Emission of electron-hole droplets or lasing action in germanium crystals

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A new interpretation is offered for the emission which has been attributed to electron-hole droplets in Ge: This emission of electron-hole droplets is laser action of the crystal.

In this letter we wish to use a few examples to show that the characteristic properties of the emission which has been attributed to electron-hole droplets in Ge[1] might also be explained in another way, on the basis of a laser model, according to which this emission stems from a selective amplification (due to stimulated transitions) of an exciton luminescence—the predominant spontaneous emission—by total-internal-reflection modes of a natural optical cavity resonator which results from the faceting of the crystal (Fig. 1). It is assumed here that the droplet bands arise when a lasing threshold is reached in the natural resonator or when conditions approach the threshold regime, and light is emitted from the crystal as a result of its scattering by various types of optical inhomogeneities.

1. Denoting by $I(h\nu)$ the light which is amplified as it passes repeatedly through the active region of the natural resonator [with an effective gain curve $g(h\nu)$], and denoting by $I_0(h\nu)$ the spectrum of the predominant spontaneous luminescence, we can write

$$I(h\nu) \approx I_0(h\nu)\exp[g(h\nu)L^*] \equiv I_0(h\nu)G(h\nu), \tag{1}$$

where L^* is the effective path length for a photon in the resonator. For lightly doped or pure deformed Ge crystals, in whose emission spectra the exciton bands are substantially broadened, the maximum of the lasing band at a relatively low pump level J or at a relatively high temperature T (with respect to the threshold value of J at $T = \text{const}$ and that of $T = J = \text{const}$) should be slightly shifted from the maximum of $G(h\nu)$. As J is increased (under the condition $T = \text{const}$) or as T is reduced (with $J = \text{const}$), however, i.e., as the lasing threshold is approached, and the $G(h\nu)$ curve becomes sharply narrower, this maximum should shift toward the $G(h\nu)$ maximum and should stabilize near that position.

It can be seen from Figs. 1 and 2 that experiments[2,3] support these arguments. We wish to stress that despite the observed shift of the maximum and despite the deformation of the droplet emission band as J or T is varied, the energy position found for the $G(h\nu)$ maximum from the experimental data and expression (1) remains constant, as we would expect on the basis of the laser model. In both cases, this energy position is the position predicted by the laser model (shown by the arrow in Figs. 1 and 2).

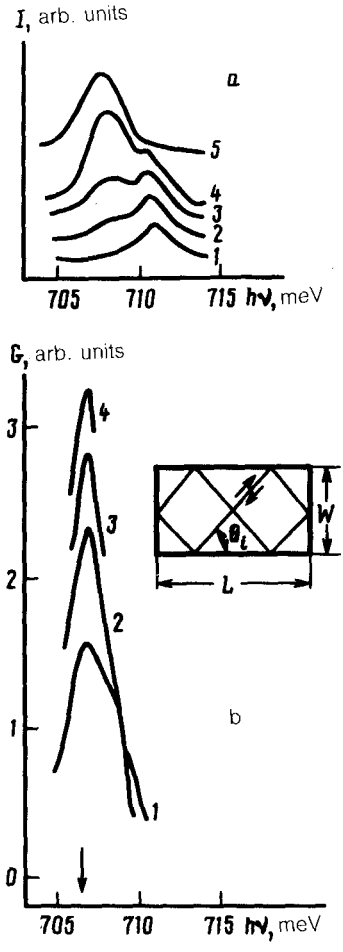
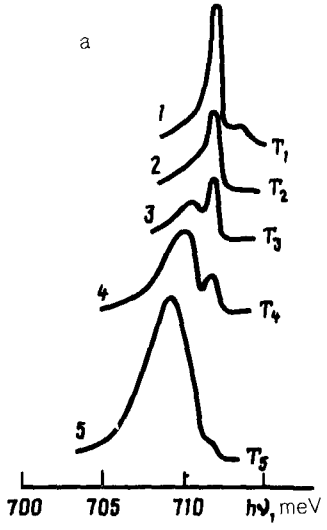


FIG. 1. The spectra[2] $I(h\nu)$ (a) and curves of $G(h\nu)$ obtained from them (b) for deformed Ge ($T = 4.2$ K; J increases from spectrum 1 to spectrum 5). Curves 1–4 in part *b* show the result of a division of the corresponding spectra 2–5 in part *a* by spectrum 1 in part *a*. The inset shows one of the total-internal-reflection modes for a Ge sample with a geometric shape typical of that in studies of the droplet emission (with a rectangular cross section).

To determine the $G(h\nu)$ curves, we replaced the spectrum $I_0(h\nu)$ by the spectrum $I(h\nu)$ at the lowest J (Fig. 1) or at the highest T (Fig. 2); i.e., we made use of the circumstance that the shape of the exciton luminescence spectrum of the crystal does not change substantially upon slight variations in J and T in the part of the spectrum of interest here.

2. Since the gain α of Ge is very small in magnitude ($\approx 10^{-3}$–10^{-2} cm^{-1}) at low T in the region of the droplet emission bands, the optical loss of the natural resonator ($\alpha + \rho$) includes an important component from the scattering by the crystal faces (ρ). According to the laser model, the lasing develops on total-internal-reflection modes, each of which corresponds to a certain light propagation direction in the crystal, which forms a closed path (Fig. 1). For a natural resonator with a rectangular cross section (Fig. 1), we know that a direction of this nature is specified by the formula $\tan\theta_i = (W/L)(l_i/w_i)$, where l_i and w_i are the numbers of reflections from



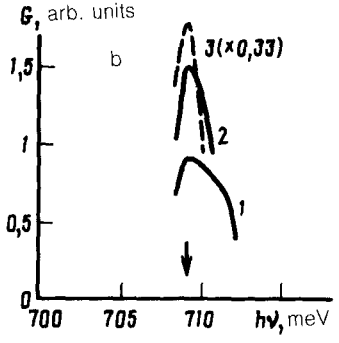


FIG. 2. $I(h\nu)$ spectra[3] (a) and curves of $G(h\nu)$ obtained from them (b) for lightly doped Ge ($J = \text{const}$, 4.2 K $= T' > T_2 > T_3 > T_4 > T_5 = 1.7$ K). Curves 1–3 in (b) are the results of the division of spectra 2–4, respectively, in part *a* by spectrum 1 in part *a*.

faces L and W, respectively, and θ_i is the glancing angle with respect to face L ($\theta_0 \leqslant \theta_i \leqslant \pi/2 - \theta_0$, where θ_0 is the limiting angle of total internal reflection). It is easy to show, by following Ref. 4, that the effective loss coefficient due to scattering upon reflection from the crystal faces for the ith total-internal-reflection mode of the natural resonator (ρ_i) is given by

$$\rho_i = [\ln(1/r^*)/W][(\operatorname{tg}\theta_i + W/L)/\sqrt{1 + \operatorname{tg}^2\theta_i}], \tag{2}$$

where r^* is the effective coefficient during total internal reflection (with a scattering loss $r^* < 1$). Since we have $W/L \leqslant 1$ and $0.25 < \tan\theta_i < 4$, we find $0.25 < (\tan\theta_i + W/L)/\sqrt{1 + \tan^2\theta_i} < 1.5$. It follows that we have $\rho_i \sim 1/W$ approximately; i.e., the threshold for lasing (or that for droplet emission) increases with decreasing thickness of the crystal.

In samples of small dimensions the component of the optical loss of the resonator, which stems from the absorption of the crystals, will be relatively small in comparison

with scattering by the crystal faces. Consequently, the threshold for lasing (or that for droplet emission) in this case should not depend strongly on T, since the latter affects only the absorption of the crystal. The experimental results support this interpretation.[5]

3. If the laser model corresponds to reality, the droplet-emission spectra should exhibit an effect which has been studied well in in-resonator laser spectroscopy: The weak additional absorption which is introduced in the resonator manifests itself in a pronounced erosion of the lasing band if the spectral position of the absorption line $[\alpha_\Lambda(h\nu)]$ is in the region of the wider lasing band. If we denote by $\bar{I}_0(h\nu)$ the lasing band before the weak additional absorption is introduced in the resonator, and if we denote $\bar{I}(h\nu)$ the resultant lasing band, we can write

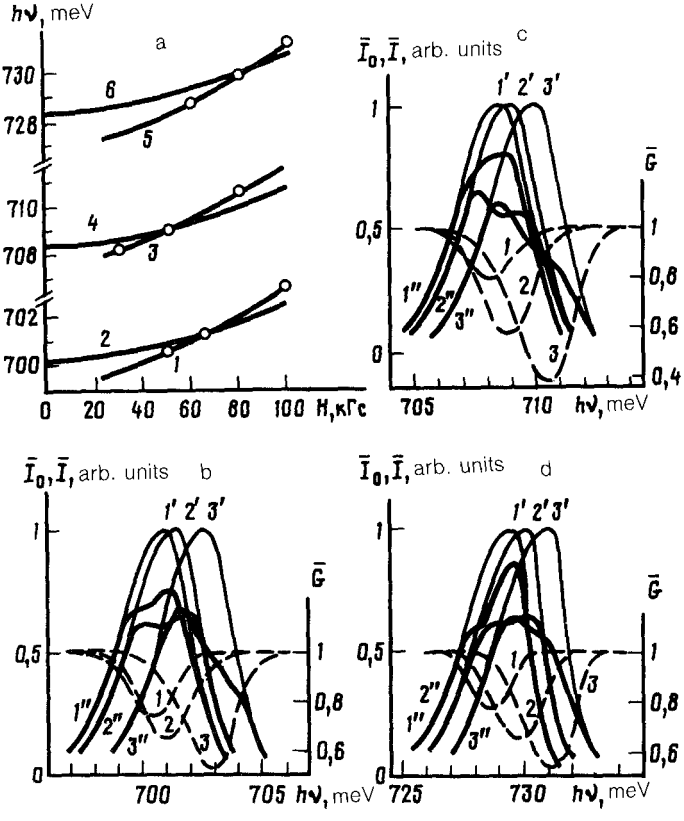


FIG. 3. a: Energy position of the additional absorption lines [involving $TO + TA$ phonons (1), TO phonons (3), and $2TA$ phonons (5)][6] and of the emission $\bar{I}_0(h\nu)$ [with the emission of $TO(2)$, $LA(4)$ and $TA(6)$ phonons][7] versus H. b,c,d: Curves of $\bar{G}(h\nu)$ (1–3), experimental spectra of $\bar{I}(h\nu)$ (1"–3"), and $\bar{I}_0(h\nu)$ (1'–3') [with emission of TO (b), LA (c), and TA (d) phonons][7] at the following values of H (kG): 50, 65, and 100 (b); 30, 50, and 80 (c); 60, 80, and 100 (d). The positions of the maxima of the $\bar{G}(h\nu)$ curves are shown by the points in Fig. 3(a).

$$\bar{I}(h\nu) \approx \bar{I}_0(h\nu) \exp[-\alpha_\Lambda(h\nu) L^*] \equiv \bar{I}_0(h\nu) \bar{G}(h\nu). \quad (3)$$

It turns out that a weak additional absorption can be arranged in the natural resonator by placing the Ge crystal in a strong magnetic field[6] $\mathbf{H} \| [100]$. In this case, new absorption lines should appear in the Ge absorption spectrum because of transitions [involving *TO* (36.0 meV), *TA* (8.2 meV), and *LA* (27.5 meV) phonons and various combinations thereof] from the valence band to states which are coupled to the lowest-lying L level in the conduction band. With increasing H, these new absorption lines intensify and should shift into the violet region of the spectrum more rapidly than the droplet-emission bands. Some of these weak absorption lines pass through a region of some sort of droplet-emission band as H is increased [Fig. 3(a)]. Experiments confirm [Figs. 3(b), 3(c) and 3(d)] that an erosion is indeed observed in the droplet-emission spectra at this time. Furthermore, for each of these bands the energy positions calculated from (3) for the maxima of the $\bar{G}(h\nu)$ curves on the basis of the experimental $\bar{I}(h\nu)$ and $\bar{I}_0(h\nu)$ lines given in Ref. 7 and the maxima of the corresponding weak absorption lines coincide. The intensity of $\bar{G}(h\nu)$ increases significantly with increasing H, and their maxima pass through the middles of the lines of the various droplet-emission bands at very different values of H, but at values which are strictly determined in the laser model.

We conclude with a discussion of the mechanism for the formulation of a population inversion in the exciton system in Ge.

States with a population inversion apparently arise in the course of indirect exciton transitions which are due predominantly to an inelastic exciton-exciton interaction.[8] In the course of this interaction, one of the indirect excitons decays into a free electron and a free hole, or it goes into one of the excited states, while another annihilates, emitting a certain type of phonon and a photon with the corresponding energy deficiency. Evidence in favor of this suggestion comes from the circumstance that this exciton-exciton mechanism for the formation of a population inversion in the exciton system makes it possible in principle to arrange, over a wide spectra region, a gain $[g(h\nu)]$ substantially higher than the absorption by free carriers (α_H), in contrast with the well-studied exciton-phonon mechanism[8,9] and the exciton-electron (or hole) mechanism.[8] This absorption by free carriers is the predominant type of absorption in the case of Ge, and it is a component of the loss in the natural resonator which is impossible in principle to eliminate. The reason is that in the case of the exciton-exciton mechanism for the formation of a population inversion in the exciton system we would have $g \sim n_{ex}^2$, while in the case of the exciton-phonon mechanism we would have $g \sim n_{ex}$, and in the case of the exciton-electron (or hole) mechanism we would have $-g \sim n_{ex} n_e(n_h)$, where $n_e(n_h) < n_{ex}$. The explanation here is that at low value of T the nonequilibrium carriers in Ge quickly combine to form excitons [$n_e(n_h)$ and n_{ex} are the densities of free electrons (free holes) and excitons, respectively].

It might appear at first glance that the exciton-exciton mechanism for the formation of a population inversion in the exciton system contradicts the shape of the lasing (or droplet-emission) band which is observed in Ge and also the energy position of its maximum [this mechanism for the formation of a population inversion in the exciton system should correspond to the $g(h\nu)$ gain line: a broad, structureless band with a

stretched-out long-wavelength edge and with a maximum shifted in the long-wavelength direction from the exciton line by an amount roughly equal to the exciton binding energy (≈ 3 meV for Ge), which is far smaller than the observed shift]. Actually, there is no contradiction since the shape of the lasing (or droplet-emission) band and its spectral position in the case of a selective loss [$\alpha(h\nu)$] in the natural resonator are determined, as follows from Ref. 10, not by the shape of the $g(h\nu)$ gain line but (approximately) by the curve of $[g(h\nu) - \alpha_H]/[\alpha(h\nu) + \rho]$. In other words, they are determined substantially by the shape of the absorption edge in this part of the spectrum.

[1]Ya. E. Pokrovskiĭ and K. I. Svistunova, Pis'ma Zh. Eksp. Teor. Fiz. **9**, 435 (1969) [JETP Lett. **9**, 694 (1969)].
[2]J. P. Wolfe *et al.*, Phys. Rev. B **18**, 1479 (1978).
[3]B. V. Novikov *et al.*, Fiz. Tverd. Tela (Leningrad) **15**, 459 (1973) [Sov. Phys. Solid State **15**, 326 (1973)].
[4]V. P. Gribkovskiĭ, *Theory of Light Absorption and Emission in Semiconductors*, Naukai tekhnika, Minsk, 1975.
[5]V. M. Asnin *et al.*, Zh. Eksp. Teor. Fiz. **84**, 2129 (1983) [Sov. Phys. JETP **57**, 1239 (1983)].
[6]J. Vitins *et al.*, Phys. Lett. **70A**, 137 (1979).
[7]H. L. Stormer and R. W. Martin, Phys. Rev. B **20**, 4213 (1979).
[8]C. B. Guillaume *et al.*, Phys. Rev. **177**, 567 (1969).
[9]W. P. Dumke, Phys. Rev. **127**, 1559 (1962).
[10]M. S. Brodin *et al.*, Kvant. Elektron. (Moscow) **16**, 489 (1989) [Sov. J. Quantum Electron. **19**, 324 (1989)].

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