Effect of nonlinear multipassage "nondamping" of sound

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We report observation of multipassage "nondamping" of sound in Te under conditions where this effect is impossible in accordance with the nonlinear theory. The observed effect is attributed to nonlinear concentration interaction of the sound signal with the amplified noise flux.

We used in the measurements oblique-cut single-crystal samples of Te. The piezoactive transverse—sound wave was polarized along the two-fold symmetry axis X and its propagation direction coincided with the direction of the minimum sound velocity $v_s = 1.05 \times 10^5$ cm/sec ($T = 77$ °K), which made an angle $\theta = -26°30'$ with the Y axis in the YZ plane. Samples measuring $3.8 \times 4.0 \times 6.5$ mm were cut from left-modification single crystals of Te with hole density $p = (2-3) \times 10^{14}$ cm^{-3} and mobility $\mu = (1.5-3.5) \times 10^3$ cm^2/V-sec ($T = 77$ °K).

The measurements were performed in "transmission." To excite and receive the sound of frequency $f = 95$ to 205 MHz, converters of Y-cut quartz were glued to the samples. The change of the sound amplitude in the field was compensated with an attenuator. The measurements were made with both the sample and its holder immersed in liquid nitrogen.

According to the linear theory, the electronic absorption coefficient (gain) of the sound α is determined by the formula[1]

$$\alpha = 4.34 K^2 \frac{\omega}{v_s} \frac{\omega \tau_M \gamma}{(\omega \tau_M \gamma)^2 + (1 + q^2 R_D^2)^2} \qquad (ql << 1). \qquad (1)$$

Here q is the wave vector of the sound, l is the carrier mean free path, $\omega = 2\pi f$, K is the electromechanical coupling constant, $\tau_M = \epsilon/4\pi\sigma$ is the Maxwellian relaxation time, σ is the conductivity, ϵ is the dielectric constant, R_D is the Debye radius, $\gamma = (1 - \mu E/v_s) = (1 - E/E_{\mathrm{cr}})$ is the supercriticality parameter, and $E_{\mathrm{cr}} = v_s/\mu$ is the critical field at which the damping of the sound gives way to amplification (all the quantities pertain to the selected crystallographic direction).

In our case $q^2 R_D^2 < 0.1$ and $\omega\tau_M = 0.02$ to 0.06, and consequently at $E < 10 E_{\mathrm{cr}}$, according to (1), the dependence of α on E should be linear with good accuracy. Circular (or multipassage) amplification is possible only in fields $E > 10 E_{\mathrm{cr}}$.

Measurements in the forward field (when the directions of the sound and of the drift coincided) yielded a linear dependence of α on E up to a field intensity $E \cong 1.1 E_{\mathrm{cr}}$, when deviation from linearity sets in under the influence of the amplified noise. The slopes of the linear sections for different frequencies agreed with the theory at $K^2 = 0.14$, and the acoustic gain reached 70 dB/cm.

It is observed at the same time, however, that when E is increased above E_{cr} the oscilloscope screen displays, in addition to the first pulse (one forward passage) also a second pulse (three passages), a third pulse (five passages), etc. With further increase of the field, each of the succeeding pulses grows larger than the preceding one, until all become approximately equal in magnitude (Fig. 1, $E = 1.1 E_{\mathrm{cr}}$, $f = 133$ MHz). The presented oscillogram shows 9 pulses (17 passages) of undamped sound.

This means that under the conditions of our measurements circular or multipassage electronic amplification of the sound signal takes place in the Te samples and compensates, on the average, the lattice damping of the sound, the reflection losses, and also the losses due to the difference between the directions of the phase and group velocities of the sound (for our oblique cut, the angle between them is approximately 3°).

It is obvious that the linear theory cannot explain the observed effect. Nor can the effect be attributed to nonlinearity of the sound itself, for nowhere in the sample did the intensity of the sound wave exceed 10^{-5} W/cm^2 in these measurements.

It is natural to assume that the cause of the multipassage electronic amplification of the sound, under the conditions of our experiment, is the influence exerted on the sound by the amplified noise flux via the mechanism of concentration nonlinearity. The growing noise effectively captures the carriers, and the sound propagates, as it were, in a medium with altered parameters, in particular with lower conductivity, for which the interaction is weaker and has a different field dependence. In Te, it is precisely the large constant of the electromechanical coupling which contributes to the observation of such an interaction between the noise and the signal.

However, if this is the nature of the multipassage amplification of the sound, then it should be observed also in the inverse field, since the difference between

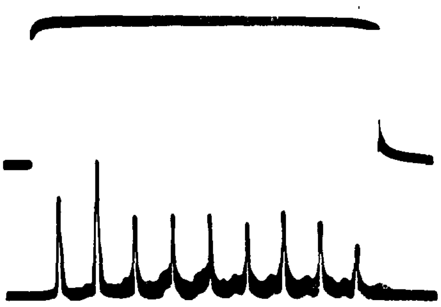

FIG. 1. Sweep 20 μ sec/div: upper trace—pulse of forward drift field, scale 20 V/div, $\gamma = -0.1$; lower trace—echo pulses of sound $f = 133$ MHz. Scale 2 V/div.

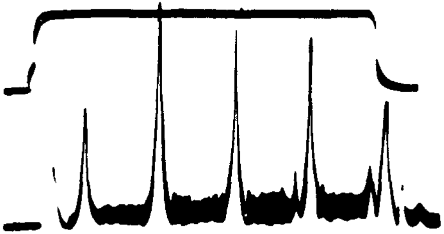

FIG. 2. Sweep 10 μ sec/div: upper trace—pulse of inverse drift field, scale 50 V/div, $\gamma = +2.50$; lower trace—echo pulses of sound $f = 95$ MHz, scale 2 V/div. Input sound intensity $I_{in} = 3$ W/cm^2.

the inverse and the direct field lies in this case only in the conditions of the first passage (damping rather than amplification of the sound). We recall that, according to the linear theory, the damping increases linearly with $|E|$ in the inverse field; the acoustic signal, according to the estimates, then becomes unobservable.

Indeed, in the inverse field, the sound pulse first vanishes but reappears at $|E| = 1.1E_{cr}$, followed by other pulses, so that a sequence of undamped sound pulses (Fig. 2) appears on the oscilloscope screen in this case when $|E| = 1.4E_{cr}$.

A decrease of the input sound intensity by as much as 30 dB leaves the ratio of the amplitude of these pulses practically unchanged, and leads only to their joint decrease and vanishing in the noise.

If the turning on of the drift field precedes the introduction of the sound into the sample by a time corresponding to 1–1.5 passages, no quantitative changes are observed in the oscillograms. On the other hand, if the drift field was turned on 0.5–1.5 passages after the introduction of the sound, then sound pulses were also produced, but only 20–25 μsec after the application of the drift field. These results also offer evidence favoring the decisive role of noise in the observed effect.

In measurements in the inverse field, the level of the thermal noise entering the receiver is lower. This made it possible to trace the behavior of the sequence of echo pulses with further increase of the field. It turned out that at $|E| > 1.4E_{cr}$ their amplitude decreased with increasing $|E|$, until they were drowned out by the noise at $|E| = 2.5E_{cr}$. One cannot exclude the possibility that this effect is connected with the decrease of the carrier capture, as a result of their being "blown out" by the field.

These observations are not only of independent interest, but also offer a new insight in the behavior of enhanced noise flux in semiconductors.

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[1] D. L. White, J. Appl. Phys. **33**, 2547 (1962).