PROC, 15TH INT. CONF. PHYSICS OF SEMICONDUCTORS, KYOTO, 1980
J. PHYS. SOC. JAPAN 49 (1980) SUPPL. A p. 479-482

NEW MECHANISM OF ELECTRON-HOLE DROPLET INSTABILITY

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A new type of instability of e-h droplets (recombination instability) is considered, and the theory of this instability is developed [1]. The phenomenon is caused by the condensation flow from the gas (i.e., exciton) phase on the droplet surface and the recombination flow inside drops, giving rise to the instability of the spherical shape of droplets. The motion of drops in an inhomogeneous exciton gas and their interaction through the gas phase are studied too.

1. Introduction

It follows from experimental data that the e-h liquid (EHL) exists in semiconductors in the form of droplets of $\sim 10\ \mu m$ in size. The fact that EHL exists in such a disperse phase only is ascribed to the effect of the phonon wind [2,3]. Below we consider the processes in the electronic subsystem exclusively, and show the existence of new mechanisms of the e-h droplet (EHD) instability. According to the order of magnitude estimates, these mechanisms may restrict the droplet radii, side by side with phonon wind. The motion of EHD in an inhomogeneous exciton gas and their interaction through the gas phase are considered as well. It is shown that both the direction of the motion and the sign of the interaction may change depending on the parameter values.

2. Recombination Instability

The instability mechanisms considered below are illustrated in Fig.1. The qualitative patterns of the phenomena are as follows.

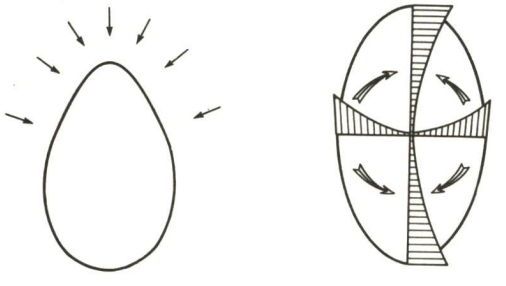

Fig. 1 (a) Distribution of the condensation flow near the elongated part of EHD. (b) Distribution of the pressure and meridional flows in an elongated EHD

Suppose the concentration of excitons in the exciton gas n_∞ is higher than their concentration n_r near the EHD surface. When the spherical form of the surface of a droplet is changed

fluctuationally (Fig. 1(a)), the density of condensation flow of excitons on the elongated part of the surface increases, and the flow on its flattened part decreases. As a result, the initial fluctuation grows and the instability of the droplet form develops. This instability may result in the fission of the drop into a number of the droplets of smaller size (below it is called the condensation mechanism of instability).

The recombination of the EHL inside the drop produces both the recombination flow in it and the pressure gradient maintaining this flow. When the droplet form deviates from the spherical one, the pressure distribution becomes asymmetric; it is illustrated in Fig. 1(b). Such a pressure distribution gives rise to meridional flows, which also are shown in Fig. 1(b); they strengthen the nonsphericity (recombination mechanism of instability).

Since both mechanisms act simultaneously, we designate the whole phenomenon as recombination instability. There is a definite analogy for the first mechanism in the kinetics of usual phase transitions [4]; on the contrary, the second mechanism is specific for EHL.

The increment of instability grows is (for detail see [1]):

$$\lambda=\frac{L-2}{3\tau_0}\left(\frac{R_{st}}{R}\right)^2+\frac{L}{3\tau_0}\left\{1-3(L-1)(L+2)\frac{\sigma\tau_0\tau_\ell}{mNR^3}-(L-1)\frac{\Lambda^*T\tau_\ell}{mDR}\left(\frac{R_{st}}{R}\right)^2\right\}. \quad (1)$$

Here $L > 1$ is the number of spherical harmonic describing the EHD deformation, τ_0, τ_ℓ and N are life-time, mean free time and concentration of e-h pairs in EHL, σ is surface tension, T is temperature, D and Λ^* are diffusion coefficient and effective mean free path of exciton in a gas phase, R is droplet radius (it is supposed that $R \gg \Lambda^*$), and

$$R_{st}^2=\frac{3D\tau_0}{N}(n_\infty-n_T) \quad (2)$$

is the "steady-state" droplet radius.

The first term in eq. (1) corresponds to the condensation instability mechanism, and the second to the recombination instability mechanism. The third term describes the stabilization of droplet form due to surface tension, and the fourth due to gas-kinetic pressure; we shall first omit the last term. The quadrupole instability ($L = 2$) is controlled by recombination mechanism and develops at $R > R_2^{is}$:

$$R_2^{is}=(12\sigma\tau_0\tau_\ell/mN)^{1/3}. \quad (3)$$

If $R_2^{is} \ll R_{st}$, the condensation mechanism producing the octupole instability ($L = 3$) is more effective:

$$R_3^{is} = 7.5 \left(R_2^{is}\right)^3 / R_{st}^2 \quad . \tag{4}$$

Under these conditions the fission of droplets occurs at the space scale R_3^{is} with the characteristic time $\tau_3 \sim \tau_0 (R_3^{is}/R_{st})^2 \ll \tau_0$. Since R_3^{is} depends on supersaturation $n_\infty - n_T$, and R_2^{is} does not, the quadrupole instability has to develop under low, and octupole instability - under high supersaturation conditions.

The last term in eq. (1) may be omitted only when the hybrid parameter $v_T \tau_\ell / R$, including the parameters of both liquid and gas phases, is small ($v_T \tau_\ell / R < 1$); here v_T is the thermal velocity of excitons. If this parameter is large, the gas-kinetic pressure suppresses the recombination instability. It is important that in evaporation regime, when $n_\infty \ll n_T$, R_{st} may be neglected in eq. (1). Under these conditions the instability develops whenever the criterion of eq. (3) is fulfilled (at arbitrary value of the hybrid parameter).

Choosing the parameter values, close to those of Ge, $D \sim 10^3$ cm^2/sec, $\tau_0 \sim 10^{-4}$ sec, $\tau_\ell \sim 10^{-9}$ sec, $\sigma \sim 10^{-4}$ dyne/cm, $n_\infty \sim 3 \cdot 10^{14}$ cm^{-3}, $N \sim 10^{17}$ cm^{-3}, $m \sim 10^{-27}$ g we get $R_{st} \sim 300\,\mu$m and $R_2^{is} \sim R_3^{is} \sim 100\,\mu$m. This estimate deviates not too strongly from the value 16 - 20 μm for the effective upper bond of EHD radii, determined experimentally [5,6], and may be brought into better agreement with it by a slight change in the parameter values. In addition, the anisotropy of σ, resulting in nonsphericity of the equilibrium droplet shape, has to diminish the R^{is}. Thus, it seems that the recombination instability may be an effective mechanism, restricting the upper bond of EHD radii.

3. Motion and Interaction of EHDs

There are two basic physical mechanisms resulting in the motion of EHD in an inhomogeneous exciton gas. The first is connected with the momentum transfer from gas to droplets due to asymmetry of the exciton flow and of the exciton concentration distribution. The momentum transfer imparts hydrodynamic velocity to EHL, and the stationary regime is setting in owing to the friction of the EHL on the lattice (hydrodynamic mechanism). The second mechanism is connected with asymmetric condensation of excitons from supersaturated vapour on the droplet surface. It results in motion of the center of a droplet without any motion of the EHL relative to the lattice (condensation mechanism). These mechanisms lead to droplet motion in opposite directions: in the first case along the exciton gas flow, in the second case - against it. The total velocity of a droplet is $\vec{V} = \vec{V}_c + \vec{V}_h$, where $\vec{V}_c$ and $\vec{V}_h$ are the contributions to $\vec{V}$ coming from the condensation and hydrodynamic mechanisms.

To illustrate the effect of both mechanisms we list here some results for the case $\Lambda^* \ll R$, when diffusion approximation holds. The expression for droplet velocity in the condensation regime is

$$\vec{V}_c = \frac{3D}{N} \nabla n_\infty \,. \tag{5}$$

It is valid, when $\gamma = 1$, γ is the sticking coefficient of excitons on the EHD surface. The V_h, having the opposite sign, is small, as compared with V_c, when the hybrid parameter $\Lambda^*/v_T R \ll 1$. In the opposite case, when $\gamma = 0$, dominates the drift velocity caused by hydrodynamic mechanism

$$\vec{V}_h = -\frac{3}{2} \frac{T\tau_\ell}{mN} \nabla n_\infty \,. \tag{6}$$

At intermediate values of γ the condensation mechanism dominates when $\gamma R/\Lambda^* \gg 1$, $\gamma \gtrsim (v_T \tau_\ell / R)^{1/2}$. Proceeding from physical consideration γ is likely to be quite close to unity. Therefore, the value of the hybrid parameter is of a decisive significance. If $v_T \tau_\ell / R < 1$, V_c dominates, but if $v_T \tau_\ell / R > 1$, V_h dominates. For the parameter values used above and for $\nabla n_\infty \sim 3 \cdot 10^{16} \cdot \mathrm{cm}^{-3}$ the velocity $V \sim 10^3$ cm/sec. Although the motion of droplets in an inhomogeneous exciton gas has been discussed earlier (for review see [7]), the both formulas (5) and (6) differ from that known from literature.

As a consequence of the nonuniform exciton concentration distribution around the drops, there should arise interaction, attraction or repulsion, among them. The corresponding velocity of droplet motion in condensation regime at $\gamma = 1$ is

$$\vec{V}_c = \frac{3DR}{N} (n_\infty - n_T) \frac{\vec{r}}{r^3} \,, \tag{7}$$

r is the distance between droplets. It is seen from eq.(7) that the interaction follows the inverse square law, and the sign of the velocity is regime-dependent: in the condensation regime $(n_\infty > n_T)$ droplets are repulsed, and in evaporation regime $(n_\infty < n_T)$ they are attracted. Let us mention in conclusion that in Knudsen limit the velocity has an opposite sign.

4. References

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