Size effect in the absorption of hypersound in dielectric materials

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The existence of a new phenomenon—dependence of the absorption coefficient of longitudinal hypersonic waves on the transverse dimension of macroscopic ($d \gg l_f$, d is the plate thickness and l_f is the average length of the free path of thermal phonons) dielectric plates—was established.

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As is known, the absorption of high-frequency acoustic waves in dielectric materials when the inequality $\omega\tau_f \gg 1$ is satisfied (ω is the frequency of the acoustic wave and τ_f is the lifetime of thermal phonons) is determined by three-phonon processes. In particular, the $L + L \rightarrow L$ processes are mainly responsible for the absorption of longitudinal hypersonic phonons. The absorption coefficient (AC)Γ in this case is proportional to the frequency of the acoustic wave and to the fourth power of the temperature. Deviations from the indicated frequency and temperature dependences of the AC, which are observed in experiments involving a number of dielectric materials and

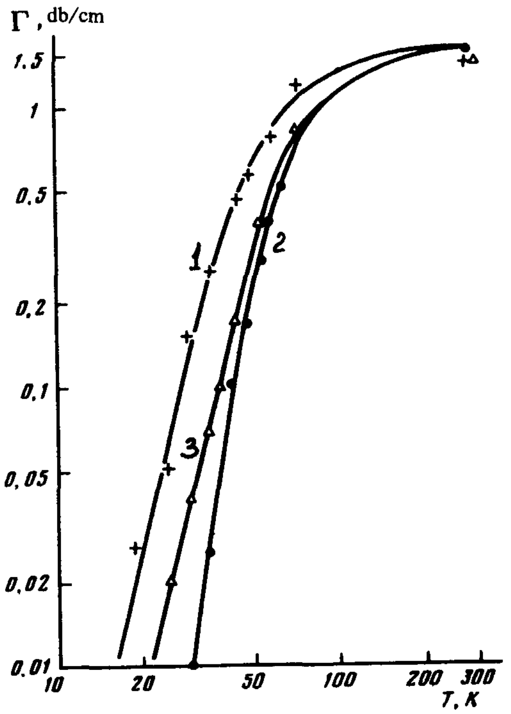

FIG. 1. Temperature dependence of acoustic wave absorption in a YAG crystal at a frequency of 2.5 GHz: 1, in a massive sample; 2, in a 0.02-cm-thick plate; 3, in the same plate covered by a KhSL-type lacquer.

semiconductors, are usually interpreted as the consequence of a strong dispersion of longitudinal acoustic phonons or as the anisotropy of the elastic, third-order moduli, or they are attributed to the influence of another resolved process $L + T_1 \rightarrow T_2$[1] (L, T, and T_2 denote polarization of phonons that participate in the three-phonon process, L is the longitudinal phonon, and T_1 and T_2 are the transverse phonons).

In this paper we establish the existence of a new phenomenon—the size effect in the absorption of hypersound in dielectric materials. We show that in macroscopic dielectric plates the AC of quasi-longitudinal, high-frequency, acoustic waves depends on the transverse dimension of the plate in a wide temperature range. By limiting the size of the plate, we can observe a gradual transition from a frequency-temperature dependence of the AC of the type $\Gamma \sim \omega T^4$ in massive samples to other dependences characterized by a weaker frequency dependence of the acoustic wave and a more critical temperature dependence as the cross section of the plate decreases. Thus, the lattice absorption of a quasi-longitudinal hypersound wave decreases noticeably with decreasing thickness of the plate.

Investigation of the size effect in the hypersound absorption was performed by using yttrium-aluminum garnet crystals $Y_3Al_5O_{12}$ (YAG) and alumomagnetsium spinel $MgAl_2O_4$. The acoustic waves of frequency $f = 2.5$ GHz were excited and detected by using texturized, zinc-oxide piezoelectric converters sputtered on the face of a crystal that was cut in the $\langle 110 \rangle$ direction. The AC was measured by using the standard echo method with a large (> 10) number of pulses. The measurement accuracy of the absolute value of the AC of sound was $\geqslant 0.02$ db/cm. Typical crystal dimen-

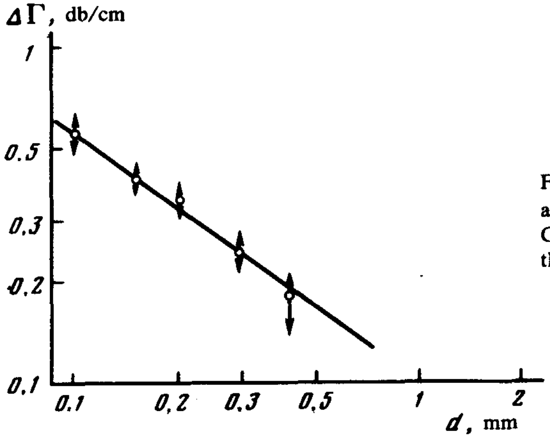

FIG. 2. Variation (decrease) of acoustic wave absorption in YAG plates at a frequency of 2.5 GHz and $T = 77$ K as a function of the plate's thickness.

sions were $1 \times 0.4 \times d$ cm^3 and the plate thickness was varied sequentially in the experiment from 0.4 to 0.01 cm.

Figure 1 shows the typical results of the measurements of the temperature dependences of the AC of the longitudinal acoustic wave propagating in a massive YAG sample (curve 1); the AC, which depends linearly on the frequency, is proportional to T^n, where $n \lesssim 4$. In the YAG plate with a transverse dimension $d = 0.02$ cm, which was cut and then ground to specified dimensions from the original massive sample, the frequency dependence of the AC appears to be noticeably weakened, and the more critical temperature dependence is described by curve 2.

In accordance with the standard procedure, we subtracted the residual (temperature independent) losses from the total absorption in the analysis of the experimental data. Thus, despite the fact that the residual losses in the plates sometimes differed from the corresponding values in the massive sample, the indicated procedure in all the cases gave completely reproducible results.

Figure 1 also shows the results of an investigation of the effect of the condition of the plate's surface on the magnitude and temperature dependence of the AC (curve 3). This dependence was obtained by coating the wide, lateral surfaces of the plate with a layer of KhSL-type lacquer.

The curves, analogous to those in Fig. 1, were plotted for a set of plates with thicknesses in the range of 0.05 to 0.01 cm. Drawing the profile of the family of curves for a constant temperature, we can trace the decrease of the absorption of acoustic waves with decreasing plate thickness. These dependences are shown in Fig. 2, where the decrease of the absorption in the plate is plotted along the Y axis (relative to the massive sample) as a function of its thickness d at a temperature of 77 K. In all the cases the linear sound absorption mode was in effect.

It is now assumed that the $L + L \rightarrow L$ process plays the main role in the absorption of longitudinal hypersonic waves in YAG at low temperatures (see, for example, Ref. 2), and the Herring process $L + T_1 \rightarrow T_2$ is disregarded. At the same time, because of the small, elastic anisotropy in the YAG (elastic anisotropy factor is equal to

1.03) the volume of the interaction region in the phase space and hence the number of phonons that effectively interact with the longitudinal hypersonic wave greatly increase as compared with the case of appreciable anisotropy or lower hypersonic frequency. Under these conditions the contribution of the Herring process to absorption increases. Note that the Herring asymptotic formula $\Gamma \sim \omega^2 T^3$, valid for crystals with a cubic symmetry to which YAG belongs, cannot be used here. A crude estimate shows that under the examined conditions $\Gamma \sim \omega^m T^n$ with $1 < m < 1.5$ and $3.5 < n < 4$, which corresponds to the observed dependences.

Thus, we shall assume that in the low temperature region (this region is distinguished by the condition $\omega\tau_f > 1$) both mechanisms in the massive samples contribute comparably to the absorption. In the region of lower temperatures ($\omega\tau_f \gg 1$) the Herring process plays the main role. The transverse directional phonons, in the space of the phonon wave vectors near the points (or lines) of degeneracy of the phonon isoenergetic surfaces, are in this case the main contribution to the absorption of hypersonic phonons.

Limitation of the sample's size apparently eliminates the indicated degeneracy, which facilitates effective weakening of the Herring process. Under these conditions Γ begins to depend strongly on the sample's size, and there is a qualitative rearrangement of the frequency and temperature dependences $\Gamma(\omega, T)$ in a wide temperature range, which is associated with a transition to the absorption regime $L + L \to L$, which, because of a considerable dispersion of longitudinal acoustic phonons in YAG, is characterized by a more critical temperature dependence $\Gamma(T) \sim T^7$ and a weakened frequency dependence (AC should be almost independent of the frequency).

We note that under experimental conditions an effective suppression of the contribution of the Herring mechanism to the absorption requires only a small (~0.2–0.3%) relative variation of the velocities of the transverse phonons of different polarizations in the neighborhood of the degeneracy points.

The given qualitative picture of the size effect in the absorption of the longitudinal hypersonic waves is incomplete, since it does not identifiy the causes that eliminate the degeneracy. At present, and unambiguous conclusion about the observed size effect cannot be made in the absence of experimental data for dispersion and lifetimes of the acoustic phonons as well as for the anharmonicity constants.

We note, moreover, that if the suggested qualitative picture is valid, then, after measuring the absorption of the longitudinal hypersonic waves in the massive samples and in thin plates at low temperatures, we can separate in "pure form" the collinear interaction mechanism $L + L \to L$ and the Herring interaction mechanism, and determine in this manner the total number of anharmonicity constants for the investigated crystal, the dispersion of the longitudinal acoustic phonons, and their lifetimes.

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