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ACOUSTOELECTRIC INSTABILITY AND ACOUSTOOPTIC INTERACTION IN INDIUM ANTIMONIDE

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The spectrum of a round-trip amplified acoustic flux in the n-type indium antimonide at liquid nitrogene temperature in the frequency range from 150 up to 2300 MHz has been studied using the method of acoustic signal registration by means of piezoelectric transducers. The propagation direction distribution of the flux in the frequency range from 40 up to 280 MHz has been studied using an acoustooptical method at the light wavelength 10.6 μ in Bragg's diffraction regime. It has been shown that the flux development is strongly influenced by the nonlinear interaction of the flux components. The prevailing nonlinear process is a generation of sum and difference frequency waves.

АКУСТОЭЛЕКТРИЧЕСКАЯ НЕУСТОЙЧИВОСТЬ И АКУСТООПТИЧЕСКОЕ ВЗАИМОДЕЙСТВИЕ В АНТИМОНИДЕ ИНДИЯ

В работе исследован спектральный состав усиленного многопролетного акустического шума в антимониде индия n-типа при температуре жидкого азота в диапазоне частот от 150 до 2300 МГц при помощи метода регистрации акустического сигнала посредством пьезоэлектрических преобразователей. Изучено также распределение по направлениям распространения усиленного многопролетного шума в диапазоне частот от 40 до 280 МГц при помощи акустооптического метода на длине волны 10.6 мкм в режиме брэгговской дифракции. Установлено, что большое влияние на нарастание шума оказывает нелинейное взаимодействие между его составляющими. Преобладающим нелинейным процессом оказалась генерация волн суммарной и разностной частот.

I. INTRODUCTION

The growth of the acoustic flux under conditions of acoustoelectric amplification has been extensively investigated both experimentally and theoretically in such

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piezoelectric semiconductors as CdS, ZnO, GaAs (see e.g. [1]). It has been shown [2—6] that due to the nonlinear interaction the essential transformation of the amplified flux spectrum takes place. There are several processes of nonlinear interaction among the flux compontents which are responsible for this transformation. The prevailing process in the case of the strong nonlinearity (CdS, ZnO, the later stage of the flux development in GaAs) is the interaction between the strong component of the flux with the maximum linear gain frequency f_m ("pump" wave) and the weak flux components with the subharmonic frequency $f_m/2$. This process is sometimes called "parametric" and it is similar to that observed in nonlinear optics. In the case when the nonlinearity is not so strong (the early stage of the flux development in GaAs), the prevailing process of interaction is the mixing of two strong components with the frequencies near f_m giving the waves of sum and difference frequencies. However, this case of nonlinear interaction has not been sufficiently investigated. It is clear that the weaker piezoelectric the material under investigation is, the longer hold the conditions of weak nonlinearity. From this point of view the best material for the investigation of nonlinear interaction under the conditions of weak nonlinearity is indium antimonide which has an electromechanical coupling constant much lower than the other piezoelectric semiconductors mentioned above. The investigations of the acoustoelectrically amplified flux spectrum became possible only after the method of the excitation of the round-trip acoustoelectric instability in n-InSb had been proposed [7], and the acoustooptical method for investigation of the acoustic flux at the optical wave-length $\Lambda = 10.6\ \mu$ had been developed [8]. The purpose of the present work is to investigate the frequency and distribution of the propagation direction of the acoustoelectrically amplified flux in n-InSb with the aim to clarify the prevailing processes of the interaction among the acoustic flux components.

II. EXPERIMENTAL METHOD

Measurements were carried out at the liquid nitrogen temperature. The single crystal of n-InSb used in the experiment were cut in the form of rectangular bars along the crystallographic direction [110] with the typical dimensions $20 \times 4 \times 4\ mm^3$. The end faces of the samples were optically polished flat and in parallel, and the piezoelectric plates of x-cut $LiNbO_3$ with dimensions $2 \times 2 \times 0.1\ mm^3$ were bonded to them. Leads were attached with an indium solder to both ends of the sample. The voltage pulses, which had an amplitude sufficiently high to create the electron drift with the velocity $v_D \gg v_S$ and the duration $\tau \gg t_T$, were applied to the sample. Here v_S is the sound velocity, $t_T = L/v_S$ is the sound transit time through the sample, L is the sample length. When the voltage is switched on, the acoustic flux growth takes place in the sample due to the round-trip acoustoelectric amplification. The frequency distribution of the flux was measured by means of the selective tunable receiver which registered the electric signal on the $LiNbO_3$ plate either at the anode or at the cathode end of the sample. The measurements were performed in the frequency range from 150 to 2300 MHz. The distribution of the propagation direction of the acoustic flux was investigated by Bragg's diffraction method at the 10.6 μ wavelength of a CO_2 laser. A more detailed description of the experimental set-up is given in paper [8]. The measurements were carried out in the acoustic frequency range from 40 up to 280 MHz. The range is limited by the diffraction geometry. It is difficult to realize Bragg's diffraction regime at frequencies lower than 40 MHz because of the reasonable dimensions of a sample. The upper frequency limit is determined by the condition of the total internal reflection of diffracted light from the back side of the InSb sample. One can find that the acoustic frequencies $f > 2v_S/\Lambda$ the diffracted beam cannot leave the sample with parallel side faces. For InSb in the case of fast shear (FS) waves ($v_S = 2.3 \times 10^3$ m/sec) and for $\Lambda = 10.6\ \mu$ one finds the upper acoustic frequency limit to be 430 MHz.

III. AMPLIFIED FLUX FREQUENCY DISTRIBUTION

The dependences of the mean amplitude of a noise signal, measured by the receiver, the input of which was connected with the $LiNbO_3$ plate, are shown in Figs. 1, 2 as functions of frequency. The different curves correspond to the different time intervals from the beginning of the drift pulse. One can see three maxima in the spectrum of the flux. The central one corresponds to the linear acoustoelectric amplification regime. The flux growth can be briefly described as follows. The piezoactive fast shear components of the thermal background are amplified in the electron drift direction. Reflecting from the end face of the sample they are converted to the piezoelectrically non-active slow shear (SS) modes which propagate backward being attenuated only by the lattice. At the opposite end face they are reconverted to the fast shear modes, which are further amplified, and so on. Thus, the growth of the central maximum is determined by the condition

$$\alpha(f) > \alpha_{ae}(f) - \alpha_l(f) - \pi_c \qquad (1)$$

where $\alpha(f)$ is the net round-trip gain, $\alpha_{ae}(f)$ is the linear acoustoelectric gain, $\alpha_l(f)$ is the lattice attenuation of the FS and the SS waves in the forward and backward directions respectively, π_c are the conversion and reconversion losses. The position of the peak intensity (0.9 GHz) and the width of the central maximum (400 MHz) show a satisfactory agreement with predictions of the theory of linear acoustoelectric amplification for arbitrary ql [9] (q is the acoustic wave number and l is the electron mean free path) taking the lattice attenuation and conversion losses into account (dashed lines in Figs. 1, 2).

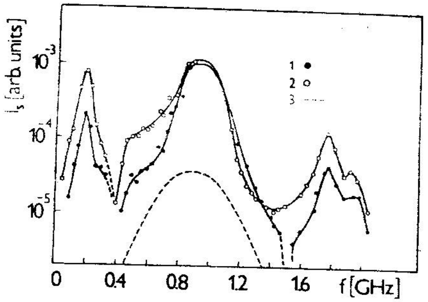

Fig. 1. Frequency distribution of amplified acoustic flux. Fast shear mode. Drift current 15 amps. Time from the beginning of drift pulse in μsec: 1 — 100, 2 — 160. Curve 3 shows calculated net linear gain.

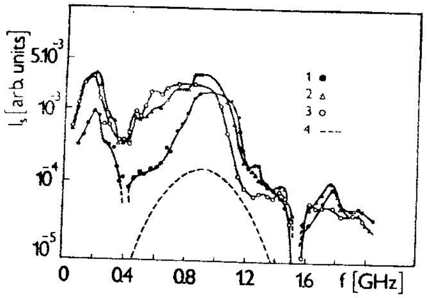

Fig. 2. Frequency distribution of amplified flux. Fast shear mode. Drift current 20 amps. Time from the beginning of drift pulse in μsec: 1 — 60, 2 — 100, 3 — 160. Curve 4 shows calculated net linear gain.

Two side maxima in the measured flux spectrum appear at frequencies where the condition (1) is not satisfied. The flux growth in these regions can be explained only if the nonlinear interaction is taken into account. The energy necessary to the growth of side maxima is transferred from the central one. The nonlinear mixing of two strong components f_1, f_2 of the central maximum gives the waves of the difference $f_3 = f_1 - f_2$ and the sum $f_4 = f_1 + f_2$ frequencies. The highest difference frequency is determined by the central maximum width. It is about 400 MHz in our case. The difference frequency tends to zero when f_1 approaches f_2. The halfwidth of the central maximum determines the position of the low frequency peak (200 MHz). The position of the high-frequency peak is determined by the double frequency of the central one (1.8 GHz).

IV. AMPLIFIED FLUX PROPAGATION DIRECTION DISTRIBUTION

The acoustoptical method in the given experimental situation allows to perform measurements only in the low frequency part of the flux spectrum. Thus, only the difference frequency wave propagation direction distribution could be obtained. The acoustic flux intensity dependence (to be more exact, the intensity of diffracted light which is proportional to the diffracting acoustic wave intensity) upon the propagation direction in the plane (110) at the frequency of 40 MHz is shown in Fig. 3. One can see that the acoustic flux propagates at a narrow angle of 1°. The maximum intensity of the flux is obtained in directions forming an angle of 0.5° with the long axis of the sample. This can be explained by the fact that due to the dispersion of the sound velocity the wave vector of the difference frequency wave is

not collinear with the wave vector of the reference wave. The conditions of synchronism in the three waves interaction process imply

$$\omega_3 = \omega_2 - \omega_1 \tag{2a}$$

$$q_3 = q_2 - q_1 \tag{2b}$$

where $q = \omega_i/v_i$, $v_i = v_0(1 + \Delta v_i)$, $\omega_i = 2\pi f_i$, $v_0 = (c/\varrho)^{1/2}$. Velocity dispersion in the case of $ql \gg 1$ is given by the relation [10]:

$$\Delta v_i = \frac{K^2}{2}\,(1 + (\omega_0/\omega)^2)^{-1} \tag{3}$$

where K is the electromechanical coupling constant, ω_0 is the frequency corresponding to the condition $qR_D = 1$, and $R_D = (\varepsilon kT/e^2 n)^{1/2}$ is Debye screening

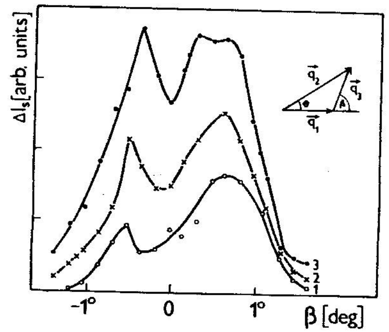

Fig. 3. Propagation direction distribution of amplified flux. Fast shear component in the plane (1$\bar{1}$0). Frequency 40 MHz. Time from the beginning of drift pulse in μsec: 1 — 75, 2 — 95, 3 — 115. The triangle in right upper corner shows the geometry of non-collinear three wave interaction.

length. The synchronism conditions are satisfied in the noncollinear interaction process, where the wave vectors of interacting waves form a triangle shown in the insert of Fig. 3. The angle between reference wave vector $\mathbf{q}_1$ and the difference wave vector $\mathbf{q}_3$ can be easily found from the triangle:

$$\cos(\pi - \beta) = \frac{1}{2}\left(\frac{q_1}{q_3} + \frac{q_3}{q_1} - \frac{q_2^2}{q_1 q_3}\right). \tag{4a}$$

Let ω_1, $\omega_2 \approx \omega_0$; then from (3) one gets $v_1 \approx v_2 = v_0\left(1 + \frac{K^2}{4}\right)$.

If $\omega_3 \ll \omega_0$, then $v_3 \approx v_0$. Introducing $\xi = \omega_1/\omega_3$ we get

$$\cos(\pi - \beta) = \frac{K^2}{4}\,\frac{\xi + 1}{\xi} - 1. \tag{4b}$$

For the complementary angle β one obtains

$$\beta = K[(\xi + 1)/2\xi]^{1/2}. \tag{5}$$

In our experiment $\xi \gg 1$, thus $\beta \approx K/\sqrt{2}$. Using the value of $K = 3.74 \times 10^{-2}$ [11] we calculate $\beta = 1.54°$. The experimentally measured value is three times less than the calculated one. The discrepancy can be explained at least by two reasons. First, we have used the velocity dispersion relation (3) which is valid when the condition of collisionless interaction $ql \gg 1$ is fulfilled. Our experimental situation corresponds to the case of intermediate regime $ql \sim 1$. Another reason of discrepancy is a possible weakening of the dispersion due to the nonlinearity in the strong acoustic flux.

V. CONCLUSIONS

We have measured the frequency and propagation direction distribution of acoustoelactrically amplified flux in the piezoelectric semiconductor *n*-InSb. The strong influence of nonlinear interaction between the flux components has been demonstrated. The prevailing nonlinear process is the generation of sum and difference frequency waves from the "linearly" amplified flux. In comparison with other piezoelectric semiconductors, in InSb this process can be observed for a much longer time due to a relative weakness of piezoelectric properties of indium antimonide. The "parametric" process which predominates in strong piezoelectrics is not important in our case. Only the very beginning of subharmonic growth can be noticed in the flux spectrum after a sufficiently long time of the flux development (the curves 1 of Fig. 1 and 2, 3 of Fig. 2).

REFERENCES

[1] Kuzmany, H.: Phys. Stat. Sol. (a) *9* (1974), 25.
[2] Bruun, M., Wettling, W., Meyer, N. I.: Phys. Lett. *1 A* (1970), 31.
[3] Palik, E. D., Bray, R.: Phys. Rev. B *3* (1971), 3302.
[4] Zucker, J. Zemon, S.: J. Ac. Soc. Am. *49* (1971), 1037.
[5] Parker, T. E., Bray, R.: Phys. Lett. *45* A (1973), 347.
[6] Diakonov, A. M., Ilisavskii, Yu. V., Kulakova, L. A.: Fiz. tverd. tela *14* (1972), 95.
[7] Domarkas, A., Chiplys, D.: Pisma v ZhTF *3* (1977), 1215.
[8] Damarkas, A. D., Diakonov, A. M., Chiplys, D.: Fiz. tverd. tela *24* (1982), 1302.
[9] Gulyaev, Yu. V., Ivanov, S. N., Kozorezov, A. G.: Phys. Stat. Sol. (b) *85* (1978), 487.
[10] Johri, G., Spector, H. N.: Phys. Rev. b *15* (1977), 4955.
[11] Drichko, I. L., Illisavskii, Yu. V., Galperin, Yu. M.: Fiz. tverd. tela *11* (1969), 2463.

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