Static friction of electron-hole drops in germanium

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Investigation of the hysteresis in the EHD exciton system under conditions of inhomogeneous deformation showed that the drops are retained by some defects in the crystal and remain stationary until the force exceeds a certain magnitude that depends on the radius of the drop.

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An electron-hole drop, which is produced in an ideal crystal, moves like a Brownian particle; the corresponding diffusion coefficient $D = v_T^2 \tau_p = (kT/Vn_0 m^*)\tau_p$ is $\sim 10^{-2}$ cm^2/sec for a drop of volume $V = 10^{-12}$ cm^3 ($n_0 = 2\times 10^{17}$ cm^{-3} is the density of the carriers in the drop, m^* is the effective mass of the particle pair, and τ_p is the relaxation time of the drop's momentum $\sim 10^{-8}$ sec). Therefore, if the excited region of the crystal is $x^3 \sim 10^{-3}$ cm^3, then the drops must leave it in the time $t \sim (x^2/D) \sim 1$ sec. Investigation of the hysteretic effects[1,2] showed, however, that the drops do not leave the excitation regions during the time $\sim 10^3$ to 10^6 sec; it was assumed[2] that the drops were captured by the impurity centers.

Investigation of the hysteretic effect of the condensation process due to a nonuniform deformation of the crystal[3] showed that the threshold of the "down-going" branch of the G-hysteretic dependence of the radiation intensity of EHD on pumping gradually approaches the threshold of the "up-going" branch G_+. If the drops are mobile $\mu = D/kT \sim 5\times 10^{13}$ sec/g (see above), then the hysteresis will disappear at a very slight deformation; a smooth decrease of the hysteresis is attributable to the fact that the drops with a small radius are nonstationary and those with a large radius can move in the field of nonuniform deformation.

In this paper we show that the drops are held by the crystal defects. To displace the drop a force, which depends on its radius, must be applied to it. Thus, the drops have a "static friction."

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The experiment was performed in the following way. A pure n-Ge sample ($N_d, N_a = 3\times 10^{10}$ cm^{-3}),[1] cut in the form of a trigonal prism, was irradiated by two light sources —a LG-38 continuous gas laser and a GaAs pulsed laser with a repetition frequency $f\sim 0.5$ Hz. Since the crystal was subjected to a uniaxial compression along the [100] axis, the nonuniform deformation ϵ exerted a force $F\sim \text{grad}\,\epsilon$ on the drops.

As shown in Ref. 4, if the sample is illuminated by a continuous excitation source with an intensity $G > G_+$ and then subjected to a strong light pulse of short duration, the system of EHD and excitons will become totally stable—for the given pumping the number of drops will be maximum and their radius will be minimum. The exciton concentration will also be minimum. Thus, when there are two light sources and G increases smoothly, the radiation intensity of EHD in described by curve 1 (Fig. 1a);

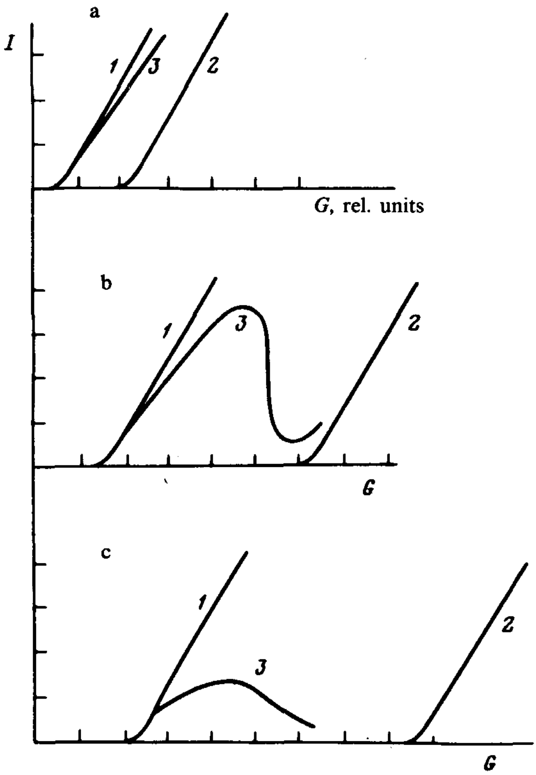

FIG. 1. Dependence of the radiation intensity of EHD I on pumping G at different pressures. 1, Down-going hysteresis branch plotted with the intensifier pulse turned on and a smoothly increasing G; 2, up-going branch plotted for a slowly increasing G; 3, radiation intensity of EHD obtained after the intensifier pulse was turned off at point A. a, $P=0$; b, $P\approx 100$ kg/cm^2; c, $P\approx 200$ kg/cm^2.

the increase in the radiation intensity corresponds to the increase in the number of drops of size $R_{\min}$ and the threshold point corresponds to $G_{\min}$ and $n_{\min}$. In the absence of the intensifier pulse we have the up-going branch with the threshold G_+ (curve 2), which corresponds to the formation of maximum size drops $R_{\max}$ in the supersaturated exciton gas ($n_e \gg n_{T\infty}$). Thus, curves 1 and 2 correspond to the maximum permissible radii of the drops. If the intensifier pulse is turned off at some point when dependence 1 is plotted, then, as G increases, the number of drops will remain constant and equal to that attained at point A; the $I(G)$ dependence is determined by the increase in the radius of the drops (curve 3) and by the simultaneous increase of

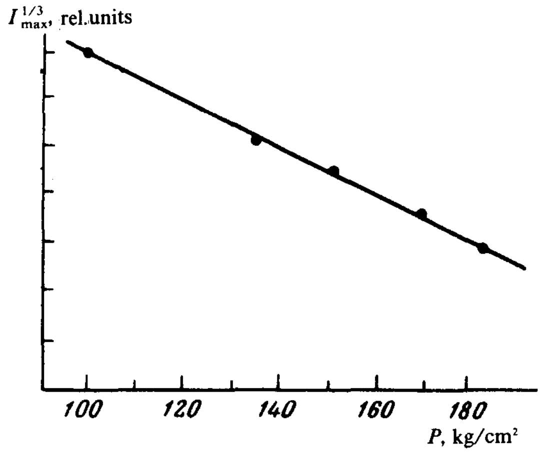

FIG. 2. Dependence of $I_{max}^{1/3}$ on pressure, according to curves 3 in Fig. 1.

the exciton density. The dependences 1–3 were plotted for different values of the nonuniform deformation (Figs. 1b and 1c).

G_- and G_+ increase with increasing threshold pressure, since the binding energy of the particles in the drop decreases at small deformations.[5] It can be seen that starting with the pressures $p \geqslant 100$ kg/cm^2 (grad $p \geqslant 200$ kg/cm^2) the $I(G)$ dependence (curve 3 in Fig. 1) is nonmonotonic. As the radius of the drops increases, the radiation intensity initially increases to $I_{max}(p)$ and then decreases. The irreversible decrease of the radiation intensity apparently indicates that the drop, having grown to a certain size $R^*(p)$, is unable to stay in place and leaves the excitation region. Since new drops cannot be formed ($G < G_+$), a striking effect can be observed—the radiation intensity decreases with increasing excitation level.

Figure 2 shows the dependence of $I_{max}^{1/3}$ on the pressure gradient. This curve is a qualitative representation of the dependence of the maximum radius of the stationary drop ($I \sim R^{*3}$) on the magnitude of the applied force. It can be seen that $R^* \sim 1/F$. To obtain a more exact $R^*(F)$ dependence, we must take into account the variation of the lifetime of the drops and the increase of the minimum radius of the drops in the deformed Ge. It can be shown that both these factors produce a negligible change in the dependence of R^* on F.

If a drop is captured by the impurity center with a binding energy ϵ_1 and, after increasing to a radius R^*, it breaks away with a force F, then we can use the following relation in the simple model to describe the escape of a drop.

$$\epsilon_1 = \gamma \frac{4\pi}{3} n_0 R^{*3} \rho ,$$

where ρ is the characteristic radius of the restoring force. If we assume that the binding energy between the drop and the center is ~ 5 MeV, ρ is $\sim 10^{-6}$ cm, and R^* is $\sim 3 \times 10^{-5}$ cm, then we can estimate the force γ that must be applied to the pair of particles in the drop in order for it to break away from the center; it turns out that γ is ~ 200 MeV/cm. The value of γ, which was experimentally estimated from the shift of the peak of the radiation line of EHD under pressure,[5] $\gamma \approx [d(h\nu_{max})/dp]$, is $\leqslant 1$ MeV/cm. This value differs from the estimated force of the simple capture model by 2 orders of magnitude. The experimental dependence $R^* \sim (1/F)$ also differs from the $R^* \sim 1/F^{1/3}$ dependence for this model. Thus, the mechanism of capture and separation of EHD from the lattice defect requires further study.

In conclusion, we note that the static friction of EHD can explain the results obtained earlier; it was shown in Refs. 6 and 7 that upon dispersal of the drops by the phonon wind there occurs a threshold pumping, which corresponds to the average minimum density of the nonequilibrium carriers $\bar{n}^* \approx 10^{15}$ cm^{-3}. At $\bar{n} < \bar{n}^*$ there is no dispersal and at $\bar{n} > \bar{n}^*$ the drops begin to move at the minimum velocity of $v_{\min} \approx 5 \times 10^3$ cm/sec.

If the drops scatter from a layer of thickness L, then the force F acting on the drop is given by the expression[8] $F = 4\pi\xi^2 L(\bar{n}/n_0)V$ ($\bar{n}$ is the average density of the particles in the layer, ξ is the constant for electron-phonon drag, and V is the volume of the drop). Equating F to the force F^*, which holds the drop of radius $R \sim 1$ μm in place $[F^* = \gamma(4\pi/3)n_0R^3]$, we obtain $\bar{n} \sim 10^{15}$ cm^{-3}. After the drop begins to move, its velocity $v \sim (\gamma\tau/m^*) \approx 3 \times 10^3$ cm/sec.

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