"Drop formation" on heating of a gas of noninteracting excitons

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(Submitted April 2, 1976)
Pis'ma Zh. Eksp. Teor. Fiz. **23**, No. 10, 559–561 (20 May 1976)

It is shown that when an ideal exciton gas is heated it becomes stratified if the momentum relaxation time of the "hot" excitons is an increasing function of their energy. A similar effect is realized also when an electron-hole plasma is heated.

PACS numbers: 71.80.+j

At large exciton concentrations, when their interaction is attractive, drops of electron-hole liquid are produced.[1] The energy of the interaction between the excitons is quite small, and its magnitude, and possibly even the sign, depend strongly on the details of the energy spectrum of the particular semiconductor.[1] This communication calls attention to the fact that a phenomenon analogous to drop formation can occur also in a system of an ideal (noninteracting) gas of excitons as it is heated.

In semiconductors, large-radius excitons are produced as a result of binding of nonequilibrium electrons and holes produced by photoexcitation or injection from a p–n junction. The energy released when the carriers are bound into an exciton is transferred to phonons or excitons. At large exciton concentrations, the last process can be decisive. As a result, the exciton temperature can differ from the lattice temperature T_0 when the time of collisions between the excitons is shorter than the characteristic time of scattering of their energy by the phonons. Under these conditions, the exciton density n and their effective temperature T are determined by the following system of equations[2,3]:

$$\frac{\partial n}{\partial t} = -\operatorname{div} J + R_2 - \frac{n}{\tau_r}\,; \qquad \frac{3}{2}\frac{\partial nT}{\partial t} = -\operatorname{div} q_\epsilon + W - n\frac{T-T_0}{\tau_\epsilon}, \tag{1}$$

where R_2 and τ_r are the generation rate and the recombination time of the excitons, $\tau_\epsilon = \tau^0 (T/T_0)^S$ is the relaxation time of the kinetic energy, and W is the power input to the exciton system due to the binding of the electrons and holes into excitons, and also due to scattering of their kinetic energy by the excitons. The exciton-concentration flux density J and their energy density q_ϵ are, if the exciton relaxation time has a power-law dependence on the exciton momentum and on its energy ($\tau_p \sim T^\alpha$), respectively[2,3]

$$J = -\nabla(Dn) = -D\nabla n - (\alpha+1)\,Dn\frac{1}{T}\nabla T, \tag{2}$$

$$q_\epsilon = -\left(\frac{5}{2}+\alpha\right)\nabla(DTn) = -\left(\frac{5}{2}+\alpha\right)[DT\nabla n - (2+\alpha)\,Dn\nabla T], \tag{3}$$

where D is the exciton diffusion coefficient.

Linearizing Eqs. (1)—(3) with respect to perturbations of the type $\delta T = (\delta T)_0 \exp(\gamma t + ikr)$, we obtain the dispersion equation

$$\frac{3}{2}\tau_\epsilon\tau_r\gamma^2+\left[k^2\tau_\epsilon L^2(5+3\alpha+\alpha^2)+\frac{3}{2}\tau_\epsilon+\tau_r\left(1-S+S\frac{T_0}{T}\right)\right]\gamma$$

$$+k^4l^2L^2+k^2\left\{l^2(2+\alpha)-L^2\left[\alpha+S-(1+\alpha+S)\frac{T_0}{T}\right]\right\}+1-S+S\frac{T_0}{T}=0, \quad (4$$

from which it follows that the homogeneous distribution of the exciton density becomes aperiodically unstable with respect to

$$k_0=(Ll)^{-1/2}(1-S+ST_0/T)^{1/4} \quad (5$$

at

$$\alpha+S-(1+\alpha+S)\frac{T_0}{T}>2\frac{l}{L}\left(1-S+S\frac{T_0}{T}\right)^{1/2}+(2+\alpha)\left(\frac{l}{L}\right)^2, \quad (6$$

where $L=(D\tau_r)^{1/2}$ is the diffusion length of the excitons and

$$l=\left[\left(\frac{5}{2}+\alpha\right)D\tau_\epsilon\right]^{1/2}$$

is their cooling length (their energy range). In real semiconductors, the excit recombination time τ is larger by several orders of magnitude than τ_ϵ,[1] and consequently $l/L\lesssim 10^{-1}$—10^{-2}. Owing to the smallness of this ratio, condition (is satisfied for heated excitons when

$$\alpha+S>0. \quad (7$$

We emphasize that this condition is much less stringent than the overheat instability condition $\alpha+S>1$.[2,3] (Large-radius excitons are macroscopic formations,[1] and their relaxation times can therefore not be expected to differ in principle from the relaxation times of the electrons and holes of which they are made up.) At low temperatures, as a rule, the carrier momentum is scattered by charged centers. In this case $\alpha=3/2$, and since[2,3] $S\geq -1/2$, the condition (7) is satisfied independently of the energy relaxation mechanism and as follows from (6), the critical temperature at which the stratification takes place is $T_{cr}\leq 2T_0$.

Stratification of an ideal exciton gas is connected with the fact that the characteristic length of the exciton concentration distribution L greatly exceeds th characteristic length of their cooling l. In fact, consider the evolution of the temperature fluctuation δT produced in a region with characteristic dimension $(lL)^{1/2}$. Since this dimension greatly exceeds l, we can assume that the excito heat-balance equation $W=n(T-T_0)/\tau_\epsilon$ is locally satisfied. At the same time, t hot excitons will be intensively ejected, on account of the heat flow, from this more heated region, so that their concentration in this region decreases, and consequently the power given up to the lattice excitons will decrease. Since th power W delivered to the exciton system is homogeneous, this leads to a furth increase of the fluctuations δT. As a result, the exciton gas breaks up into regions with characteristic dimension $(lL)^{1/2}$, which amounts to 10^{-2}—10^{-3} cm for realistic semiconductor parameters. The onset of regions with different exciton densities and temperatures should manifest itself, first of all, in an anomaly of the scattering of long-wave light, and should also be naturally ac-

ɔmpanied by a certain broadening of the exciton emission line and by a shift
: its maximum. These effects are observed at large exciton concentrations
ıd are interpreted as the result of formation of electron-hole drops produced
/ the interaction of the excitons.[1] We see, however, that another interpreta-
on of these experimental data is possible in principle. Moreover, there is
ıfficiently weighty experimental proof[4] that these effects are connected pre-
.sely with the essentially nonequilibrium conditions under which the exciton
ıdiation is emitted.

At relatively high temperatures or excitation levels, the excitons cease to
ɛist and break up into almost free electrons and holes.[1] The stratification
echanism considered above pertains also to this case, and when the effective
ırrier masses are equal, the condition for the stratification of a quasi-neutral
ectron-hole plasma and the magnitude of the critical vector K_0, with respect
which this stratification takes place, are determined exactly by expressions
) and (5), respectively. Naturally, the electron-hole plasma is much easier
heat both in the photogeneration process and in an electric field. The strati-
cation condition (7) is satisfied here not only for nondegenerate but also for
:rongly degenerate carriers, inasmuch as in the latter case $\alpha = 0$ and $S = 1$ re-
ırdless of the relaxation mechanism.[5]

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