Production and decay of exciton liquid-phase embryos in germanium under conditions of non-uniform strain

B. M. Ashkinadze and I. M. Fishman

A. F. Ioffe Physicotechnical Institute, USSR Academy of Sciences

(Submitted August 9, 1977)
Pis'ma Zh. Eksp. Teor. Fiz. **26**, No. 6, 484–487 (20 September 1977)

Excitons are usually condensed in Ge in the form of drops that can grow to dimensions on the order of several microns. These drops are in stable equilibrium with the excitons [on the ascending branch of $n(r)$, see R. N. Silver, Phys. Rev. **B11**, 1569 (1975); V. S. Bagaev, N. V. Zamkovets, L. V. Keldysh, N. N. Sibel'din, and V. A. Tsvetkov, Soviet Phys. JETP **43**, 783 (1976)].

PACS numbers: 71.35.+z

We have investigated exciton condensation under conditions when the produced embryo drop was immediately removed from the crystal region in which the exciton concentration was sufficient to ensure its further growth—i.e., under conditions when all the drops were in unstable equilibrium with the exciton gas—on the descending branch of $n(r)$. It turned out that in such a system of small embryonic droplets a number of effects are observed, analogous to phenomena that occur at high levels of excitation in germanium crystals.[2]

To remove rapidly the drops from the region in which they were produced and could grow, a non-uniform strain was produced in the sample (Fig. 1). It is known that in the case of uniaxial uniform strains the energy per pair of particles in the drops increase slightly (at low pressures), and the exciton energy decreases with increasing strain.[3] Consequently, in the case of non-uniform

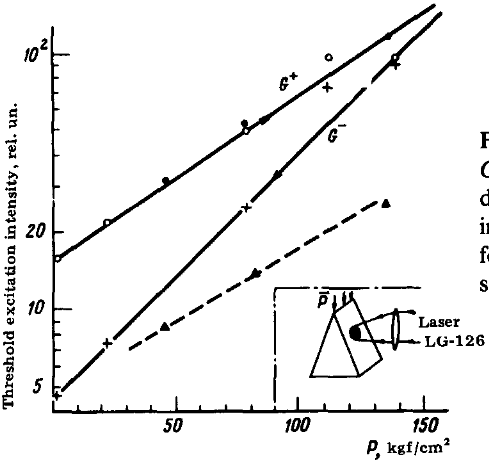

FIG. 1. Change of the thresholds of the ascending G_+ and descending G_- branches of the dependence of 709-meV radiation on the pump with increasing pressure P; $T = 1.8$ K: 0, +—non-uniform pressure, ●▲—uniform pressure. The insert shows the experimental setup.

strain the drop and the excitons are acted upon in the pressure region up to P_{cr}[3] by forces directed in opposite directions. The drops will then leave the excitation region and go to the region of low strain, while the excitons, to the contrary, will go to the region of high strain. Since the drop mobility is much higher than that of the excitons, one can expect the spatial separation of the EHD and of the excitons to be caused mainly by the drop motion.

Under these conditions it is possible to produce an appreciable number of small droplets that are situated on the unstable branch of $n(r)$, and to study the behavior of such a system.

The fact that all drops were on the optical branch of $n(r)$ was revealed by an investigation of the hysteresis[4] that leads to an ambiguous dependence of the drop radiation intensity (the 709-meV line) on the excitation level. When the pump is increased, the first drops are removed when an appreciable supersaturation of the exciton gas is reached, $n^*/n_{T_\infty} = \exp(2\sigma/n_0R^*kT)$; if the excitation increases slowly, the produced embryo, with radius R^*, have time to grow to the maximum radius $R_{\max}$ possible at the given temperature, and determined from the condition $n^* = n_{T_\infty}\exp(2\sigma/n_0kTR_{\max}) + (R_{\max}/3v\tau_0)n_0$.[1] With further increase of the pump, the number of drops of radius $R_{\max}$ will increase in the system. If the excitation level is now decreased, then the exciton concentration begins to decrease and consequently also the drop radius R. At $n^{**} \geqslant n_{T_\infty}$ the drops reach a minimum radius $R_{\min}$, corresponding to a stable state of the system, and this point determines the threshold of the descending hysteresis branch.

In our experiment the Ge sample was excited by laser light (1.15 μm); a chopper operating at 120 Hz was placed past the sample ahead of the monochromator entrance slit. For each value of the applied pressure we plotted the hysteresis of the recombination radiation of the liquid phase and investigated the pressure-induced shift of the thresholds of the ascending and descending hysteresis branches (G_+) and (G_-) (Fig. 1).

1. It is seen that both thresholds increase under pressure, but the threshold G_- at which the radiation vanishes shifts more rapildy than G_+, so that the hysteresis vanishes at a pressure ~140 kgf/cm². For a sample with the same orientation, but in the form of rectangular parallelepiped—under uniform deformation—the threshold G_+, and G_- also vary with pressure, as seen from the figure, but G_+/G_- remains practically constant.

The increase of the threshold G_+ is due to the decrease of the binding energy of the particles in the drops under pressure. The vanishing of the hysteresis at $P = 150$ kgf/cm² in an inhomogeneous-

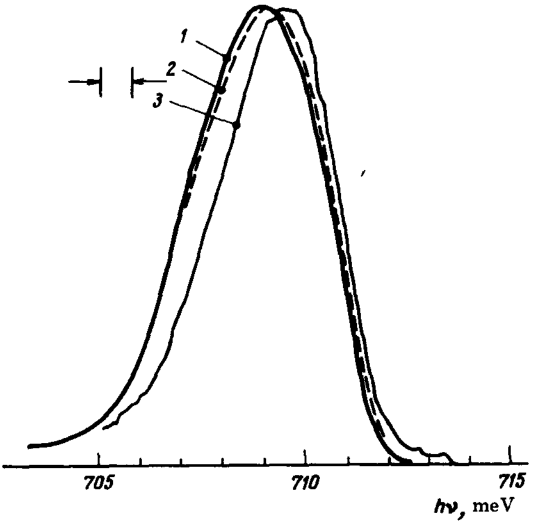

FIG. 2. Emission spectra of drops in the absence of pressure (1), under uniform pressure $P = 150$ kgf/cm^2 (2), and under non-uniform pressure $P = 150$ kgf/cm^2; $T = 1.8$ K.

ly compressed sample means that none of the drops reaches a radius exceeding $R_{\min}$, where they can exist for a long time and lead to hysteresis, i.e., all the drops have dimensions $R^* < R < R_{\min}$.

2. The drop dimensions were estimated from an analysis of the EHD emission spectra (Fig. 2). It is seen that in the case of a non-uniform pressure of ~ 150 kgf/cm^2, the spectrum shifts by ~ 0.3 meV towards the shorter wavelengths, and the emission line becomes slightly narrower. At higher pressures ($P > 250$ kgf/cm^2) the line shifts, as usual, towards longer wavelengths. Under uniform pressure, as seen from Fig. 2, there is practically no shift of the spectrum. The short-wave shift of the spectrum can apparently be attributed to a decrease in the binding energy per pair of particles in the small-radius drop[5]: $\phi = \phi_0 - 2\sigma/n_0R$ and the average radius of the drop can be estimated at $R = 2\sigma/n_0\Delta\phi \sim 4\times 10^{-6}$ cm, which is close to the dimension of the critical embryo.[4]

In the case of non-uniform pressure ~ 150 kgf/cm^2, the EHD radiation intensity, at a pump exceeding the threshold value by approximately one order of magnitude, decreases by a factor 3–5 in comparison with the undeformed sample.1)

The decrease of the radiation intensity is apparently due to a decrease in the lifetime of the small droplets drawn out of the excitation region. In fact, if a drop would turn out to be in an "empty" crystal, then it would become annihilated as a result of recombination and evaporation. The characteristic lifetime of the drop is then equal to the "cutoff time" t_c,[3] which amounts to $\sim 2\times 10^{-5}$ sec for a drop of radius $\sim 10^{-4}$ cm and 2 K. At $R \lesssim 10^{-5}$ cm, however, the role of evaporation from the drop increases because of the lowering of the binding energy per pair of particles in the drop, and the time t_c drops abruptly to $t_c < 2\times 10^{-7}$ sec.

No such catastrophic decrease of the lifetime and of the radiation intensity of the drops is observed because, as shown in[6], at sufficient EHD density, when the condition $4\pi R^2 v_T N_k > 1/\tau_l$ is satisfied, the evaporated excitons will stick rapidly to other drops and slow down their annihilation.

4. The foregoing considerations explain, in our opinion, a number of effects investigated in[2] and occurring at high excitation levels. It is known that when a certain threshold pump is reached, the drops move away[3] from the excitation region and this causes (a) a decrease of the lifetime in the drops[6] (or saturation of the EHD radiation signal under stationary excitation[2]) and (b) a

threshold-dependent appearance of clusters of a dense plasma in the case of microwave conduction.[2]

It can be assumed that when the dispersal of the drops begins, an appreciable fraction of the drops leaves the excitation region before it manages to grow to the dimension $R_{\min}$. These small droplets with radius $R < R_{\min}$ will be evaporated rapidly, and when $R \gtrsim R^*$ is reached and the binding energy of the particles in drops is close to zero, the instantaneous evaporation—"explosion" of the embryo—takes place and leads to the appearance of a short-lived small cluster of dense plasma or of "metallized" excitons. The number of such "explosions" increases sharply when the dispersal and fragmentation of the drops begins, and it is this which leads to the threshold-like appearance of microwave radiation.

To verify this assumption, the sample was placed inside an 8-mm band waveguide and subjected to non-uniform pressure. It was observed that the threshold for the appearance of sharply fluctuating microwave absorption2) shifted to appreciably lower excitation levels, whereas the pressure of the condensation phenomenon (emission of the 709-meV line) increased, as noted above, and at $P \sim 200$ kgf/cm^2 these thresholds turned out to be practically equal. Thus, when the produced embryos (droplets) were removed rapidly from the excitation region, the appearance of dense-plasma clusters was observed.

The authors thank S.M. Ryvkin and A.V. Subashiev for useful discussions.

1)This fact was noted in a number of papers (see, e.g.,[3]).

2)Under stationary excitation, the anomalous microwave absorption is registered in the form of a threshold-dependent increase of the noise in the microwave channel.

---

[1] R.N. Silver, Phys. Rev. B **11**, 1569 (1975); V.S. Bagaev, N.V. Zamkovets, L.V. Keldysh, N.N. Sibel'din, and V.A. Tsvetkov, Zh. Eksp. Teor. Fiz. **70**, 1501 (1976) [Sov. Phys. JETP **43**, 783 (1976)].

[2] B.M. Ashkinadze and I.M. Fishman, Pis'ma Zh. Eksp. Teor. Fiz. **22**, 336 (1975); **24**, 342 (1976) [JETP Lett. **22**, 158 (1975); **24**, 309 (1976)].

[3] I.C. Hensel, T.G. Phillips, and G.A. Thomas, The Electron-Hole Liquid in Semicond., to be published.

[4] R.M. Westervelt, I.L. Staehli, E.E. Haller, and C.D. Jeffries, in: Proc. Oji Seminar on Physics of Highly Excited States, Japan, 1975.

[5] B. Etienne, C. Benoit à la Guillaume, and M. Voos, Phys. Rev. Lett. **35**, 536 (1975).

[6] B.M. Ashkinadze and I.M. Fishman, Fiz. Tekh. Poluprovodn. **11**, 408 (1977) [Sov. Phys. Semicond. **11**, 235 (1977)].