Sound absorption in a strongly doped compensated semiconductor

M. B. Gitis, Yu. V. Gulyaev, and I. A. Chaĭkovskiĭ

Institute of Radio Engineering and Electronics, USSR Academy of Sciences
(Submitted 29 August 1978)
Pis'ma Zh. Eksp. Teor. Fiz. **28**, No. 8, 537–540 (20 October 1978)

We calculate the sound-absorption coefficient in strongly doped compensated piezosemiconductors and consider its main features. The relations obtained are used to interpret some available experimental data on sound absorption in CdS and CdSe at low temperatures.

PACS numbers: 43.35.Cg, 62.30. + d

Strong absorption of sound in a piezosemiconductor is due to modulation of the spatial distribution of the free carriers by the longitudinal electric fields that accompany the ultrasonic wave.[1,2] The very presence of a sufficiently high concentration of the free carriers in the strongest piezosemiconductors of the II–VI group with large band gap (CdS,CdSe) is due to strong doping of the semiconductor either by impurities or by point defects that occur when the crystal is grown. Therefore when a compensating impurity that leads at sufficiently high concentrations to vanishing of the metallic conductivity into such a semiconductor, and the onset of a considerable inhomogeneity of the electron density[3] should substantially alter the acoustic properties of the sample. At low tempeatures, neglecting electrons at the percolation level, such a semiconductor can be regarded as a dielectric with imbedded metallic drops insulated from one other.[4] At ultrasound frequencies not exceeding 10^8–10^9 Hz, the acoustic wavelength greatly exceeds the dimension of the inhomogeneities and the skin-layer thick-

 0021-3640/78/200497-03$00.60

ness, so that the sound propagation is described by the ordinary elasticity-theory system of equations for piezoelectric media and by Maxwell's equations. It is necessary, however, to introduce into the electric induction vector **D** additional terms that take into account the polarization **P** of the drops by the electric field that accompany the piezoactive sound wave. Since all the sound-absorption singularities of interest to us are connected with longitudinal electric fields in the ultrasonic wave, which occur when the wave propagates perpendicular (shear wave) or along (longitudinal wave) the hexagonal axis of the crystal, we confine ourselve henceforth to a one-dimensional treatment. The equations of the problems are then

$$\rho \frac{\partial^2 u}{\partial t^2} = c \frac{\partial^2 u}{\partial x^2} - \beta \frac{\partial E}{\partial x},$$

$$\frac{\partial D}{\partial x} = 0,$$

$$D = \epsilon E + \beta \frac{\partial u}{\partial x} + VN\alpha E. \tag{1}$$

Here u is the mechanical displacement in the wave, ρ,ϵ,β, and c are the density dielectric constant, piezoelectric modulus, and elastic modulus of the crystal, E is the alternating piezoelectric field of the wave, α is the polarizability of the drops, N is the number of drops per unit volume, and V is the volume of the drop.

If we assume for simplicity that the drops are spherical, then according to Ref. 5

$$\left.\begin{array}{l} \alpha = \epsilon \dfrac{\kappa_d - \epsilon}{\kappa_d + 2\epsilon} \\ \kappa_d = \epsilon + i \dfrac{4\pi\sigma_d}{\omega}, \qquad \sigma_d = e\mu n_d \end{array}\right\}, \tag{2}$$

where ω is the cyclic frequency of the sound, σ_d is the electric conductivity of the drop, and μ and n_d are the mobility and concentration of the electrons in the drop.

Expressing N in terms of the electron density n averaged over the volume, $N = n/Vn_d$, and calculating from (1) and (2) in standard fashion the sound absorption coefficient Γ, we obtain

$$\Gamma = \frac{1}{2} \frac{\beta^2}{\epsilon c} \frac{n}{n_d} \sqrt{\frac{\rho}{c}} \frac{\omega^2 \tau}{1 + \omega^2 \tau^2}, \qquad \tau = \frac{3\epsilon}{4\pi\sigma_d}. \tag{3}$$

Thus, a characteristic sound absorption, due to the conduction electrons and manifesting itself only for piezoactive elastic waves, should be observed in strongly doped compensated (SDC) piezosemiconductors. In contrast to ordinary sound absorption in semiconductors,[1,2] however, in this case there is no unique connection between the electric conductivity σ of the sample and the sound absorption coefficient;

this can serve as a basis for an experimental separation of the two mechanisms. Another peculiarity of Γ in SDC piezosemiconductors is connected with the dependence on the sample illumination, since the process starts first with establishment of quasiequilibrium in the band, followed, with different characteristic times, by establishment of equilibrium between the band and the levels.[6] Therefore the kinetics of the establishment of stationary values of Γ and σ in SDC piezosemiconductors, after the illumination is turned on, is described by different characteristic times. As for numerical estimates, for CdS at frequencies 10^8 Hz and at $\omega\tau = 1$ and $n/n_d = 0.01$ we have for shear waves $\Gamma \approx 30$ dB/cm.

It is easy to see that a study of the $\Gamma(\omega\tau)$ dependence makes it possible to use acoustic methods for an experimental determination of the electron density in the drop, inasmuch as at $\omega\tau = 1$ we have $\Gamma \propto n/n_d$, and the proportionality coefficient can be easily calculated from independent measurements.

SDC semiconductors can be obtained not only by introducing a compensating impurity, but also by lowering the temperature, so that the electrons in the conduction band are bound with donors and cease to screen effectively the internal random potential. In other words, a piezosemiconducting crystal that is ordinary at room temperature goes over, if the temperature is sufficiently lowered, into a state with inhomogeneous carrier density distribution, wherein the ordinary sound-absorption mechanism vanishes and the regularities described above appear.

The characteristic features of the behavior of SDC semiconductors at low[3] and not too low[7] temperatures will lead to distinct temperature dependences of Γ. It is probable that this mechanism can be used to explain the experimental results on sound absorption in CdS and CdSe at low temperatures,[8,10] which so far have not found a convincing theoretical explanation. All the characteristic features of sound absorption in SDC piezosemiconductors, which were described above, have been observed in these experiments. The reduction of the results of Ref. 9 in accordance with (3) yields for n/n_d, in various samples, values 10^{-4}–10^{-3} which are perfectly reasonable.

[1]A.R. Hutson and D.L. White, J. Appl. Phys. **33**, 40 (1962).

[2]V.L. Gurevich, Fiz. Tverd. Tela (Leningrad) **4**, 909, 1380 (1962) [Sov. Phys. Solid State **4**, 668 (1962); 1015 (1963)].

[3]B.I. Shklovskiĭ and A.L. Éfros, Zh. Eksp. Teor. Fiz. **61**, 816 (1971) [Sov. Phys. JETP **34**, 435 (1972)].

[4]Yu. S. Gal'pern and A.L. Éfros, Fiz. Tekh. Poluprovodn. **6**, 1081 (1972) [Sov. Phys. Semicond. **6**, 941 (1972)].

[5]L.D. Landau and E.M. Lifshitz, Élektronika sploshnykh sred (Electrodyamics of Continuous Media), GIFML, 1959 [Pergamon].

[6]A. Ya. Shik, Zh. Eksp. Teor. Fiz. **71**, 1159 (1976) [Sov. Phys. JETP **44**, 2199 (1976)].

[7]Yu. V. Gulyaev and V.P. Plesskiĭ, Zh. Eksp. Teor. Fiz. **71**, 1475 (1976) [Sov. Phys. JETP **44**, 772 (1976)].

[8]E.M. Ganapol'skiĭ and V.V. Tarakanov, Fiz. Tverd. Tela (Leningrad) **10**, 993 (1968) [Sov. Phys. Solid State **10**, 785 (1968)].

[9]Yu. V. Gulyaev, A.M. Kmita, A.V. Medved', and A.I. Morozov, Fiz. Tverd. Tela (Leningrad) **12**, 690 (1970) [Sov. Phys. Solid State **12**, 536 (1970)].

[10]A.M. Kmita, A.I. Morozov, and V.A. Fedorets, Fiz. Tverd. Tela (Leningrad) **13**, 1011 (1971) [Sov. Phys. Solid State **13**, 841 (1971)].