Mandel'shtam–Brillouin scattering spectrum of ZnO crystal in an electric field

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The increase in sound fluctuations in ZnO placed in an electric field is studied using the Mandel'shtam–Brillouin light scattering method, beginning at the thermal noise level.

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The sound fluctuations in piezoelectric semiconductors, placed in an external electric field, increase as a result of electron–phonon interaction.[1] These fluctuations, in particular, change the molecular light-scattering spectrum.[2–5] In this paper, we report the first observation of the change in intensity of the Mandel'shtam-Brillouin component (MBC) in the spectrum of light, scattered in the semiconducting single crystal ZnO, from the minimum values of the scattering intensity in the absence of a field, its growth following a hyperbolic law for low fields, exponential increase in fields comparable to the critical E_c value, and, finally, saturation of intensity, when the field greatly exceeds a critical value.[1)]

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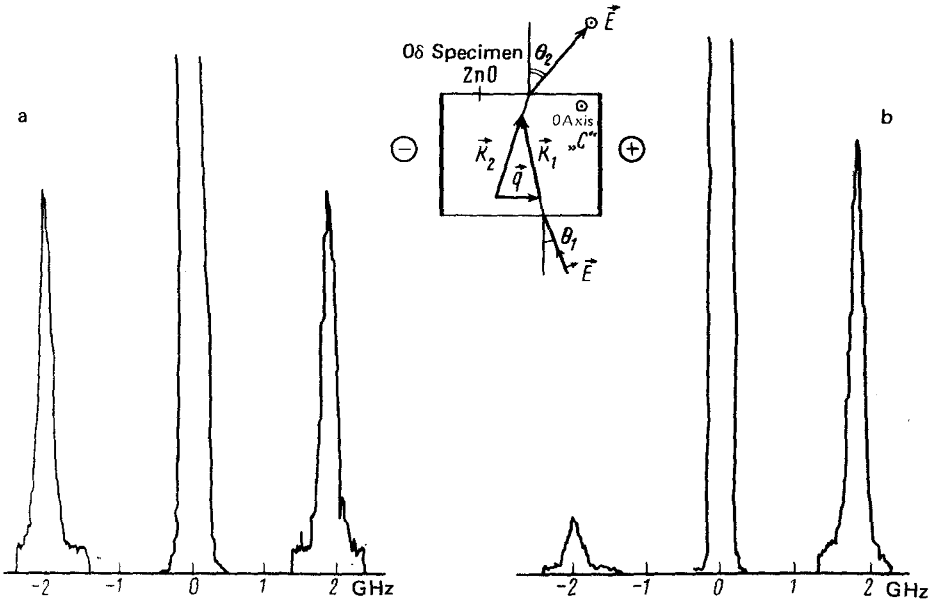

FIG. 1. Spectrum of light scattered by the crystal a) with field $E = 0$ and b) with field $E = 2840$ V/cm. The duration of the action of the field is 1/200 of the time for accumulating the signal in each channel of the spectrum analyzer (the vertical scale in Fig. 1b is reduced by a factor of 7 as compared with that in Fig. 1a). Inset at the top of the figure: section of the specimen in the scattering plane. $\mathbf{k}_1$, $\mathbf{k}_2$, and $\mathbf{q}$ are wave vectors of the incident and scattered light and of the sound wave, respectively. ⊖⊕ are the cathode and anode contacts in the crystal.

The scattering was excited by light from a single-frequency argon laser ($\lambda = 514.5$ nm) manufactured by Spectra Physics Company (model 165), with an output power of 0.2 W.

The scattered-light spectrum was analyzed with the help of a three-pass Fabry–Perot interferometer with piezoelectric scanning, self-tuning, and stabilization in the assembly with FÉU and a detecting single-channel accumulator manufactured by the Bërlei Company. The dispersion region of the interferometer is 5 GHz; the sharpness of the bands in the spectrum was of the order of 60. The data were extracted from the memory of the spectrum analyzer channels on a digital printer and a plotter. The specimen, which was prepared from a single crystal of ZnO, grown by a hydrothermal method, had the shape of a parallelipiped with sides of 8.6, 6.6, and 4.7 mm; the "C" axis was parallel to the shortest edge. The electrical conductivity of the specimen was 3×10^8 s^{-1}, while the electron mobility was $\mu = 100$ cm^2/V · s. The scattering plane was perpendicular to the "C" axis. The angle of incidence of light on the specimen was $\theta_1 = 3°$ and the incident light was polarized in the plane of incidence. The exit angle of the scattered light from the crystal was $\theta_2 = 18°$ (see top of Fig. 1). A polarization prism, transmitting light with oscillations perpendicular to the scattering plane, was placed in the scattered light beam. Under these conditions, only components due to scattering of light by a transverse acoustic wave, which is a piezoactive wave propagating perpendicular to the hexagonal axis and

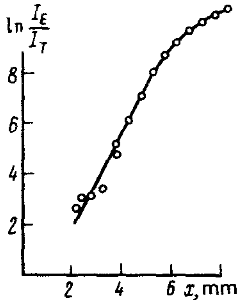

FIG. 2. $\ln(I_E/I_T)$ as a function of the coordinate x in the crystal with a field $E = 2840$ V/cm.

polarized along this axis, should be observed in the fine-structure spectrum of the scattered light.

The electric field, applied to the specimen, was a rectangular pulse with duration not exceeding 0.3 ms, synchronized with the frequency at which the accumulator channels were switched (in our experiments, 50 Hz). Pulses with longer durations led to inadmissible heating of the specimen.

Examples of traces of the fine-structure spectra in ZnO in the absence of a field and in a field are presented in Figs. 1a and b. With the geometry of the experiment indicated and the chosen direction of the field, there is a strong increase in the anti-Stokes component.

Figure 2 shows $\ln I_E/I_T$ as a function of x (x is the distance in the specimen, measured from the cathode to the scattering volume) with fixed field E. Here, I_T is the intensity of light at the maximum of the anti-Stokes component in the absence of an electric field and I_E is the maximum in an external electric field. The results of the experiments show that in the range from 2 to 5 mm, the intensity of the anti-Stokes component increases almost exponentially and, correspondingly, the intensity of the sound wave increases. The gain for sound γ, determined from the slope of the linear part of the curve in Fig. 2, is $\gamma = 18 \pm 1$ cm^{-1}. The electromechanical coupling constant calculated from this slope is $K = 0.23$, which agrees with Ref. 6.

For large distances from the cathode, the MBC intensity saturates, apparently indicating the presence of nonlinear phenomena in the sound wave.

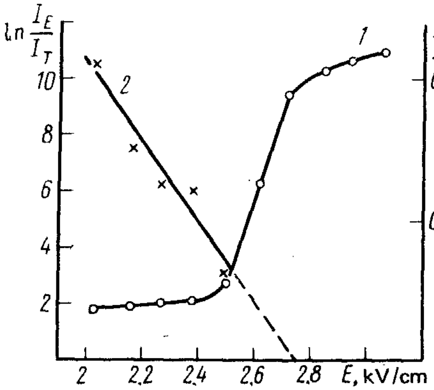

FIG. 3. $\ln(I_E/I_T)$ as a function of the field E with $x = 7.2$ mm: ○ are for curve 1. The E dependence of I_T/I_E; x are for curve 2.

Figure 3 shows $\ln(I_E/I_T)$ as a function of the field intensity at a fixed point in the crystal (curve 1).

As the magnitude of the electric field is changed from values that are less than critical to values greater than E_c, the field dependence of $\ln(I_E/I_T)$ changes.

In fields lower than critical fields, the intensity of the anti-Stokes MBC and, therefore, of the sound flux increases with the field following a hyperbolic law $I_E/I_T \sim (E_c - E)^{-1}$, consistent with the behavior predicted in Ref. 2.[2] As an illustration of this newly discovered characteristic, Fig. 3 also shows the field dependence of I_T/I_E (curve 2). The experimental points satisfactorily follow a straight line, while the intersection of the continuation of the straight line with the abscissa axis gives a value for the critical field that agrees well with E_c calculated from the known values of the velocity of sound $W = 2.7 \times 10^5$ m/s and the mobility of current carriers μ in ZnO.

In fields that differ little from the critical field, as the electric field intensity increases, the light intensity and, therefore, the sound intensity are observed to increase exponentially. With further increase in the field intensity, the intensity of the anti-Stokes component saturates, just as the intensity of the sound fluctuations corresponding to it.

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[1] The critical field E_c is that field for which the drift velocity of electrons is equal to the velocity of sound W.

[2] In Ref. 5, only the fact that an electric field less than the critical value or close to it affects the intensity of the Mandel'shtam-Brillouin components is mentioned.

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