The effect of the phonon wind on the formation of electron-hole droplets in a semiconductor

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It is shown that the maximum size of a large electron-hole drop in a inhomogeneously deformed semiconductor depends on the intensity of the phonon wind and the geometry of the nonuniform compression. At high intensities of the phonon wind a cloud of small droplets should form instead of a single drop.

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The phonon wind—the flux of nonequilibrium phonons formed in the recombination of excited carriers in semiconductors—exerts a substantial effect on the electron-hole liquid.[1–5] Being scattered or absorbed by electrons and holes, these phonons create space forces, just as if the liquid were uniformly charged with some charge density.[2] The mutual repulsion of electron-hole droplets in Ge has been observed experimentally.[5] The photon wind may also be responsible for the experimentally observed upper limit on the size of the drops.[2]

In this letter we examine theoretically the effect of the phonon wind on the formation of large drops in an inhomogeneously deformed semiconductor. Such drops are confined near the maximum of the deformation in the potential well created by nonuniform compression of the semiconductor and can reach sizes of up to 1 mm (in

Ge).[6,7] It was assumed in Ref. 8 that they are formed from fine droplets which arise rapidly in the generation region and "drain down" relatively slowly into the bottom of the potential well.

We shall show that the phonon wind can become important in the later stages of the formation of a large drop. For example, it can cause such a large mutual repulsion of the fine droplets that a large drop will form only in a potential well with rather steep walls. In wells with gently sloping walls the electron–hole liquid should exist as a cloud of fine droplets, as it does in an undeformed crystal. It can also happen that a large drop formed in the central part of the potential well will be surrounded by a cloud of fine droplets "soaring" on the phonon wind. None of these cases has yet been observed experimentally. Evidently, these effects would be simpler to detect in semiconductors with relatively short lifetimes of the electron-hole liquid and, hence, high intensities of the phonon wind (e.g., silicon).

We will examine the behavior of a cloud of fine electron-hole droplets in a spherically symmetric potential well $U(r)$ created by an external nonuniform compression. By analogy with electrostatics, we describe the effect of the phonon wind with the aid of a phonon-wind potential $\Phi(\mathbf{r},t)$. We write a system of gas-dynamic equations for the potential $\Phi(\mathbf{r},t)$, the average density of carriers in the condensate $N(\mathbf{r},t)$, and the local velocity of the droplets $\mathbf{V}(\mathbf{r},t)$:

$$\frac{\partial N}{\partial t} + \operatorname{div} N\mathbf{V} = 0, \tag{1}$$

$$m\left(\frac{\partial \mathbf{V}}{\partial t} + (\mathbf{V}\vec{\nabla})\mathbf{V} + \gamma\mathbf{V}\right) = -e_*\vec{\nabla}\Phi - \vec{\nabla}U \tag{2}$$

$$\Delta\Phi = -4\pi e_* N, \tag{3}$$

where $m = m_e + m_h$ and $e_* = p/n_0$ are the effective mass and the "charge" (due to the phonon wind) of an electron-hole pair, n_0 is the density of the electron-hole liquid, and γ is the coefficient of viscous friction of the liquid against the semiconductor.[9] In the derivation of Eqs. (1)–(3) it was assumed that the equilibrium properties of the liquid and the parameters of the phonon wind do not change from point to point. This is not the case when the semiconductor is strained inhomogeneously. If, however, the pressure range within the sample is not too large, these variations can be neglected.[10] In addition, Eqs. (2) and (3) do not take into accound the retardation of the phonon wind. They are therefore applicable under the condition $V \ll S$, where S is the speed of of sound in the semiconductor.[1]

Equations (1)–(3) have the steady-state solution

$$\Phi_{st}(r) = -\frac{1}{e_*}U + \text{const}, \tag{4}$$

$$N_{st}(r) = \frac{1}{4\pi e_*^2}\Delta U, \tag{5}$$

where $\Delta = (1/r^2)(d/dr)r^2(d/dr)$. It can be shown that the distribution (5) is stable in the region where $\Delta U > 0$, i.e., where this solution is physically meaningful. Outside this region $N_{st} = 0$.

If the potential energy depends quadratically on the radius: $U = U_0 + \frac{1}{2}ar^2$ (which is true in any case in a small enough region around the bottom of the well), the steady-state distribution of the condensate is uniform:

$$N_{st} = \frac{2a}{4\pi e_*^2} \qquad \phi_{st} = -\frac{ar^2}{2e_*} + \text{const}. \tag{6}$$

This is a familiar result from electrostatics: The potential inside a uniformly charged sphere depends quadratically on the radius.

We will now take into account that according to the meaning of the average density of carriers in the condensate, the inequality $N \leqslant n_0$ should hold (equality means that the investigated volume is completely filled by electron-hole liquid).

We will consider the following possibilities:

1. *$N_{st}(r) < n_0$ everywhere in the sample.* A large drop does not form. A stationary distribution of fine droplets is established in the potential well with a density given by Eq. (5).

2. *$N_{st}(r) > n_0$ everywhere in the sample.* The phonon wind does not inhibit the formation of a large drop; its dimensions are limited only by the total number of photoexcited carriers.

3. *The sample contains a region in which $N_{st} > n_0$. Outside this region the opposite inequality holds.* The phonon wind does not inhibit the formation of a large drop inside the region. The drop can continue to grow until its "charge" is no longer comparable to the charge which a cloud of point droplets of the same radius would have for the steady-state distribution (5). As the radius increases further, the repulsion of the small droplets by the phonon wind exceeds the attraction toward the bottom of the well, and the large drop ceases to grow. Consequently, the radius of the large drop will not exceed the value R_m determined by the condition

$$\rho v_m = e_* \int_{v_m} N_{st}(r)\, d^3r \text{, where } v_m = 4/3\,\pi R_m^3. \tag{7}$$

Using Eq. (5) and evaluating the integral on the right-hand side of (7), we obtain an equation for the maximum radius of a large drop:

$$\left(r^2 \frac{du}{dr}\right)_{r=R_m} = \frac{4\pi}{3} \frac{\rho^2}{n_0} R_m^3. \tag{8}$$

We shall now make some estimates. In unstrained germanium[4] $\rho = 10^2$ $g^{\frac{1}{2}}\text{cm}^{-3/2}\cdot\text{sec}^{-1}$. In strained germanium the density of the liquid is about one fourth as large, while the lifetime τ_0 is about ten times as large as in the strained crystal.[7] Inasmuch as (..b..) (Ref. 2), it is to be expected that in strained germanium the charge density is, in order of magnitude, $\rho \cong 10 g^{\frac{1}{2}}\cdot\text{cm}^{-3/2}\cdot\text{sec}^{-1}$. In a typical experimental case $\alpha \cong 10$ meV/mm^2 near the center of the potential well.[6,7] Therefore $N_{st}(0) \cong 10^2 n_0$, and, depending on the shape of the well, either case 2 or 3 should be realized.

Case 1, in which no large drop forms at all, might obtain in silicon. The electron-hole liquid in silicon is denser and shorter lived than in germanium, and the intensity of the phonon wind in silicon should therefore be extremely high.

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[1)]The recombination of carriers is not taken into account in Eq. (1), since we are interested in times which are short compared to the lifetime of the liquid.

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