Phonon wind and dimensions of electron-hole drops in semiconductors

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It is shown that a flux of nonequilibrium phonons produced upon recombination of electrons and holes leads to instability of rather large volumes of an electron-hole liquid and to their breakup into smaller drops.

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Electron-hole drops (EHD) are sources of intense fluxes of nonequilibrium phonons produced in nonradiative recombination of electrons and holes. After being absorbed or scattered by the electron-hole liquid, these phonons transfer to it part of their quasimomentum, and this is equivalent from the macroscopic point of view to the action of a certain volume force $\mathbf{f}(\mathbf{r})$ proportional to the local phonon energy flux $\mathbf{w}(\mathbf{r})$ [1]

$$\mathbf{f}(\mathbf{r}) = A\mathbf{w}(\mathbf{r}) \ . \tag{1}$$

The EHD volume element δV located in the vicinity of the point $\mathbf{r}$ produces at a point $\mathbf{r}'$ a flux

$$\delta \mathbf{w}(\mathbf{r}') = \frac{B}{4\pi} \frac{\mathbf{r}' - \mathbf{r}}{|\mathbf{r}' - \mathbf{r}|^3} \delta V \ , \tag{2}$$

where B is the energy radiated in phonons by a unit EHD volume in a unit time. It follows from (1) and (2) that the two volume elements δV and $\delta V'$ located in the vicinities of the points $\mathbf{r}$ and $\mathbf{r}'$, respectively, repel each other with a force

$$\mathbf{F} = \frac{AB}{4\pi} \frac{\mathbf{r}' - \mathbf{r}}{|\mathbf{r}' - \mathbf{r}|^3} \delta V \delta V' \ . \tag{3}$$

In other words, the volume forces produced in the electron-hole liquid by the "phonon wind" are exactly the same as would be produced if this liquid were uniformly charged, with charge density equal, by virtue of formula (1) for $\mathbf{f}$ and $\mathbf{w}$, to

$$\rho^2 = \frac{AB}{4\pi} = \begin{cases} \dfrac{a^{(\mathrm{abs})}}{4\pi} \dfrac{n_0 E_g}{\tau_0} \dfrac{d^2 m^2}{\hbar^3 \rho_c s^2} \overline{|\mathbf{k}|}, & \hbar\overline{|\mathbf{k}|} < 2p_F \quad (4a) \\ \dfrac{a^{(\mathrm{sc})}}{4\pi} \dfrac{n_0 E_g}{\tau_0} \left(\dfrac{d^2 m^2}{\hbar^3 \rho_c}\right)^2 \left(\overline{\dfrac{|\mathbf{k}|^4}{\omega_{\mathbf{k}}^3}}\right), & \hbar\overline{|\mathbf{k}|} \gg 2p_F \quad (4b) \end{cases},$$

where n_0 and τ_0 are the equilibrium density and the lifetime of the electrons and holes in the EHD, E_g is the width of the forbidden band, d and m are certain mean values of the deformation potentials and the effective masses, ρ_c is the density of the crystal, s is the speed of sound, $a^{(\mathrm{abs})}$ and $a^{(\mathrm{sc})}$ are numerical coefficients (each $\sim 10^{-2}$) that depend on the details of the band structure and the anisotropy of the electron-phonon interaction, $\mathbf{k}$ and $\omega_{\mathbf{k}}$ are the wave vector and frequency of the phonons, and p_F is the Fermi momentum of the electrons and holes. The difference between (4a) and (4b) is due to the fact that at $\hbar|\mathbf{k}| < 2p_F$ the principal role is played by phonon absorption processes, and at $\hbar|\mathbf{k}| \gg 2p_F$ the scattering predominates.

An obvious consequence of these arguments is the conclusion that sufficiently large volumes of the electron-hole liquid cannot be stable and must inevitably break up into smaller EHD. Consider two typical situations: a spherical EHD of radius R, which grows gradually from an exciton cloud, and a plane layer of electron-hole liquid of thickness L, which can be produced and apparently is really produced in experiments in the case of very brief but quite intense lasing of a semiconductor. Elementary calculations of the oscillations of the shape of the surface of a uniformly charged incompressible liquid, analogous to[2], show that when a certain critical radius R_c is reached the EHD becomes unstable to deformations of the quadrupole type, which cause it to be divided into two parts, and

$$R_c = \left(\frac{15}{2\pi} \frac{\alpha}{\rho^2}\right)^{1/3}, \tag{5}$$

where α is the surface-tension coefficient of the EHD.

The problem of the oscillations of a flat layer under the influence of phonon wind is similar to the well-known problem of capillary-gravitational waves,[2] subject only to the fundamental difference that the force $f = 4\pi\rho^2 L$ is directed along the outward normal to the liquid surface, and it is this which leads at $L > L_c = 0.385 R_c$ to instability of all the surface waves with wave vectors q satisfying the condition $\alpha q^2 + 2\pi\rho^2 q^{-1} - 4\pi\rho^2 L < 0$. At $L \gg L_c$ the growth increment is maximal for $q = R_L^{-1}$, where

$$R_L = \left(\frac{3}{4\pi} \frac{\alpha}{\rho^2 L}\right)^{1/2} = \left(\frac{1}{10} \frac{R_c}{L}\right) R_c . \tag{6}$$

The development of this instability should lead to a breakup of the initial layer into EHD with radii $\sim R_L$, which move apart under the influence of the phonon wind with velocity $v = 4\pi\rho^2 L (M n_0 \gamma)^{-1}$, where M is the sum of the effective masses of the electron and the hole, and γ^{-1} is the time of velocity relaxation (deceleration) of the EHD.

Formulas (4) show that the intensity of the phonon wind depends strongly on the phonon frequency distribution. Thus, for the parameters of germanium ($d = 4$ eV, $m = 4\times10^{-28}$ g, $\rho_c \approx 5$ g/cm^3, $s = s_t = 3\times10^5$ cm/sec, $n_0 = 2\times10^{17}$ cm^{-3}, $\tau_0 = 4\times10^{-5}$ sec, $E_g = 0.74$ eV), depending on $|\mathbf{k}|$, the values of ρ vary in the interval $(0.1-1.0)\times10^3$ g$^{1/2}$cm$^{-3/2}$ sec^{-1}. Assuming $\alpha = 2\times10^{-4}$ g/sec^2 we obtain $R_c = (0.7-3.5)\times10^{-3}$ cm and $R_L = (0.15-1.5)L^{-1/2}\times10^{-4}$ cm. For silicon we obtain values of R_L and R_c smaller approximately by one order of magnitude.

The presented values of R_c are in reasonable agreement with the observed[4] limit $R \le 1\times10^{-3}$ cm, and do not contradict the large EHD observed in[5], since the uniaxial deformations used in[5] strongly attenuate the phonon wind.[1] There are also experimental indications in[6] that an electron-hole liquid is scattered in the form of minute drops following a strong pulsed excitation. The foregoing considerations allow us to describe this scattering. It is easy to show that an EHD separated from the initial layer at the instant of time t_0 and at the point z_0 ($z_0 \le L$, where z is the distance from the surface of the sample), moves subsequently in accordance with the law

$$z(t) = z_0\left[1 + \frac{4\pi\rho^2\tau_0}{Mn_0\gamma}\left(1 - e^{-\frac{t-t_0}{\tau_0}}\right)\right]. \qquad (7)$$

On the other hand, if the pulse of the exciting radiation is focused, so that the initially produced liquid is in the shape of a sphere of radius $R \gg R_c$, then this volume breaks up into drops with radii that differ from (6) only in the replacement $L \to R/3$, and are scattered in accordance with the law

$$r(t) = r_0\left[1 + \frac{4\pi\rho^2\tau_0}{Mn_0\gamma}\left(1 - e^{-\frac{t-t_0}{\tau_0}}\right)\right]^{1/3}, \quad r_0 \leqslant R. \qquad (8)$$

Formulas such as (7) and (8) describe also the case when the initial pulse produces a cloud of minute EHD, if the second terms in the right-hand sides of these formulas are multiplied by the fraction $\bar{n}/n_0$ of the volume occupied by the liquid phase in the cloud. At high temperatures, when most nonequilibrium carriers recombine in the gas phase, τ_0 in Eqs. (7) and (8) must be replaced by the effective lifetime τ_{eff} of the system of nonequilibrium carriers.

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