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THE FLUCTUATION SPECTRUM EVOLUTION UNDER MULTITRANSIT ACOUSTOELECTRIC AMPLIFICATION IN *n*-InSb AT LOW TEMPERATURES[1]

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New peculiarities of the acoustoelectric instability in a piezoelectric semiconductor are desctribed. The spectrum of the acoustic and electromagnetic oscilations which arise due to multitransit amplification of fluctuations in the crystal appeared to be strongly dependent on the electron gas heating when the sample was put into a liquid helium bath. It was also found that when the mean free path of electrons was bigger than the acoustic wave lenght the generation occured just near the frequency of the maximum gain. When the lattice and the electrons were heated by a drift current, additional maxima in the spectra were observed.

I. INTRODUCTION

The important problem which requires both theoretical and experimental studies is the phenomenon of highly developed phonon turbulence.

Recently in a study of the phenomenon of multitransit ("*cyclotron*") generation of acoustic and electromagnetic oscillations in crystals of *n*-InSb in a transverse magnetic field the spectrum of amplified fluctuations has been found to become narrower with time, its intensity having remained constant [1].

This result proved the dominant role of highly damping free electronic waves mediating the interaction of fluctuations [2]. The results on spectrum transformation in layered structures in strong electric fields were obtained in [3].

In the present work the results of the observation of some new peculiarities in the multitransit generation of the acoustic and the electromagnetic oscillations in *n*-InSb crystals put in liquid helium or nitrogen without a magnetic field are presented. In the experimental state the electron mean free path l exceeds the inverse wavenumber, i.e., $ql \gtrsim 1$, and a collisionless acoustoelectronic interaction takes place.

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II. EXPERIMENTAL PROCEDURE.

The crystals on n-InSb with electron concentrations $n = 1 \dots 3\ 10^{13}\,\mathrm{cm}^{-3}$ and mobilities $\mu = 1 \dots 5\ 10^5\,\mathrm{cm}^2/\mathrm{V\,s}$ were investigated. The samples were cut along the [110] axis in a rectangular form with lengths of 0.5 ... 1.0 cm and crossections of $0.7 \times 0.7\,\mathrm{mm}^2$.

Flat parallel faces for the reflection of acoustic waves (mirrors) were cleaved. Electric voltage was applied to the ohmic contacts placed near the ends. An alternating electric drift field was generated in a sinusoidal or rectangular (meander) form. The generation started under the condition of synchronism when the half of the period of an alternating field was approximately equal to the transit time for acoustic waves between the reflecting faces. In this case the acoustic flux having been amplified to one half of the period appears again in the amplifying phase of the field after reflection because the field's sign changes at the moment of the reflection. In the experiments we could control the voltage across the sample and the current flow through it. The spectrum of generation was registered by microwave radiation issuing from the sample.

For this purpose the sample was connected with a microwave receiver or a spectrum analyser.

III. THE EXPERIMENTAL RESULTS AND DISCUSSION.

The most unexpected and interesting results contrasting with those of our previous work [1] were obtained when the sample was placed in liquid helium. Fig. 1 shows an oscillogram of the voltage and the current in the sample with the sinusoidal drift field. After 5 periods the current shape was distorted evidently due to a strong acoustoelectric effect accompanying the multitransit amplification of fluctuations. The proof of an acoustoelectric nature of the phenomenon is the fact that it arises only when the frequency of a drift field is close to that of synchronization.

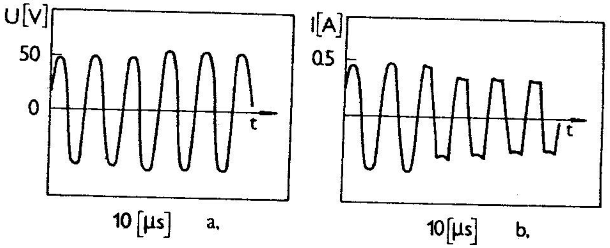

Fig. 1. The oscillogram of a) a sinusoidal voltage applied to the sample; b) a current through the sample. The sample is put in liquid He.

But even with the use of a very sensitive receiver we failed to detect microwave radiation from the sample. The possible explanation of this may be found if one takes into account that the electron temperature T_e in InSb is strongly dependent on the electric field. If we suggest that T_e at succesive moments is different, then the Debye screening length r_D depends on time and hence the frequency of maximum gain $f_m \sim \frac{\sqrt{3}\,V_s}{2\pi r_D}$ also depends on time. As a result the amplified fluctuations are distributed within the broad frequency interval. Their intensity is so small that they are not resolved by the receiver. To prove this suggestion experiments with meander form drift current were performed. In this situation the electric drift field is a constant at each half of period, the T_e and f_m must remain constant during these time intervals. Starting from a certain value of the drift current the microwave receiver began to detect an intensive microwave radiation, which after a few periods of the drift field decreased. One could suggest that at the initial stage of the generation the signal was due to the linear amplification when in accordance with [4] it had a linear dependence on field. When the current is decreased, the amplification decreases. The decrease of the amplitude of the radiation may also be explained as a result of changing the amplitude of current during the half of a period under the condition of the intensive flux generation. It also may result in a broadening of the spectrum.

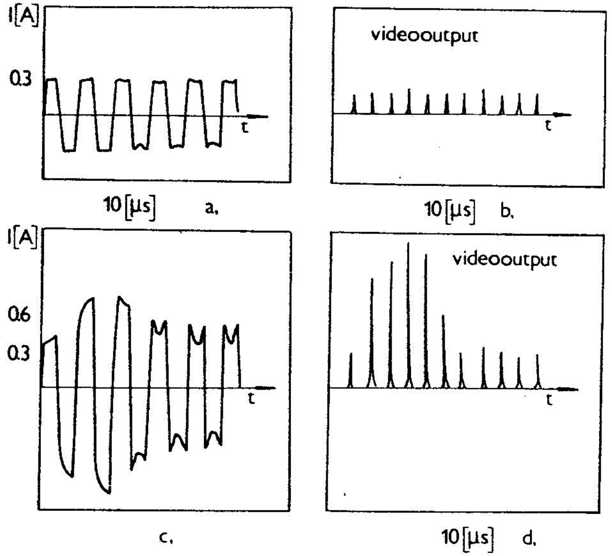

Fig. 2. The oscillogram of the current (a, c) and the videootput of the microwave receiver. The sample is put in liquid He, small "meander" — shaped voltage is applied.

The subsequent increase of the drift field results in a strong distortion of the envelope of the sequence of microwave pulses. This is illustrated in Fig. 3. During the initial periods of the field the signal is absent but after some time it appears and slowly increases with the maximum being observed at a high number of subsequent cyclotron paths of the amplified flux. The absence of the signal at the initial stage of generation may be due to the existence of the maximum in the dependence of the electronic gain on the drift velocity [4] — the high velocity then results in a small gain. With a great number of transit paths the drift velocity decreases because the current is smaller and closer to the value for obtaining the maximum gain is obtained. But this consideration cannot explain other experimental results. At a very great number of periods of the drift field the current became even greater than at the initial stage but the intensive generation still took place.

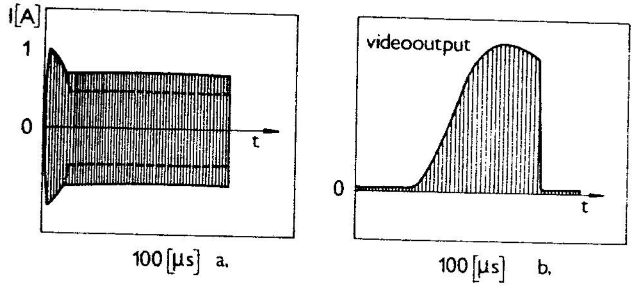

Fig. 3. The oscillogram of the envelope of the alternating drift current a) and microwave receiver output; b) in strong fields.

The complete explanation of the situation may be achieved taking into account the fact that beginning from some values of the drift current one can expect the essential heating of the lattice (and, hence, of the electrons). The estimate of the increase of the lattice temperature due to adiabatic heating ($I = 0.75\,\mathrm{A}$, $t = 400\,\mu\mathrm{s}$) gives the value $T_e = 115\,\mathrm{K}$. So the lattice heating with the gradual increase of temperature with time stabilizes the electronic temperature and as a result the measured frequency of the microwave radiation becoms independent of the from of the drift current.

The current-voltage characteristics of the sample and the dependence of the spectrum on the number N of periods of the drift field are shown in Fig. 4 and Fig. 5. The comparison of C-V-C's at various N($N = 2$ – curve 1 and $N = 11$ – curve 2) illustrates a very strong change of C-V-C that occurs after the onset of generation in the synchronization.

Fig. 5 shows the spectrum of the signal changes with time. When N is big enough, an intensive generation is observed in a relatively narrow frequency band (near 800 MHz). It is important to note that the observed transformation takes place when the shape and the amplitude of the current remain constant, hence the integral intensity of sound is also constant.

The estimate of the electron temperature from the condition of the maximum of the electronic gain $gr_D \sim \sqrt{3}$ gives the value of $T_e \sim 120\,\mathrm{K}$.

In our experiments the generation took place also at other frequencies but its intensity was smaller by the factor $10^3 - 10^5$ than at 800 MHz. Only when the applied electric field was strong ($E \sim 10^2\,\mathrm{V/cm}$), we detected an intensive signal also at 590 MHz. The relation between these frequencies is given by the factor 1.36 and it is close to 1.4 – the value obtained in [3]. Such a frequency shift is also expected in accordance with the theory developed for $ql \gtrsim 1$ [5].

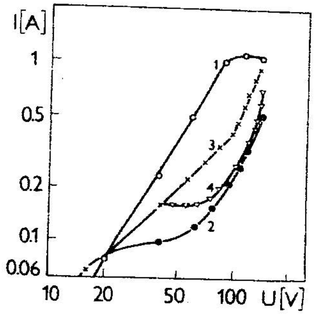

Fig. 4. Current-voltage characteristics of the sample:
1. After the 2nd period of the field. The sample is in liquid He;2. The same after the 11th period of the field (onset of the generation);
3. After the 2nd period of the field. The same is in liquid N. 4. The same after the 11th period of the field.

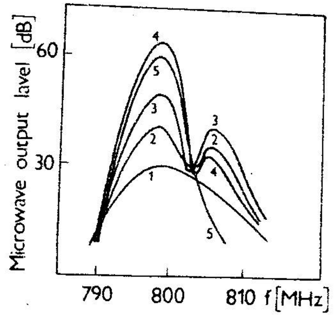

Fig. 5. The generation spectrum as a function of the number of periods of the drift field:
1. — after 30 periods; 2. — after 60 periods;
3. — after 90 periods; 4 — after 120 periods;
5. — after 150 periods.

When the sample was in a liquid nitrogen bath, the microwave oscillations were observed at any shape of the current but their intensities were different and bigger for the "meander". It is very interesting to note that at strong fields the spectra at nitrogen and helium temperature were almost the same (in both cases — the maximum at 805 and 600 MHz). At the field when it occurred the C-V-C for the sample put into N and He baths were also just the same.

These results show that in both experimental situations the electrons were heated up to the same temperature.

In other series of experiments with samples with higher mobilities ($490000\,\mathrm{cm}^2/\mathrm{V\,s}$), the high drift velocities for electrons were achieved at relatively small fields, the lattice heating being small. The C-V-C of the sample was saturated after a few periods of the field. The spectrum observed was formed quickly just before the moment of the first detection and has remained unchanged. The spectrum was centred at $f_m \sim 800$ MHz with a bandwidth of an order of 20 MHz. Usually we could observe only one spectral maximum. But in the same samples we could also see a few spectral components (just like in [6]). In those cases we always had one dominant line.

The physical picture of the processes of spectrum formation and evolution is not yet clear. There is neither information about electron gas heating in semiconductors nor a developed theory describing nonlinear interactions of fluctuations when $ql \gtrsim 1$. We can nevertheless suggest that in some cases where we observed an intensive microwave signal at f_m, the lattice heating and the corresponding increase in the lattice absorption of acoustic wave resulted in the decrease of the total amplification and determined the narrow frequency band for the generation (just like the nonlinear operator in the nonlinear theory of the amplification of fluctuations did).

IV. CONCLUSIONS

In the present work we have experimentally found some new pecularities of the multitransit generation of the acoustic and the electromagnetic oscillation when $ql \gtrsim 1$. When the sample had been put into a liquid helium bath, the evolution of the spectrum appeared to be strongly dependent on the effects of the lattice and electron heating. The effect of transformation of the spectrum narrowing towards the frequency of the maximum gain was found when the lattice and the electrons had been heated by a drift current. The additional maximum in the spectrum was found to be $f = 0.7 f_m$.

It was also shown that when the condition $ql > 1$ is fulfilled, the generation appears just near the frequency of the maximum gain.

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ЭВОЛЮЦИЯ СПЕКТРА ФЛУКТУАЦИЙ ПОД ВОЗДЕЙСТВИЕМ МНОГОПЕРЕХОДНОГО ЭЛЕКТРОАКУСТИЧЕСКОГО УСИЛЕНИЯ В ОБРАЗЦЕ *n*-InSb ПРИ НИЗКИХ ТЕМПЕРАТУРАХ

В работе описываются новые характерные черты акустоэлектрической неустойчивости в образце ьезоэлектрического полупроводника. Оказывается, что спектр акустических и электромагнитных осцилляций, которые обусловлены многопереходным усилением флуктуаций в кристалле, сильно зависит от накреба электронного газа при помещении образца в жидкую гелиевую ванну. Обнаружено также, что в случае, когда средний пробег электронов больше, чем длина акустической волны, генерирование происходило именно вблизи частоты максимального усиления. Кроме того, при нагревании решетки и электронов током дрейфа наблюдались в спектре добавочные максимумы.