INTERACTION OF ULTRASONIC SURFACE AND BULK WAVES WITH CONDUCTION ELECTRONS IN A CdS CRYSTAL

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INTERACTION OF ULTRASONIC SURFACE AND BULK WAVES WITH CONDUCTION ELECTRONS IN A CdS CRYSTAL

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The interaction of bulk (longitudinal and transverse) ultrasonic waves with conduction electrons in semiconductor crystals has been studied comparatively well (see, for example, (^{1})). This effect has led to the widely known phenomenon of direct amplification of such waves in crystals. The analogous interaction for ultrasonic surface waves propagating along one of the free faces of a crystal (Rayleigh waves) has hardly been studied. One can point only to two works (^{2,3}), where this question is touched upon briefly. Meanwhile, a detailed investigation and comparison of the interaction of surface and bulk waves in one and the same crystal could be expected to provide information on the special features of the properties of the surface layer of the crystal (as compared with the properties of the bulk). In the present work an attempt at such an investigation has been made experimentally. The experiments were carried out on a CdS crystal prepared at the All-Union Scientific Research Institute of Single Crystals (Kharkov) by the method of growth from a melt under inert-gas pressure (^{4}). The crystal had the form of a rectangular parallelepiped measuring $11 \times 12 \times 50$ mm, with the hexagonal z axis perpendicular to the 11×50 mm face.

The degree of interaction of the ultrasonic wave with the conduction electrons was characterized by the coefficient α of that additional attenuation of the wave (in amplitude) which is introduced by the conduction electrons. The dependences of the coefficient α on the specific conductivity σ of the crystal were recorded for each type of wave. All measurements were made in a pulsed regime on an apparatus consisting of a generator of rectangular electrical pulses with sinusoidal filling, a set of emitters and receivers of ultrasonic waves, a resonant amplifier, and an electronic oscilloscope. The pulse duration was varied within the range $1 \div 4$ μsec; the filling frequency was 30 MHz. The direction of propagation of the transverse waves was perpendicular to the 12×50 mm face of the crystal, and the direction of particle displacement in the wave was parallel to the z axis. The longitudinal waves propagated along the z axis of the crystal,

Figure 1

Figure 1: Figure 1

and the surface waves along the 11 × 50 mm face, the surface of which was polished.

For emission and reception of the longitudinal and transverse waves, half-wave quartz plates of X and Y cuts, respectively, measuring 5 × 5 and 9 × 12 mm, were used. Acoustic contacts of the plates with the cadmium were made by means of a thin layer of epoxy resin. Emission and reception of surface waves were carried out by the grating-structure method (^{5}). The gratings were made of duralumin, had dimensions 5 × 5 × 1.6 mm, and were placed at a distance of 5 mm from one another.

The conductivity of the crystal σ could be varied over wide limits by illuminating it with light from a K-30 cinema lamp (hereafter, for brevity, this illumination is called white light). To measure the conductivity, indium electrodes were deposited on opposite sections of the 11 × 50 mm faces of the crystal. Using a set of light filters from a standard

Fig. 1. Dependences of the attenuation coefficients of longitudinal, transverse, and surface waves on conductivity. **1** –theory, **2** –white light, **3** –light filter ZS-1, **4** –light filters SZS-10 + ZhS-12 + ZS-7, **5** –light filters SZS-10 + OS-12 + ZS-7, **6** –light filters SVS-5 + KS-11

from a catalog of colored glass, it was possible to illuminate the crystal with light of wavelengths lying in definite bands of the spectrum and to investigate the dependences $\alpha(\sigma)$ for different spectral compositions of the illumination. The following light filters and their combinations were used: 1) light filter ZS-1; 2) light filters SZS-10 + ZhS-12 + ZS-7; 3) light filters SZS-10 +

+ OS-12 + ZS-7; 4) SZS-5 + KS-11 light filters. The corresponding spectral regions were: 1) the region $\lambda = 5000 \div 5800$ Å; 2) the lines $\lambda = 5200$ and $\lambda = 5700$ Å; 3) the line $\lambda = 5700$ Å; 4) the region $\lambda = 6100 \div 7200$ Å. The indicated light filters selected spectral intervals over the entire region of maximum photosensitivity of the crystal. In addition, a water light filter 3 cm thick was always used to absorb infrared radiation.

The results of the measurements are presented in Fig. 1. Along the abscissa axes are plotted the logarithms of the conductivity ($\Omega^{-1} \cdot \mathrm{cm}^{-1}$) of the crystal with a minus sign; along the ordinate axes, the attenuation coefficients of longitudinal α_l, transverse α_t, and surface α_R waves over a path of 1 cm. The different curves in one figure correspond to different spectral compositions of the crystal illumination. Figures 1 I and 1 II also show theoretical curves for the dependences $\alpha_l(\sigma)$ and $\alpha_t(\sigma)$, calculated on the basis of formulas and data from Ref. (^{1}). For surface waves there is no theoretical curve, since no theory of their interaction with conduction electrons in CdS crystals exists.

Analyzing the curves in Fig. 1, one can state the following. 1) For surface waves, as for bulk waves, all dependences $\alpha(\sigma)$ have a relaxation character. At $\sigma < 10^{-6}$ the attenuation of waves of all types is very small; then it increases rapidly with increasing conductivity. The region $10^{-4} < \sigma < 10^{-3}$ corresponds to the maximum interaction of the waves with the conduction electrons of the crystal. In this region the waves were attenuated so strongly that for some values of σ their amplitudes could not be measured. At $\sigma > 10^{-3}$ the attenuation decreases rapidly with increasing conductivity. 2) At fixed values of the crystal conductivity σ, the attenuation coefficients of both bulk and surface waves depend substantially on the spectral composition of the crystal illumination, although according to the linear theory of the interaction of bulk ultrasonic waves with conduction electrons (^{1}), the attenuation coefficients should depend only on the ultrasound frequency, the conductivity σ, and the values of the elastic and electrical constants of the crystal. 3) The experimental attenuation curves of longitudinal and transverse waves do not coincide with the theoretical ones under any illumination. The smallest difference between them is observed under illumination with white light. In this case the experimental attenuation curve of longitudinal waves is narrower than the theoretical one and is shifted along the abscissa axis to the left by 0.4 (on the $\lg\sigma$ scale), while the experimental attenuation curve of transverse waves is approximately equal in width to the theoretical one and is shifted slightly to the right. For the other (colored) illuminations, the narrowing of the experimental attenuation curves of longitudinal and transverse waves and their shift relative to the theoretical ones are greater than under white light; 4) the regions of maximum interaction with conduction electrons for longitudinal and transverse waves approximately coincide, while for surface waves they lie to the left along the abscissa axis, on average by 0.4 (on the $\lg\sigma$ scale), and, in addition, are noticeably narrowed in comparison with the regions for longitudinal and transverse waves. 5) The dependence of attenuation on illumination for surface waves is considerably weaker than for bulk waves. An exception is red illumination (with SZS-5 + KS-11 light filters), for which the attenuation of surface waves decreases sharply in comparison with the other illuminations. 6) The relative arrangement of the attenuation curves of waves under different colored illuminations is the same for longitudinal and transverse waves and different for surface waves. Thus, for example, for longitudinal and transverse waves the curve corresponding to illumination with SZS-10 + OS-12 + ZS-7 light filters is located to the right of the curve corresponding to illumination with SZS-10 + ZhS-12 + ZS-7 light filters, whereas for surface waves it is the opposite. The curve corresponding to red illumination, for surface waves, is separated from the other curves considerably more than in the case of bulk waves.

Summarizing points 1)–6), one may say that the curves of the dependence of attenuation on conductivity under colored illumination of the crystal for surface waves differ substantially from the analogous curves for longitudinal and transverse waves, whereas the indicated dependences for longitudinal and transverse waves are very close to one another.

The dependence of the interaction of bulk ultrasonic waves with conduction electrons on the spectral composition of the illumination in CdS crystals has also been observed earlier ([6,7]). This effect is explained by the presence in the crystal of traps (electron sticking levels) of several different types with relaxation times on the order of the period of the ultrasonic wave. It is natural to assume that the analogous dependence for surface waves is caused by the presence of traps of several types in the surface layer of the crystal, where the surface wave is localized. Note that at a frequency of 30 MHz the depth of the localization layer of the surface wave is approximately 0.06 mm. As was already noted above, the dependences of attenuation on the spectral composition of the illumination and on conductivity for surface waves are different from those for bulk waves. This can be explained by a difference in the types of traps and in their concentration for the volume and for the surface layer of the crystal under investigation. Thus, for example, the small value of the attenuation coefficient of surface waves (in comparison with bulk waves) under red illumination (filters SZS-5 + KS-11) for all values of σ realized in our experiments apparently indicates that in the surface layer of the crystal (as compared with the volume) there are many traps that respond to this illumination. The quantitative differences, smaller than for bulk waves, between the attenuation coefficients of surface waves under different illuminations (except red) probably indicate a more uniform distribution of traps among the different types or a predominance of traps of one type in the surface layer of the crystal as compared with the volume.

Thus, surface waves can provide information about traps located in the surface layer of a crystal. By using surface waves of different frequencies, one may hope to obtain information on the law governing the distribution of the concentration of different traps as a function of distance from the surface of the crystal under investigation, since changing the frequency changes the depth of the localization layer of the surface wave (at 90 MHz, for example, it will be only 0.02 mm).

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