s the sound velocity, k Blotzmann's constant, and r_D the Debye screening radius. According to (2), $G \sim T_e^{1/2}$ for electron heating at low frequencies ($qr_D \ll 1$) and $G \sim T_e^{-3/2}$ at high frequencies ($qr_D \gg 1$).

However, attempts to determine the electron temperature from the curves of Fig. 1 with the aid of Eq. (1) give at the various frequencies values that are close to those obtained in[7,8] only in the frequency range ~1–2 GHz. The values obtained for the electron temperature T_e at the frequency 0.5 GHz exceed these values by three or four times in fields $E \approx 200$ V/cm.

This raises the question of the possibility of using the simple theory of[3] for the description of electron-phonon interactions over a wide range of frequencies. One of the reasons for the inapplicability of[3] in the low-frequency part of the range investigated could be

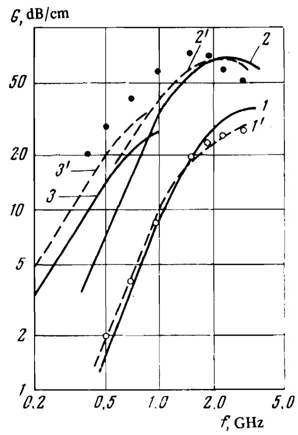

FIG. 2. Dependence of the electronic gain of ultrasound on the frequency for fixed drift velocity of the electrons: ○ – $v_d/v_s = 30$; ● – $v_d/v_s = 170$. Solid curves – theoretical. 1 – according to[3], 1' – according to[11], $v_d/v_s = 30$; 2 – according to[3]; 2' – according to[11], $v_d/v_s = 170$; 3 – according to[12]; 3' – according to[13], $v_d/v_s = 170$.

the violation of the condition $ql \gg 1$.[9] First of all, in strong electric fields, the mean free path decreases because of the lowering of the relaxation time τ_r. This change, however, is not so great and at $E \approx 200$ V/cm the mean free path decreases by no more than a factor of 1.3. A more important circumstance is the necessity of using not τ_r in the determination of the real mean free path, but τ_{loss}—the loss component of the momentum relaxation time; we note that $\tau_{loss} \leq \tau_r$ always. In correspondence with[1]

$$l = v_T \tau_{loss}, \tag{3}$$

where $v_T = (2kT_e/m)^{1/2}$ is the thermal velocity of the electron.

If we take into account the value $\tau_{loss} \approx 0.3\ \tau_p$, which was found for InSb at 77°K in a study of the nonlinear acousto-electric current at $ql > 1$,[10] then the parameter ql turns out to be of the order of unity even at 0.7 GHz. It follows then that in the frequency range 0.4–1.0 GHz, it is necessary to use a theory that is valid for arbitrary values of ql. Such a theory developed in[11] 1) under the assumption $q^2 l l_e \gg 1$, where l_e is the energy mean free path, gives for the gain an expression that differs from (2) by the factor

$$\xi = \frac{\sqrt{2m}v_s}{\pi}\int_0^\infty \frac{\chi(\varepsilon) f_0'(\varepsilon)\, d\varepsilon}{1 + (mv_s^2/2\varepsilon)\chi_1^2(\varepsilon)};$$
$$\chi(\varepsilon) = \frac{3(\tau_{loss}/\tau_r - 1)}{ql(\varepsilon)} + \frac{ql(\varepsilon)\,\mathrm{arctg}\, ql(\varepsilon)}{ql(\varepsilon) - \mathrm{arctg}\, ql(\varepsilon)} \tag{4}$$
$$\chi_1 = 3(\tau_{loss}/\tau_r - 1)/ql(\varepsilon) + q^2 l^2 (1 + q^2 l^2(\varepsilon))^{-1} (ql(\varepsilon) - \mathrm{arctg}\, ql(\varepsilon))^{-1},$$
$$l(\varepsilon) = (2\varepsilon/m)^{1/2}\tau_{loss},$$

where $f_0(\epsilon)$ is the energy electron distribution function.

The quantity ξ is a complicated function of the frequency, the ratio τ_{loss}/τ_r and the temperature of the electron gas. It is convenient to trace the effect of ξ on the agreement of theory with experiment, by means of the frequency dependence of the gain at fixed values of v_d/v_s. Such data are given in Fig. 2.

The lower series of experimental points refers to the case $v_d/v_s = 30$, when heating of the electron gas by the field can be neglected. The curve 1 is from the theory of[3], curve 1' takes into account the presence of the factor ξ in the case $\tau_{loss} = 0.3\ \tau_r$. As is seen from Fig. 2, allowance for ξ allows us to obtain very good agreement of experiment with theory over the entire frequency range. We note that the character of the frequency dependence of ξ is very sensitive to the value of τ_{loss}. Therefore, the agreement of the experimental results with the curve 1' can be used to determine τ_{loss}. The obtained value of τ_{loss} is in excellent agreement with the data from[10].

A somewhat different situation takes place for very large drift velocities. The upper series of experimental points in Fig. 2 corresponds to $v_d/v_s = 170$ ($E \approx 200$ V/cm) where, in accord with[7,8], one would expect a significant heating of the electrons up to T_e = 180–240°K. The theoretical curve 2' for the case T_e = 220°K, with account of (4) and $\tau_{loss} = 0.3\ \tau_r$, gives better agreement with experiment than curve 2, which is computed from the simple theory (Eq. (2)).

An especially large divergence is observed at low frequencies, where $ql < 1$ and curve 2' goes over into curve 3, which is given by White's theory.[12] As is shown in[13], in the case of the conditions $ql < 1$ and $\omega\tau_e \gg 1$, $q^2 l l_e \gg 1$, which are well satisfied in InSb at 77°K, the sound wave in the crystal is accompanied by an electron-temperature wave. Allowance for its effect on the dynamics of the electron clusters leads to the following expression for the gain:

$$G = 4.34K^2 q \frac{\omega\tau_M v_d/v_s}{(1 + q^2 r_D^2)^2}\varphi, \tag{5}$$

where τ_M is the dielectric relaxation time; the factor φ in the case when the relaxation time is independent of the energy is equal to 1.4. The data corresponding to (5) are shown in curve 3' and show better agreement of theory with experiment. We note that in the calculation of τ_M it is necessary to use the differential conductivity σ of the sample, which is determined from the volt-ampere characteristics at E corresponding to the considered value of v_d/v_s.

As is seen from Fig. 2, the curves 2' and 3' well describe the general character of the dependence of G on the frequency in strong electric fields. The remaining discrepancies are evidently due to the applicability of the theory only at low drift velocities $v_d \ll v_T$, while, experimentally, $v_d \approx 0.6 v_T$. We note that the effect of the electron-temperature wave[13] and the perturbation of the energy function of the electrons under the action of a sound wave[11] on the amplification effect have been observed in the experiments described earlier.

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1 R. K. Route and G. S. Kino, Appl. Phys. Lett. **14**, 97 (1969).
2 E. Voges, MOGA-70, 8th Intern. Conf., 1970, p. 3.
3 H. N. Spector, Phys. Rev. **165**, 562 (1968).
4 Yu. V. Ilisavskiĭ and D. Chiplis, Works (Trudy) of the Symposium on the Physics of Plasma and Electric Instabilities in Solids. Mintis Press, Vilnius, 1972, p. 217; Fiz. Tverd. Tela **14**, 404 (1972) [Soviet Phys.-Solid State **14**, 487 (1972)].
5 S. N. Ivanov and G. D. Mansfel'd, Fiz. Tekh. Poluprov. **4**, 40 (1970) [Soviet Phys.-Semiconductors **4**, 30 (1970)].
6 S. N. Ivanov, G. D. Mansfel'd and E. N. Khazanov, Fiz. Tekhn. Poluprov. **6**, 2403 (1972) [Soviet Phys.-Semiconductors **6**, 2013 (1973)].

[7] M. Glicksman and A. Higinbothern, Phys. Rev. **129**, 1572 (1963).
[8] L. E. Vorob'ev, V. I. Stafeev, A. Yu. Ushakov and A. V. Shturbin, Works (Trudy) of IX International Conference on the Physics of Semiconductors, Nauka Press, **2**, 809 (1969); L. E. Vorobev, V. I. Komissarov and V. I. Stafeev, Phys. Stat. Sol. **52**, 25 (1972).
[9] L. E. Gurevich, Izv. Akad. Nauk SSSR, ser. fiz. **21**, 112 (1957); A. I. Akhiezer, M. I. Kaganov and G. Ya. Lyubarskiĭ, Zh. Eksp. Teor. Fiz. **32**, 837 (1957) [Soviet Phys.-JETP **5**, 685 (1957)].
[10] P. E. Zil'berman, S. N. Ivanov, I. M. Kotelyanskiĭ, G. D. Mansfel'd and E. N. Khazanov, Zh. Eksp. Teor. Fiz. **63**, 1745 (1972) [Soviet Phys.-JETP **36**, 921 (1973)].
[11] P. E. Zil'berman and A. G. Mishin, Zh. Eksp. Teor. Fiz. 65, 1473 (1973) [Sov. Phys.-JETP 38, No. 4, 1974]; Phys. Lett. **42**, No. 7 (1973).
[12] D. L. White, J. Appl. Phys. **33**, 2547 (1962).
[13] A. S. Bugaev, Yu. V. Gulyaev and G. N. Shkredin, Fiz. Tverd. Tela **12**, 2654 (1970) [Soviet Phys.-Solid State **12**, 2133 (1971)].

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