Absorption of ultrasound by electron-hole drops in a semiconductor

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The interaction of ultrasound with electron-hole drops (EHD) in a semiconductor is considered. The sound absorption coefficient and the drift velocity of the EHD dragged by the sound are obtained. In the case of small drops, the temperature dependence of the absorption coefficient has a sharp maximum, and the EHD drift velocity reaches the speed of sound even at very small amplitudes of the sound wave.

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At a sufficiently high density of the electrons and holes in a semiconductor at low temperatures, a first-order phase transition is possible, in which the gas of the nonequilibrium carriers stratifies into two phases—gaseous and liquid—in the form of an electron-hole drop (EHD) having an equilibrium carrier density n_0 and an average radius R, and distributed in the volume of the semiconductor with a density N_0.[1] This liquid is a degenerate electron-hole plasma and interacts effectively with ultrasound, while the mechanism whereby the ultrasound is absorbed in the semiconductor filled with the EHD depends on the ratio of the wavelength λ and dimensions of the EHD.

At $\lambda \ll R$, the absorption of sound is the absorption of a spatially-homogeneous electron-hole Fermi liquid and is described by known formulas,[2] except that account must be taken of the fact that not the entire volume of the semiconductor is filled with drops.

On the other hand, if $\lambda \gg R$, the absorption mechanism is essentially different. In this approximation, each electron-hole pair in the EHD is acted upon by equal forces in the field of the inhomogeneous deformation,[3] so that the EHD are set to oscillate under the influence of the ultrasound and dissipate energy by interacting with the thermal phonons of the lattice. The friction of the drop against the lattice at low drop velocities $V \ll S$ (S is the speed of sound of the semiconductor) will be viscous, with a kinematic friction coefficient[4]

$$\gamma = \frac{2}{3(2\pi)^3} \frac{m_e^2 D_e^2 + m_h^2 D_h^2}{\hbar^2 (m_e + m_h)\rho S} \left(\frac{k_0 T}{\hbar S}\right)^5 \int_0^{\xi_0} \xi^5 \frac{\exp \xi}{(\exp\xi - 1)^2} d\xi \,, \qquad (1)$$

where $\xi_0 = 2\hbar s (3\pi^2 n_0)^{1/3}/k_0 T$, T is the crystal temperature, ρ is its density, m_e, m_h and D_e, D_h are the mass and the deformation potential of the electron and of the hole, respectively.

In a cubic single-valley semiconductor with nondegenerate bands, a small drop ($R \ll \lambda$) in the field of a longitudinal acoustic wave of frequency ω and wave vector $\mathbf{k}$ directed along the OX axis, we have $\epsilon = \epsilon_0 \sin(\omega t - kx)$ ($\epsilon = T\eta\epsilon_{ij}$ is the deformation of the crystal), is acted upon by the force

$$\mathrm{F} = \frac{4}{3}\pi R^3 n_0 D k \epsilon_0 \cos(\omega t - k\xi), \qquad (2)$$

where ξ is the x coordinate of the drop, and $D = D_e + D_h$.

The equation of motion of the drop in the field of the force (2) will take the form

$$\frac{d^2\xi}{dt^2} + \gamma \frac{d\xi}{dt} = \frac{Dk\epsilon_0}{m} \cos(\omega t - k\xi), \text{ where } m = m_e + m_h. \qquad (3)$$

We seek the solution of (3) in the form $\xi = Vt + x(t)$, where V is the constant drift velocity of the EHD and $x(t)$ are small oscillations (with amplitude $x_0 \ll \lambda$). Then $\cos(\omega t - k\xi) = \cos\Omega t + kx\sin\Omega t$, ($\Omega = \omega - kV$), and (3) takes the form

$$\frac{d^2 x}{dt^2} + \gamma \frac{dx}{dt} + \gamma V = \frac{Dk\epsilon_0}{m} \cos \Omega t + \frac{Dk^2\epsilon_0}{m} x \sin \Omega t. \qquad (4)$$

Solving (5), we obtain

$$V = \frac{D^2 \epsilon_0^2}{2m^2} k^3 \frac{1}{\Omega(\Omega^2 + \gamma^2)} \,, \qquad (5)$$

$$x = \frac{Dk\epsilon_0}{(\Omega^2 + \gamma^2)m} \left(\frac{\gamma}{\Omega} \sin\Omega t - \cos\Omega t\right). \qquad (6)$$

At $\omega \sim \gamma$, the condition $x_0 \ll \lambda$ yields $V \ll S$ at ultrasound intensities ($I = \rho S^3 \epsilon_0^2/2$):

$$I \ll \frac{m^2 \rho S^7}{D^2} \sim 10 \ \mathrm{W/cm^2} \qquad (7)$$

At $D \sim 10$ eV, $m \sim 10^{-27}$ g, $\rho \approx 5$ g-cm^{-3}, and $S \approx 5 \times 10^5$ cm-sec^{-1}, Eq. (6) enables us to determine the energy absorbed by the drop per unit time at $V \ll S$

$$\overline{\mathrm{F} \frac{dx}{dt}} = \frac{\frac{4}{3}\pi R^3 n_0 D^2 k^2 \epsilon_0 \gamma}{2m(\gamma^2 + \omega^2)}$$

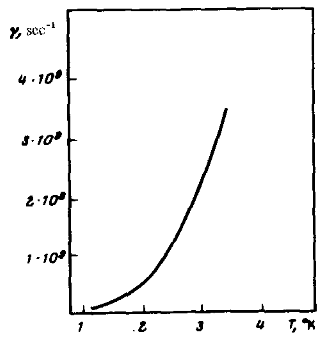

FIG. 1.

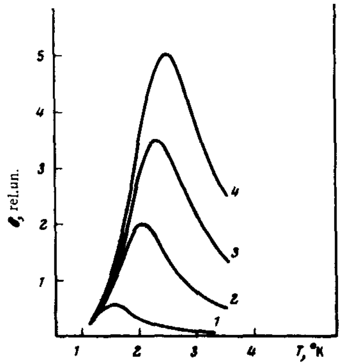

FIG. 2. Temperature dependence of the ultrasound absorption coefficient at frequencies ω equal to: 1) 10^8, 2) 4×10^8, 3) 7×10^8, 4) 10^9 sec^{-1}.

and the ultrasound absorption coefficient due to the entire aggregate of the drops is

$$\delta = \left|\frac{d\ln I}{dx}\right| = \bar{n}\frac{D^2}{\rho m S^5}\frac{\gamma\omega^2}{\gamma^2+\omega^2}, \qquad (8)$$

where $\bar{n}=(4/3)\pi R^3 n_0 N_0$ is the average density of the condensate over the entire semiconductor. At $\lambda \gg R$, the absorption coefficient does not depend on the dimensions of the drops. In order of magnitude, we have $\delta \sim 1-10$ cm^{-1} at $\omega\sim10^9$ sec^{-1} and $\bar{n}\sim10^{14}$ cm^{-3}. Figures 1 and 2 show the temperature dependences of γ and δ (at different frequencies), calculated from formulas (1) and (8) respectively (at $D=5$ eV, $m=0.5\times10^{-27}$ g, $n_0=2\times10^{17}$ cm^{-3}, $S=5\times10^5$ cm-sec^{-1}, and $\rho=5$ g/cm^3). The quantity δ is given in relative units, since its absolute value is proportional to the excitation level of the semiconductor, which depends on the experiment. As seen from these figures, the most characteristic feature of the absorption of ultrasound by small EHD at low ultrasound intensities is its sharply pronounced resonant dependence on the temperature.

At intensities $I > (\gamma^2/\omega^2)(m^2\rho S^7/2D^2)$, the drifts will be completely dragged by the ultrasonic wave: $x=St+x_0$. Equation (3) yields in this case

$$x_0 = \frac{1}{k}\arccos\frac{2\gamma S m}{Dk\epsilon_0} = \frac{1}{k}\arccos\left(\frac{\gamma}{\omega}\frac{mS^2}{D}\sqrt{\frac{\rho S^3}{2I}}\right). \qquad (9)$$

Although formally we cannot use formula (1) at $V\sim S$, there are grounds for assuming that γ remains of the same order in this case.[5]

The considered mechanism of ultrasound absorption is of course not confined to cubic single-valley crystals. It should exist in semiconductors with arbitrary band structure and anisotropy, and can occur for all types of acoustic waves, not only pure longitudinal ones.

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